

ACI MANUAL OF CONCRETE INSPECTION

SP-2(99)



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ACI MANUAL OF CONCRETE INSPECTION

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Publication SP-2(99)
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Ninth Edition

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First printing, February, 2000

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PREFACE

This manual is for the guidance, assistance, and instruction of concrete inspectors and others engaged in concrete construction, such as field engineers, construction superintendents, supervisors, laboratory and field technicians and inspectors, and workers. Journeymen may find it valuable as a reference for improving their work, and apprentices can use it as an effective instruction manual. Although designers' duties are primarily confined to office work they may find the manual a valuable tool that provides a ready description of the various details of concrete construction. Such information may enable designers to better adapt their designs to the realities of field construction.

Because of the diverse possible uses of the manual, and the varied backgrounds of the readers, it includes the reasons behind the technical instructions.

Except for the seventh edition, each previous edition included a series of minor revisions over the previous edition. The seventh edition was completely rewritten. This ninth edition was revised where deemed necessary or required due to changes in reference documents. Much of the older material has been retained because experience has shown it to be useful and technically correct. The field of concrete construction is ever-changing, however, and some of the biggest advances in modern-day construction have taken place in the concrete field. A list of only a few of the recent developments in materials, equipment, and processes includes shrinkage-compensating cement, sophisticated admixtures, fibrous concrete, epoxy resins, high capacity and automated concrete production equipment, high-strength concrete, and systems building. Although there has seldom been reason to change the fundamentals developed earlier, added material is necessary to recognize new technology. The field of inspection has been expanded drastically, and the approach and emphasis modified in recent years, without change to the basic technology of the past. The need to cover all items that affect inspection has been the reason for continuing to revise this *ACI Manual of Concrete Inspection*.

In preparing this edition of the manual, as with previous editions, the task of ACI Committee 311 was not to make policy on construction practices, but rather to interpret the policies set forth by other authorized bodies. As before, the main emphasis of the manual is on the technical aspects of inspection and construction. Administrative factors of inspection are generally limited to the first chapter. The manual covers brief summaries of many subjects in concrete technology. The reader is encouraged to read *ACI Manual of Concrete Practice* for further information.

Because this manual is general and broad in nature, no part of the manual should be included by reference in contract documents. Applicable inspection requirements for each project must be determined and specified as necessary.

ACKNOWLEDGMENTS

The manual is based on information from many sources, organizations, and individuals whose contributions are gratefully acknowledged. The published references are listed at the end of the text. References to standard specifications and methods of testing are listed separately.

The original manuscript was prepared by Joe W. Kelly, author-chairman of Committee 311, and revised over a period of years to achieve a first edition in 1941. The second edition, also in 1941, included a number of corrections and minor revisions. The third edition, in 1955, incorporated many constructive suggestions from users. The fourth edition, in 1957, brought several sections up to date and contained editorial corrections.

The fifth edition provided new information on settlement of concrete, shoring and forming, strength requirements, cold-weather concreting, and shotcrete. The sixth edition primarily provided updated information in all chapters, and included editorial and substantive changes throughout.

The seventh edition presented a complete revision of the manual by eliminating sections of the previous edition covering concreting methods no longer in use. Chapters 2, 11, 12, 13, 14, 15 (partial), 16, 17, and 18 covered material that was included in the manual for the first time. All other material was reviewed and updated as required to conform to current practice.

This ninth edition, like the eighth, has been revised as deemed appropriate by the committee. Members were assigned chapters to review, and their suggestions were discussed. Chairman Claude Jaycox was especially helpful in getting the revisions in order so the full committee could make an appropriate review. The committee thanks Mr. Jaycox.

CONTENTS

PREFACE	iii
ACKNOWLEDGMENTS	iv
CHAPTER 1—INSPECTION AND THE INSPECTOR.....	1
INSPECTION PROCESSES AND ORGANIZATION.....	1
THE INSPECTOR.....	4
REFERENCE LIBRARY	6
MEASUREMENT AND TOLERANCES	6
SAFETY	7
CHAPTER 2—STATISTICAL CONCEPTS FOR QUALITY ASSURANCE	8
TRADITIONAL QUALITY ASSURANCE	8
STATISTICAL CONCEPTS IN QUALITY ASSURANCE.....	8
BASIC STATISTICAL PROCEDURES AS APPLIED TO CONCRETE CONSTRUCTION.....	9
BASIC STATISTICAL CONCEPTS	10
STATISTICAL TOOLS.....	11
CONCLUSION.....	14
APPENDIX 1—SAMPLING BY RANDOM NUMBERS.....	14
APPENDIX 2—NORMAL DISTRIBUTION CURVES	17
APPENDIX 3—COMPUTING STANDARD DEVIATION AND REQUIRED AVERAGE CONCRETE STRENGTH.....	18
APPENDIX 4—CONTROL CHARTS ON CONCRETE MATERIALS	19
CHAPTER 3—INSPECTION AND TESTING OF MATERIALS	21
CEMENT.....	21
AGGREGATES.....	22
WATER.....	28
ADMIXTURES	28
STEEL REINFORCEMENT	29
CURING COMPOUNDS FOR CONCRETE	29
JOINT MATERIALS	29
CHAPTER 4—HANDLING AND STORAGE OF MATERIALS	31
CEMENT HANDLING AND STORAGE.....	31
AGGREGATE HANDLING AND STORAGE	31
STORAGE AND HANDLING OF POZZOLANIC MATERIALS.....	33
ADMIXTURE STORAGE AND HANDLING	33
CHAPTER 5—FUNDAMENTALS OF CONCRETE.....	34
GENERAL CLASSIFICATIONS OF CONCRETE CONSTRUCTION.....	34
CONCRETE REQUIREMENTS.....	34
NATURE OF CONCRETE	34
FREEZE-THAW RESISTANCE	37
SHRINKAGE AND SWELLING	37

CHAPTER 6—CONCRETE MIXTURES: PROPORTIONING AND CONTROL	39
METHODS OF SPECIFYING CONCRETE PROPORTIONS	39
METHOD OF PROPORTIONING FOR SPECIFIED STRENGTH OR	
WATER-CEMENTITIOUS MATERIALS RATIO (<i>w/cm</i>)	40
CONCRETE WITH POZZOLAN AND OTHER CEMENTITIOUS MATERIALS	40
PROPORTIONING FOR RESISTANCE TO VARYING EXPOSURE CONDITIONS	43
PROPORTIONS BY ABSOLUTE VOLUME	44
CONTROL OF CONCRETE PROPORTIONS	45
COMPUTATIONS FOR YIELD	48
CHAPTER 7—BATCHING AND MIXING	49
BATCHING OPERATIONS	49
MIXING OPERATIONS	53
INSPECTION	56
CHAPTER 8—INSPECTION BEFORE CONCRETING	61
PRELIMINARY STUDY	61
INSPECTION OF PREPARATORY WORK	61
FINAL INSPECTION BEFORE PLACING	68
CHECKLIST FORM	68
CHAPTER 9—CONCRETING OPERATIONS	70
SITE CONDITIONS	70
HANDLING OF CONCRETE	70
CONSOLIDATION	73
FINISHING	76
CONSTRUCTION JOINTS	79
CHAPTER 10—CURING, PROTECTION, FORM REMOVAL, AND RESHORING	81
REMOVAL AND SUPPORT OF FORMS	81
CURING	82
SPECIAL CURING CONDITIONS AND PROTECTION	84
CHAPTER 11—CORRECTION OF DEFECTS IN NEWLY HARDENED CONCRETE	
AND REPAIRS OF OLDER CONCRETE	86
PLAIN EXPOSED FORMED SURFACES	86
REPAIRS TO IN-SERVICE STRUCTURES	88
ARCHITECTURAL CONCRETE	88
STRUCTURAL CONCRETE	88
STRUCTURAL SPALL REPAIRS	89
STRUCTURAL REPAIRS USING EPOXY RESIN	90
SAFETY DURING EPOXY RESIN REPAIR OPERATIONS	91
REPAIR WITH EPOXY POLYMER CONCRETE AND MORTAR	91
INJECTION GROUTING OF CRACKS	92
CHAPTER 12—SLABS FOR BUILDINGS	94
POSITIONING REINFORCEMENT	94
MIXTURE REQUIREMENTS	94
SLABS ON GRADE	95
STRUCTURAL SLABS	97
JOINT CONSTRUCTION	98

CHAPTER 13—PAVEMENT SLABS AND BRIDGE DECKS	99
FOUNDATION (SUBGRADE AND SUBBASE COURSE)	99
FORMS	100
STEEL REINFORCEMENT	101
CONCRETE	101
PAVING	102
ACCEPTANCE	105
JOINTS	106
WEATHER PROBLEMS	108
PROTECTION FROM PREMATURE TRAFFIC	109
BRIDGE DECKS	109
 CHAPTER 14—ARCHITECTURAL CONCRETE.....	 111
GENERAL REQUIREMENTS AND COOPERATION.....	112
UNIFORMITY	113
INSPECTION PROCEDURES	114
FORMS	114
REINFORCEMENT	115
CONCRETE MATERIALS	115
MIXTURES AND MIXTURE PROPORTIONS.....	116
BATCHING, MIXING, AND TRANSPORTING	116
PLACING AND CONSOLIDATION.....	116
FINISHING—SURFACE TREATMENT	116
EXPOSED-AGGREGATE FINISH.....	117
CURING.....	118
REPAIRS	118
PRECAST MEMBERS.....	118
POST-FINISHING PROTECTION AND ERECTION.....	118
FINAL ACCEPTANCE	118
 CHAPTER 15—SPECIAL CONCRETING METHODS.....	 120
SLIPFORMING VERTICAL STRUCTURES.....	120
SLIPFORMING CAST-IN-PLACE PIPE.....	121
TILT-UP CONSTRUCTION	121
LIFT-SLAB CONSTRUCTION	123
PREPLACED-AGGREGATE CONCRETE	123
UNDERWATER CONCRETE CONSTRUCTION	124
VACUUM-TREATED CONCRETE	125
PUMPED CONCRETE	126
SHOTCRETE	128
 CHAPTER 16—SPECIAL TYPES OF CONCRETE	 132
STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE.....	132
LIGHTWEIGHT FILL CONCRETE.....	134
LOW-DENSITY CONCRETE.....	134
HIGH-DENSITY CONCRETE	136
MASS CONCRETE	137
MASS CONCRETE FOR DAMS.....	138
STRUCTURAL MASS CONCRETE	139
SHRINKAGE-COMPENSATING CONCRETE	140
 CHAPTER 17—PRECAST AND PRESTRESSED CONCRETE.....	 143
PRECAST/PRESTRESSED CONCRETE INSTITUTE	144

PRECAST CONCRETE	144
REPAIRS	148
PRECAST PRESTRESSED CONCRETE	148
CAST-IN-PLACE PRESTRESSED CONCRETE	150
CHAPTER 18—CONSTRUCTION RELATED TO CONCRETING	153
PRESSURE GROUTING	153
GROUTING UNDER BASE PLATES AND MACHINE BASES	153
MORTAR AND STUCCO	156
CHAPTER 19—TESTING OF CONCRETE AND AGGREGATES	157
SAMPLING	157
TESTS OF FRESHLY MIXED CONCRETE	157
STRENGTH TESTS	159
ACCELERATED CURING OF TEST SPECIMENS	161
COMPRESSIVE STRENGTH OF LIGHTWEIGHT INSULATING CONCRETE	161
UNIFORMITY TESTS OF MIXERS	161
DENSITY OF STRUCTURAL LIGHTWEIGHT CONCRETE	163
TESTS OF COMPLETED STRUCTURES	163
SHIPPING AND HANDLING SAMPLES	164
AGGREGATE TESTING	164
CHAPTER 20—RECORDS AND REPORTS	168
QUALITY-CONTROL CHARTS	171
BATCH PLANT AND MIXING INSPECTION	171
CONCRETE PLACEMENT	175
GENERAL RECORD REQUIREMENTS	178
RETENTION OF RECORDS	178
CHAPTER 21—REFERENCES	179
CHAPTER 22—STANDARDS, SPECIFICATIONS, TEST METHODS, AND REPORTS	180
CHAPTER 23—CHECKLIST OF INSPECTION	185
APPENDIX	188
“GUIDE FOR CONCRETE INSPECTION” (ACI 311.4R-95)	188
“GUIDE FOR CONCRETE PLANT INSPECTION AND FIELD TESTING OF READY-MIXED CONCRETE” (ACI 311.5R-97)	200
INDEX	205

CHAPTER 1—INSPECTION AND THE INSPECTOR

INSPECTION PROCESSES AND ORGANIZATION

Need for inspection

The reason for having inspection is to ensure the requirements and intent of the contract documents are faithfully accomplished. Some inspectors, not directly or indirectly responsible to the building owner, will have different responsibilities, as described later.

The term "inspection" as used in concrete construction includes not only visual observations and field measurements but also laboratory testing and the assembly and evaluation of test data. Likewise, the term inspector also applies in many instances to individuals classed as laboratory technicians who are assigned to perform the testing, particularly in the field.

One important responsibility for the concrete inspector is the quality of the materials used in the concrete. Often, low-quality raw materials, particularly aggregate materials, can be used to produce concrete of satisfactory quality if they are suitably processed or beneficiated. The final materials entering the concrete mixture, however, must be of specified quality. It is difficult and usually impossible to produce specified concrete from nonconforming materials.

On the other hand, a principal ingredient needed for specified concrete construction is good-quality workmanship in all operations and processes. This aspect becomes an important responsibility of the inspector. It has been said that most good concrete is made from tested and certified cement; sound, durable, well-graded, and properly tested aggregates; suitable admixtures; and clean, pure water. Most nonconforming concrete is made from the same good-quality materials.

Manual skills, technical knowledge, motivation, and pride of workmanship all contribute to good workmanship, which is the real key to quality concrete construction. Workers in concreting crews may have been exposed to some technical training, but seldom adequately. Many workers have pride in their work and do make an attempt to attain satisfactory quality. The need to stay within cost limits, however, often requires an emphasis on production rate. If this consideration is uppermost, quality may receive inadequate attention. Ironically, cost may suffer also. Unsophisticated pursuit of fast production may increase the cost and slow the schedule. Techniques that speed concrete placement may add material cost or require extra finishing or repair, or lengthen the curing process.

The desire for quality has led to the establishment of inspection forces to monitor and control concrete construction. The following quotation provides an example of early-day thinking and problems regarding concrete construction. "Nor is greater care required upon any works than upon such as are to withstand the action of water; for this reason, all parts of the work need to be done exactly according to the rules of the art, which all the workmen know, but few observe," wrote Sextus Julius Frontinus, the water commissioner of Rome, in the year 97 B.C. Times have changed, but the problem still exists.

Jacob Feld, one of the most noted investigators of structural failures, listed examples in his book, "Lessons from Failures of Concrete Structures," showing that a high percentage of failures of concrete structures that he had investigated were

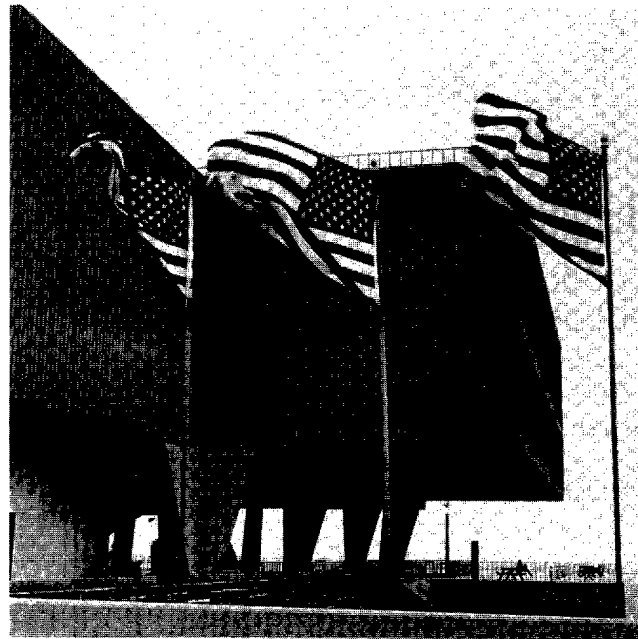


Fig. 1.1—Concrete is able to provide any structural or architectural shape and any surface design.

caused, at least in significant part, by poor construction—in other words, poor workmanship. He stated, "Competent and strict, almost unfriendly, supervision seems to be one key to the problem of how to prevent failures." He added further, "The one thing which these failures conclusively point to is that all good concrete construction should be subjected to rigid inspection... It is believed that only by this kind of inspection is it possible to guard against the failure of concrete structures."

For every monumental structural collapse, there are innumerable instances of minimal failure, if this is defined as nonconformance with design requirements. This is particularly true for properties such as durability, watertightness, and other desirable qualities.

But there is requirement of even more than all the foregoing to ensure good concrete work. Fifty years ago, the late, great F. R. McMillan said it in the foreword to the first edition of his famous *Concrete Primer* (McMillan and Tuthill 1987)

"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."

Importance of specifications

This manual provides details and descriptions of practices involved in good workmanship as well as procedures considered necessary to ensure satisfactory concrete construction.

It cannot be emphasized too strongly, however, that the inspector is governed strictly by the requirements of the contract documents, which are a part of the contract defining the work. Other references and this manual can be used only as sources of information for background data and to serve as additional guidance on items not covered by the contract documents. In



Fig. 1.2—Concrete's ability to be formed in any shape lets artistry and function go hand in hand.

some situations, inspectors will be governed by "performance criteria supplied by management" or "provisions of applicable building codes or regulations." Administrative instructions, including description of specific duties, must of course be provided by the agency employing the inspector.

The contract documents are the main criteria governing the decisions and actions of an inspector; therefore, clear specifications and drawings are essential. (Although the inspector has no control over the contract documents for the project under construction, the inspector should provide feedback to the designer in the form of suggestions for changes to use in succeeding contract documents, if appropriate.) Much of the friction in construction arises from differing interpretations of indefinite or incomplete contract documents. The contract documents need not be voluminous, but they should be carefully written and specific.

Development of inspection organizations

The presently used inspection organizations were developed from those originally set up years ago by governmental agencies to oversee the operations of contractors performing construction for the agency as the owner. Such inspection would sometimes deteriorate into an adversarial relationship between the inspector and the contractor's forces. Recognizing that everyone benefits from a job well organized and well done, modern-day inspection has developed into a cooperative effort between the inspector and the workers' supervisors. In earlier days, inspection would also frequently be so detailed and intense that it became unnecessary for the contractor to perform any inspection or testing as part of the control of the operations. In recent years, much emphasis has been directed toward returning the responsibility for control testing and inspection to the contractor, where it rightfully belongs.

Functional classification

Responsibilities for, and the duties of, inspection as applied to concrete construction have been broadened to the point where inspection organizations are employed mainly for the following purposes:

- Represent the owner of the structure being built and provide assurance that the owner receives what is being paid for;
- Ensure and document compliance with the specifications and drawings;
- Represent the contractor (the builder), function as part of the construction team, and provide in-process evalua-



Fig. 1.3—ACI-certified field technician performing a slump test.

tion of the quality of operations as part of the contractor's quality-control program. This helps to assure the contractor that the finished construction will meet all requirements of the contract documents and thus will be accepted by the owner's representative;

- Function as part of the fabricating or manufacturing team of a producer of concrete materials or products who furnishes to the construction industry, rather than only to a specific project. Examples of such operations are cement mills, aggregate producers, ready-mixed concrete producers, precasting plants, and prestressing yards. These inspection forces operate essentially as those described in Item 2 to aid in ensuring that finished products will meet the requirements of the contract documents for a specific project; and
- Represent governmental bodies (licensing boards, and building-permit boards) charged with enforcing building codes and other regulations. In this case, the inspection forces will have responsibility only for ensuring that the finished structure conforms to requirements of the codes or regulations.

Inspection organization

Regardless of classification, an inspection group or team may consist of a number of individuals or, for very small projects, may be only one individual—even spending only part-time at an individual project (Fig. 1.3). Inspection (including testing) may be performed by a variety of groups, such as the following:

- Inspection force maintained by the owner. Examples would be permanent or semipermanent forces of governmental agencies or large industries with continuing building programs;
- Inspection force maintained by a commercial design firm (architect-engineer firm) for work on projects designed by the firm;
- Inspection force from commercial laboratories who are employed for testing and for inspection services;
- Inspection force trained and maintained by a contractor to provide quality-control (in-process) inspection for the firm on projects it constructs; and

- Inspection force trained and maintained by a concrete material and product manufacturing and fabricating firm for its own in-house use in quality-control (in-process) inspection and testing.

Responsibilities

1. *Inspection for the owner (acceptance inspection).* ACI 311.4R was prepared to guide architects, engineers, and owners in the development of effective inspection organizations and programs. It is concerned with the acceptance-inspection program required to assure owners that the requirements of the contract documents (drawings and specifications) are fulfilled. It states in part:

For the protection of the owner and the public, the responsibility for inspection should be vested in the designer as a continuing function of design responsibility. The responsibility of the designer for inspection maybe discharged directly, or through employees, or may be delegated to an inspection organization selected by the designer. In those cases in which the owner provides the engineering service, the owner should select the inspection organization. The fee for inspection should be a separate and distinct item and should be paid by the owner directly to the designer or to the inspection organization. Inasmuch as final responsibility for inspection rests with the designer, close surveillance should be maintained over whoever is carrying out the details of inspection. At no time should acceptance inspection or testing be made a function of the construction contractor, except when required by law or applicable regulations or when the owner considers that its interest is best served by such an arrangement. The practice of materials testing laboratories providing adjunct services for the construction company on the same construction project should not be allowed because this practice poses potential conflict of interest. Furthermore, as a professional service, the selection of inspection services should be based on qualifications.

The guide further states that the designer should avoid the undesirable practice of arranging payment for acceptance inspection and testing services through the contractor. Such practice is not in the owner's interest. Impartial service is difficult under such circumstances, and the cost is eventually paid by the owner in any case.

When construction is performed under a normal construction contract, the inspection forces representing the owner have no responsibility or authority to manage the contractor's forces. The owner's inspection forces are responsible for, and can only be involved with, determining that materials, procedures, and end products conform to the requirements of the contract documents or to generally accepted standards of the industry. There should be no question about requiring the contractor to meet all requirements of the contract documents. For the inspector to accept less than required is shortchanging the owner, whereas requiring more than called for in the contract documents may place an improper burden on the contractor.

2. *Inspection by the contractor.* Inspection and testing, variously referred to as quality-control inspection or in-process inspection, is performed by forces maintained or hired

specially by the contractor. In some construction contracts, particularly those with some government agencies, the contractor is required to provide a specified amount of such inspection and testing as part of a required formal quality-control program. Even when not contractually required, many contractors maintain a quality-control program that includes inspection and testing forces separate from the line of supervision. These forces report directly to management. The cost is often returned many times over through reduction of rejections and savings in replacements and repairs. Sometimes this inspection work is an informal and automatic part of the contractor's operations, performed by regular production supervisors.

Inspection performed by or for the contractor, particularly when contractually required, will often be much more detailed than is the usual present-day practice for acceptance inspection. The contractor's forces will make a much more detailed inspection of form alignment, positioning of embedments and reinforcing bars and general placement practices. Even if not required by the contract documents, the contractor often uses his own quality-control inspection to ensure against later rejection of work that would be very costly to replace or correct. If such items are not covered by a formal quality-control inspection team, they should be covered by the contractor's supervisory personnel.

When the contract documents require extensive quality-control inspection and testing by the contractor, the owner should not reduce or eliminate his own acceptance-inspection. The contractor's quality-control inspection program then becomes the owner's acceptance-inspection program and nullifies the system. The objections are exactly as stated previously against the practice of having the contractor hire and pay an inspection force to perform acceptance testing for the owner. When the owner requires the contractor to have a quality-control program, the owner should maintain formal oversight of quality acceptance to provide assurance that the quality-control program achieves its objectives.

3. *Inspection by the manufacturer or fabricator.* These programs should parallel the contractor's programs and can be as varied, depending on contractual requirements and on the manufacturer's quality control.

4. *Inspection by governmental enforcing agencies.* This type of inspection is generally performed by permanent inspection forces maintained by the agency. The amount of inspection is often less than required by other programs. One inspector may handle a large number of projects, visiting the smaller ones only once or reviewing the inspection performed by others.

Duties of inspection force

Although the basic approach will be the same, detailed duties and emphasis may vary for the numerous inspection forces involved on a project. The owner's inspection forces will often place emphasis on inspection of the finished structure, inspection of concrete materials as they are delivered to the mixer, and testing of the unhardened and hardened concrete. On the other hand, the contractor's quality-control inspection forces will emphasize inspection of materials production pro



Fig. 1.4—Building design accented with vertical patterns and joints; quality construction provides a highly functional and aesthetic workplace.

cesses, setting of formwork, and the concreting processes, with reliance on the owner for inspection of the finished structure. These are the most frequently encountered assignments:

1. Identification, examination, and acceptance of materials. This will include verification of quality based on certifications and test results from producers and suppliers, as well as the sampling and testing of materials delivered to the job site.
2. Control of batching and mixture proportioning and adjustment, tests for consistency, air content, temperature, and density of concrete.
3. Examination of the foundation, forms, reinforcing steel and embedded items, cleanup, and other work preparatory to concreting.
4. Inspection of the mixing, conveying, placing, consolidating, finishing, curing, and protection of concrete.
5. Preparation of any required concrete specimens for laboratory tests, and curing and protecting these specimens.
6. General observation of contractor's plant and equipment, working conditions, weather, and other items affecting the concrete or other related parts of the structures.
7. Evaluation of test results and performance charts.
8. Verification that unacceptable items and procedures are corrected.
9. Preparation of records and reports.

THE INSPECTOR

Qualifications of the Inspector

Inspectors must be persons of integrity who have both practical experience and a technical understanding of the principles involved in the assigned construction. They should know how and why the work is to be done in a certain way. Inexperienced but technically trained persons should

undergo a period of on-the-job training under the supervision of more experienced individuals before working alone.

Increasing attention to control of quality and to refinements of concrete construction often calls for higher standards of materials and workmanship than were formerly accepted. Sophisticated design methods place more reliance on the assurance of uniformly high-quality concrete. Superior concrete can be produced without excessive cost if its producers are vigilant and aware of its requirements.

Inspectors, to be effective, should have sufficient support from management. Inspectors must be observant, able to evaluate the relative importance of various work items, and provide greater attention to the important matters. Above all, inspectors must be completely familiar with all acceptance criteria of the contract documents. Inspectors should always promptly document and report nonconformances to the contractors and their own supervision.

Education and certification of inspectors

Properly trained inspectors are much more effective than those without training. Inspectors can get initial technical education at junior colleges, trade schools, and similar educational institutions but should continually improve their technical training. It is well worthwhile for employers to encourage this effort and provide assistance. The employer should provide periodic training courses to make certain that the inspectors receive up-to-date knowledge and training.

Certification of inspectors and technicians is becoming the norm and should be mandatory. It provides third party assurance that the inspector or technician possesses at least the basic skills and knowledge to perform the job. Some states directly require certification, but in most cases the requirement is placed in industry standards and then specified in the building codes. The following industry standards, for example, contain a certification requirement or recommendation for certification: ACI 301, ACI 311.4R, ACI 311.5R, ACI 349, ASTM C 39, ASTM C 78, ASTM C 94, ASTM C 685, ASTM C 1077, and ASTM E 329.

ACI provides programs for the certification of: 1) Concrete Field Testing Technician, Grade I; 2) Concrete Laboratory Testing Technician, Grade I and Grade II; 3) Concrete Strength Testing Technician; 4) Concrete Transportation Construction Inspector; 5) Aggregate Testing Technician; and 6) Concrete Flatwork Technician and Flatwork Finisher. Additional programs may also be initiated.

Authority of the inspector

It is imperative that the inspector's supervisor, at the start of each job, explain clearly and in detail the authority that the inspector has, as well as action to be taken in various situations that may be encountered. It is recommended that the duties and responsibilities be provided to the inspector in written form. An inspector may be authorized to do the following:

1. Refuse approval to commence placement of concrete until the preliminary conditions (such as preparation of forms and construction joints and the placing of reinforcement) are satisfactory and accepted, and until inspection personnel are available for the actual concreting operation.



Fig. 1.5—A certified inspector monitors the installation of an auger-cast precast pile.

2. Refuse to accept the use of materials, equipment, or workmanship that does not conform to the contract documents, or that will cause improper construction relative to the contract documents.

In the previous two cases, the inspector is usually authorized to take direct action with the contractor's supervisory personnel, reporting immediately thereafter to his own supervisor. The inspector should stop work only as a last resort, when it is evident that unsatisfactory concrete will result from continuing operations, and only after obtaining the approval of the inspector's supervisor. On minor points not covered by instructions or acceptance criteria, it will be necessary for the inspector to exercise personal judgment and to make decisions, thereby settling as many problems on the job as possible. Matters of general policy or major points not specifically covered by instructions, however, should be brought immediately to the attention of the inspector's supervisor.

The quality-assurance/quality-control duties and responsibilities of the owner, engineer, contractor, and supplier need to be clearly detailed in the contract documents and thoroughly understood by all parties. Preferably, these duties and responsibilities should be reviewed at a preconstruction or concrete preplacement meeting. The purpose of clearly defining each party's authorities and responsibilities before concrete is placed is to avoid the need to ascertain who is liable after the concrete is placed.

Relations with the contractor, supervisors, and workers

1. *Inspectors representing the owner*—If the requirements of the contract documents are fulfilled, the contractor is entitled to complete the work at the lowest possible cost. By cooperating with the contractor in every way consistent with the owner's interests, the inspector may contribute to reducing the cost of construction and doing so should secure the contractor's cooperation. Inspections should be made



Fig. 1.6—A certified inspector and a contractor discuss project concreting operations.

promptly when requested. Conditions that will apparently lead to unsatisfactory work should be anticipated whenever possible, and should be pointed out to the contractor at the earliest opportunity to avoid waste of materials, time, and labor. The inspector should not delay the contractor unnecessarily, nor interfere with the contractor's methods unless it is evident that acceptable work will not be produced (Fig. 1.5). Demands should never be made on the contractor that are not in accordance with the contract documents. If the contract documents permit a choice of methods, the inspector may suggest one of the methods specified but not demand that it be the method employed.

The inspector should maintain an impersonal, agreeable, and helpful attitude toward contractors and their employees (Fig. 1.6). Familiarity should be avoided, and no personal favors should ever be accepted from contractors or any of their employees. By dealing fairly and recognizing and commending good work, the inspector can usually secure the respect and cooperation of the contractor's supervisors and workers. The inspector should particularly refrain from criticizing the contractor's organization or workers, and from boasting of mistakes discovered.

Instructions should be given only to the authorized representatives of the contractor. Preferably, instructions should be given in the form of a caution that the faulty work will not be acceptable under the contract documents. Matters involving a potential change in cost, time of completion, or other factors of a significant nature should be documented by written communication to the authorized representative of the contractor. A clear line of communication should be established. Instructions that may be subject to controversy should preferably be issued in writing. The inspector may inadvertently waive the owner's rights by telling the contractor how to do a certain piece of work. This should be avoided unless the owner agrees, as liability for that portion of construction may thus automatically be assigned to the owner or the owner's

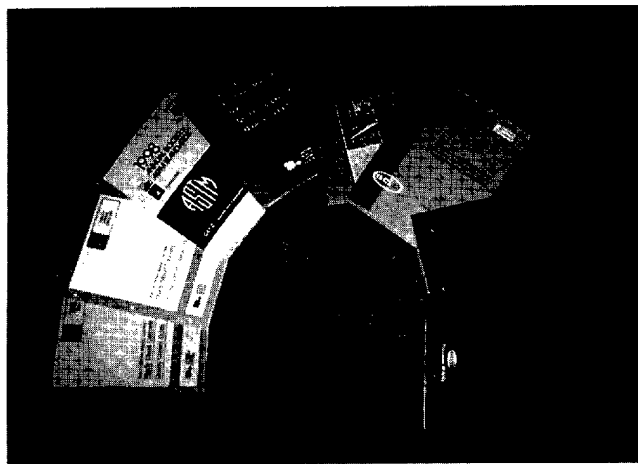


Fig. 1.7—A reference library is helpful to the concrete inspector.

er's representative. The inspector should not attempt to "run the job" but should watch the various operations carefully.

The inspector usually deals directly with subcontractors' supervisors. If the inspector's instructions are disregarded, the matters requiring correction should be immediately referred to the general contractor who is legally responsible.

A good start is important; an incorrect method is corrected more easily the first time it is practiced than after it has been in use. Because hasty and unsatisfactory work is most likely to occur at the beginning or end of construction, the inspector should be on the job during those times. The inspector should be on the job at all times while concrete is being placed, finished, and repaired.

An important item not often understood properly is that samples should be taken in a random manner. Inspection of the various details and operations should be at irregular intervals.

A most frequent and important difference of opinion between the inspector and the placing crew concerns the slump of the concrete. The placing crew may want a high slump (for example, a wet mixture with possibly 6 to 8 in. slump) because it will flow into place with practically no shoveling or other effort. With the use of modern superplasticizers, however, this problem has a practical solution. Instead of adding water, which increases the w/cm and reduces strength, a superplasticizer can be used to greatly increase slump and produce allowable concrete without reduction in strength. With modern placing equipment and vibrators, lower-slump concrete can, however, be placed and consolidated without undue expense to the contractor. The inspector should insist that concrete be placed within the specified slump range, unless otherwise authorized by the designer in writing.

2. Inspectors employed by the contractor—The basic approach to inspection and the inspector's relations with work crews, as discussed previously for inspectors representing the owner, also applies to inspectors employed by the contractor. In many instances, however, they will have a different approach to their relationship with the supervisors and the work crews, as they are all employed by the contractor. The actual

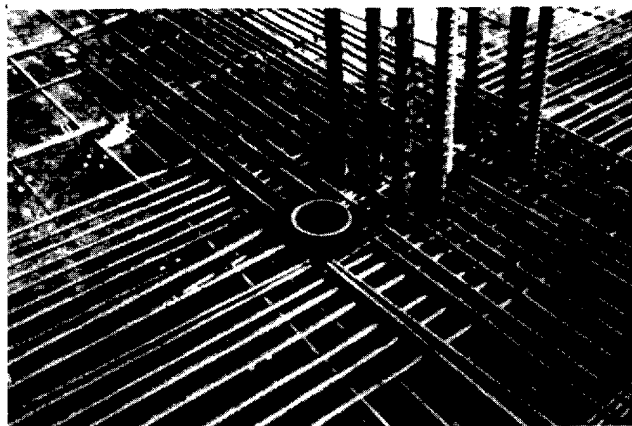


Fig. 1.8—The inspector must be alert to unwarranted changes by other trades. The plumber who cut this reinforcement to make space for his pipe probably did not realize that safety hangs in the balance.

relationships must be explained in detail in instructions given to inspectors by the contractor's management.

REFERENCE LIBRARY

In addition to the contract documents, and other documents referenced therein, the concrete inspection force should have at hand a working reference library (Fig. 1.7). As a minimum, the following should be readily available in addition to this manual:

ACI SP-15; *Placing Reinforcing Bars* (CRSI 1997a); ACI 318; *Concrete Manual* (USBR 1981); *Design and Control of Concrete Mixtures* (PCA 1994); and ACI 311.4R and ACI 311.5R (both of which are reprinted in the Appendix of this manual).

Additional references may be selected for specific jobs or subjects, as suggested by the lists of references and standards at the end of this manual.

MEASUREMENT AND TOLERANCES

A common and erroneous assumption is that specified tolerances for lines, grades, dimensions, and surface finish apply to the setting of forms, screeds, and grade strips. This, however, is not the case. Tolerances apply only to the completed concrete. Forms, screeds, and grade strips should be set at the exact position indicated on the drawings insofar as possible, so the finished concrete will conform to the required measurements.

Usually the governing measurements of line, grade, and dimensions are made by the designer. The inspector checks the alignment of forms and screeds, as well as positioning of reinforcement and embedded items, and makes determinations of length, volume, and weight as required to ensure that the quantities of materials and finished work meet all requirements. Recognizing that even the most careful measurement can never be exact, the inspector should exercise judgment as to the tolerance to be permitted in specific cases if the contract documents do not state limiting values or permissible tolerances (Fig. 1.8). Measurements must be evaluated in a reasonable manner that will withstand questioning and review by higher authority. It is obvious that forms and reinforcing steel can be

be aligned to the nearest hundredth of an inch; hence, permissible deviation from exact value should be governed by the effect that such deviation will have on the structural action or on the appearance of the structure. For example, a displacement of reinforcing bars of 1/2 in. might be of no consequence in a foundation, but could seriously weaken a thin slab, or impair protection of the bars from corrosion. Standards for tolerances not covered by the contract documents should be established early in the construction period.

SAFETY

The inspector should be aware of safety regulations and requirements at all times, keeping informed of local and OSHA requirements that often change. This knowledge will

have a definite effect on the performance of the inspector. To ignore safety aspects will imperil the inspector's own job and subsequent responsibility. All unsafe conditions should be immediately reported to the contractor or other proper authority and to the inspector's supervisor. Safe working practices should be encouraged by pointing out dangerous conditions or other possible sources of danger. Inspectors representing the owner or designer, however, may be prohibited from pointing out safety violations to the contractor because doing so may result in an unintended assumption of liability by the inspector's employer. Inspectors should consult their supervisor for guidance on whether and how to be involved in safety matters.



CHAPTER 2—STATISTICAL CONCEPTS FOR QUALITY ASSURANCE (QUALITY CONTROL AND QUALITY ACCEPTANCE)

Quality assurance, as used herein, refers to all of the programs and functions involved in obtaining the quality of concrete materials and concrete itself that will provide satisfactory service of the desired concrete structures. It includes design, production, sampling, testing, and decision criteria. The two functions that make up quality assurance are *quality control*, primarily a function of the contractor, and *quality acceptance*, primarily a function of the owner or the owner's representative.

In the past, to a large extent, the owner has been assured of quality primarily through the combined skills and experience of the designer and the contractor involved. Properly applied, such an approach has produced concrete structures of satisfactory quality. Modern concrete construction, however, has attained a rate such that the approach used in the past has often been unable to keep pace. In addition, the work load of skilled designers has increased to the point that many activities and decisions have been delegated to individuals whose skills and experience often are inadequate for on-the-spot decisions made previously by the skilled designer. Further complicating the problem are legal requirements for documentary evidence of satisfactory compliance.

TRADITIONAL QUALITY ASSURANCE

Many specifications for concrete used in the past (and still being used) are recipes or prescription-type specifications rather than end-product specifications. Some also spell out, in detail, the operations of the contractor and the equipment to be used in the production of concrete. Such specifications were developed because adequate quality definitions and test methods, and their evaluation, pertaining to the quality of the end product were lacking. Attempts to define required end-product quality and the values used were usually based on experience and judgment rather than any rational concept. These specifications, combined with the skills of experienced designers and the cooperation of experienced contractors with skilled workers, have produced good concrete structures. Sometimes, the resulting structures, however, have been of less-than-desired quality.

Under the previous procedure, a random, supposedly representative, sample is usually taken. This sample is tested and the result compared with the specified value of the particular characteristic. If the test result is within the specified tolerances, the material passes and is accepted. If not, the material *fails* to pass. Engineering judgment must then be applied and a decision made as to whether the material may be said to *substantially comply*, and thus be accepted, whether the material truly *fails* and must be rejected, or whether the material should be retested. *Substantial compliance* is not defined, and can vary from person to person and job to job, creating confusion and disputes. Actual research has shown that as much as 30% of some construction controlled by traditional methods has been outside the stated limits when closely examined by statistical methods using random sampling, even though it was considered com-

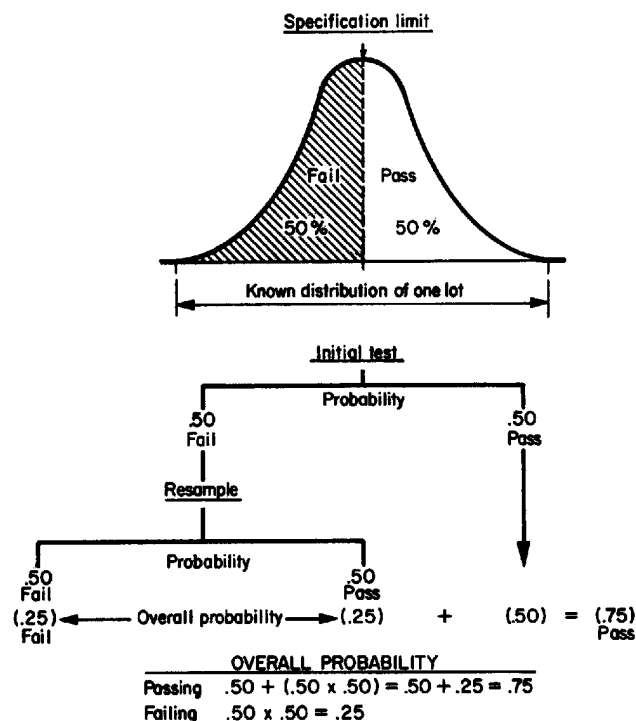


Fig. 2.1—Probability of acceptance when resampling.

pletely acceptable under the control practices used (California Department of Transportation 1968).

When a failing test is encountered, retesting without upgrading the material being tested is not an appropriate action (unless the original test has been performed improperly, in which case the entire test should be voided). Even if the results of the two tests (original test and retest) are averaged, there is a built-in bias because the second test is taken only if the first test fails, not if it passes. For example, consider a material that has a 50% chance of passing the specification limit and a 50% chance of failing. For each test on a certain lot, there is always a 50% chance that the result will pass and a 50% chance that it will fail. When a test is made and the result fails, however, if it is decided to retest the same lot, the retest also has a 50% chance of passing and a 50% chance of failing. But, because a second test is made only if the original test fails, this second test has biased the original test so that the overall situation actually becomes a 75% pass, 25% fail probability. This is illustrated graphically in Fig. 2.1 (Pennsylvania State University, College of Engineering 1974).

STATISTICAL CONCEPTS IN QUALITY ASSURANCE

The science of statistics is a versatile tool. Its use permits decisions to be made with an established degree of confidence.

Contract documents can be written using statistical concepts to express quality requirements as target values for contractors, and to express compliance requirements as plus or minus tolerances. Tolerances for the target value, prescribed by design needs, can be based on statistical analyses of the variations in materials, processes, sampling, and

Table 2.1—Types of sampling

	Protects against known defects	Protects against unknown defects	Protects against cycles and patterns	Low inherent risk	Low risk in unknown situations	Simple organization	High reliability	Does not require knowledgeable sampler
JUDGEMENT SAMPLING (based solely on judgement of sampler)	✓	X	?	?	X	✓	?	X
QUOTA SAMPLING (making judgment distribution of sample by time of day, location, etc., according to distribution of facts)	✓	X	✓	?	X	X	?	X
SYSTEMATIC SAMPLING (selecting successive observations at constant intervals in a sequence)	✓	✓	X	✓	?	✓	✓	✓
STRATIFIED SAMPLING (selecting each of two or more parts independently from a corresponding part)	✓	✓	✓	✓	?	?	✓	✓
RANDOM SAMPLING (selecting sample in such a manner that each individual has the same chance of being chosen)	✓	✓	✓	✓	✓	X	✓	✓

Note: ✓ = satisfies column heading requirement; X = does not satisfy column heading requirement; and ? = may or may not conform to heading, according to situation.

ing existing in traditional construction practices. Tolerances derived in this manner can be both realistic and enforceable. They take into account all of the normal causes of variation and allow for the expected distribution of test results around the mean. Provisions can be made both for control to the stated level and for control of the variation from this level.

In addition to indicating the acceptable and unacceptable material in construction, it is also common in highway construction to use statistical methods to indicate "gray areas" where the test results show that the material is not completely in compliance with the requirements but can be accepted if and when permitted by the contract documents.

Contract documents based on statistical concepts are widely used and becoming more common. Public agencies, particularly the various state highway departments, use these concepts often because statistical concepts are particularly appropriate and valuable for use on projects involving high rates of production and large volumes of concrete or other materials, such as highway paving projects, large dams, and airfield paving. Use of statistical concepts has proved not only feasible but very effective and efficient where properly applied.

BASIC STATISTICAL PROCEDURES AS APPLIED TO CONCRETE CONSTRUCTION

Statistical procedures for quality assurance are based on the laws of probability; consequently, these laws must be allowed to function. The major requirement for proper functioning is that the data be collected by *random* sampling. A true random sample is one in which all parts of the whole have an equal chance of being chosen. Without true random samples, statistical procedures give false results.

Randomness is obtained only by positive action; a random selection is not merely a haphazard selection, nor one declared to be without bias. Selection by the proper use of a standard table of random numbers is acceptable. It is possible and feasible to adapt the use of random numbers to the laboratory, to the field, and to the factory. Mechanical randomizing devices (dice, and spinning wheel) are sometimes used, but no device is acceptable as random in the absence of passing certain statistical tests. The difficulties in attaining randomness are greater than generally known. Applications of a table of random numbers are shown in Appendix

1 in this chapter. Presently, hand-held calculators and personal computers are available that will generate pseudo-random numbers meeting all statistical tests. A discussion of the preparation of sampling plans is presented in ASTM E 105. Sampling programs commonly used are listed below. Table 2.1 shows the advantages and disadvantages of these programs (McMillan and Tuthill 1987). Normally, no one type of sampling is used alone.

1. *Judgment sampling* is sampling that is based solely on the judgment of the sampler with no other restrictions. The sampler decides when and where a sample should be taken.

2. *Quota sampling* is a type of judgmental sampling based on time of day, geographic areas, etc., according to the known distribution of facts.

3. *Systematic sampling* involves the selection of successive observations in a sequence of time, area, etc., at constant intervals.

4. *Stratified sampling* involves dividing a given quantity of material into independent parts, each to be sampled separately. Stratified sampling is inherent in any acceptance sampling based on use of *sublots*.

5. *Random sampling* involves the selection of a sample in such a manner that each increment comprising the lot has the same chance of being chosen for the sample (California Department of Transportation 1968).

Examples of sampling by random numbers, using the typical table of random numbers, are given in Appendix 1 in this chapter (Pennsylvania State University, College of Engineering 1974).

In addition to randomness, the *lots concept* is also essential to the proper application of statistics to assurance sampling of construction. The importance of this method cannot be over-emphasized. A lot can be considered as a prescribed and defined quantity of material (whether it be by volume, area, tonnage, time of production, units, etc.) that is produced from the same process for the same purpose. This is the quantity that is offered for acceptance as a unit. All sampling and testing requirements are defined in relation to and are applied to that quantity. Only by establishing the size of the lot can we select the proper sampling location and frequency to determine the quantity of material that is within the specified limits. Under the concept of *lot-by-lot* sampling and testing, the

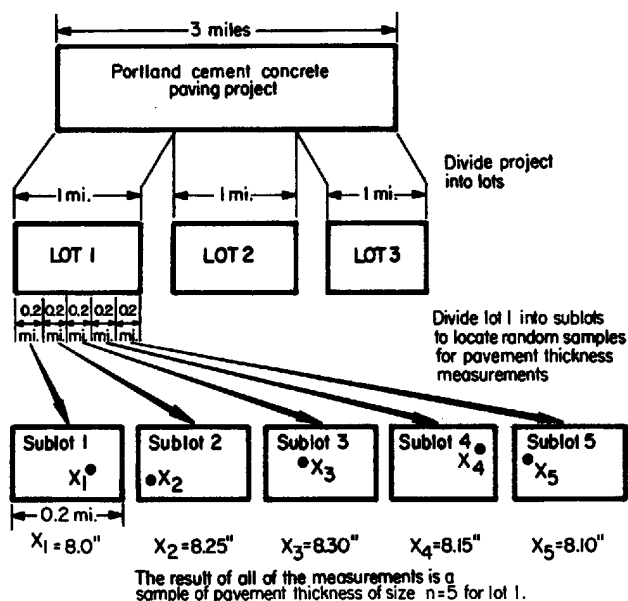


Fig. 2.2—Designation of lots and sublots.

process of concrete construction may be thought of as the production of a succession of lots that are each presented to the designer for acceptance or rejection. This is illustrated for concrete pavement in Fig. 2.2 (CRSI, 1997b). To implement the acceptance plan, each lot is considered to be made up of subdivisions of equal sizes called *sublots*. Sampling locations are randomized within the boundaries of each sublot. An advantage of this concept is to stratify or separate the lot into smaller components. Although it should not be a principal objective, this better ensures that the sampling and testing crews will have their work spaced out so that they are busy most of the time and not excessively overloaded at any time. Some inefficiency of the testing forces, however, will have to be accepted. It also ensures that there will be no excessive periods without any sampling and testing, which is particularly important during startups—both project starts and daily starts.

A sample is that portion of the lot that is taken to represent the whole. The term sample is used in a statistical sense. The term is not to be confused with the individual *test portions* or *sample increments* that make up the *sample*. Fig. 2.3 illustrates the relationships between test portions, sample increments and the sample (CRSI 1997). (Note: In discussions of sampling and testing of materials or concrete in other chapters, the term “sample” generally refers to each individual quantity of material taken for test.)

Normally, it is desirable for each sample to be made up of four or five sample increments (in other words, there should be four or five sublots per lot). The average of the test values of sublots in a lot, however, will have a range smaller than the range of the values of the individual test portions in the entire lot.

BASIC STATISTICAL CONCEPTS

Research has shown that test results of construction materials and operations form a definite pattern grouping around a central value called the mean. The measurements

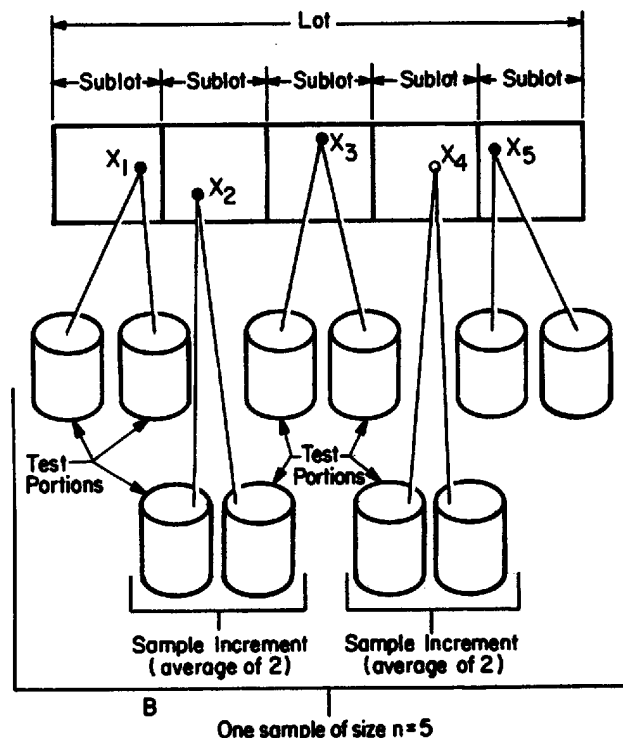


Fig. 2.3—Definition of test portion, sample increment, and sample.

generally group around the average in a symmetrical pattern, thereby allowing the use of statistics based on the familiar bell-shaped *normal distribution curve*. Although slight variation from the symmetrical curve may occur, especially when the number of test results is small, the error in assuming *normal* distribution is usually not large. The assumption of a normal distribution permits the use of established relationships of mean (average) and standard deviation to establish realistic contract document tolerances for selected sample sizes. Such tolerances can be established by statistical analysis, together with engineering judgment.

A typical distribution of results of compressive strength tests made on concrete of one specific mixture (Fig. 2.4) is given in ACI 214. Superimposed on these plotted results is a normal (bell-shaped) distribution curve computed from test results. This particular set of test results and distribution curve would be considered a reasonably good fit. All statistical control procedures for concrete construction, including control charts, assume the distribution of test results (regardless of concrete or material quality) will approximate such a normal curve.

Definitions

Symbols and terms used in this chapter are defined below. The following definitions are commonly used in statistical assurance programs for concrete and are primarily obtained from ACI 214.

n = number of tests in sample

The total number of test results or values under consideration.

X = individual test result

Separate test results (may be written X_1, X_2, X_3 , etc. to indicate specific test results).

$\bar{X}$ = average, specifically, sample average, called "bar X "

This is the arithmetic mean of all test results; the sum of all test result values divided by n , the number of values.

$$\bar{X} = \frac{X_1 + X_2 + X_3 + \dots + X_n}{n}$$

s = sample standard deviation

The sample standard deviation is the square root of the average obtained by dividing the sum of the squares of the numerical differences of each test result from the sample average by one less than the number of tests.

$$s = \sqrt{\frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n - 1}}$$

A simpler and more adaptable form for many desk calculators is

$$s = \sqrt{\frac{1}{n - 1} \left(\sum (x_i^2) - \frac{(\sum X_i)^2}{n} \right)}$$

where n = number of values;

$\sum X_i$ = sum of n values; and

$\sum (x_i^2)$ = sum of squares of n values.

V = coefficient of variation

This is the sample standard deviation expressed as a percentage of the average.

$$V = \frac{100s}{\bar{X}}$$

R = sample range

The numerical difference between the largest observed value (highest test result) and the smallest observed value (lowest test result).

f'_c = specified compressive strength of concrete

Usually 28-day strength, but can be specified at any age.

f_{cr} = required average strength of concrete

Ensures that no more than the permissible proportion of test results will fall below the specified strength.

Normal distribution curves

See Appendix 2 in this chapter for examples and discussion.

Application of normal distribution curves to concrete compressive strength

In concrete construction, frequently too much emphasis is placed on the results of individual cylinder tests. Low tests

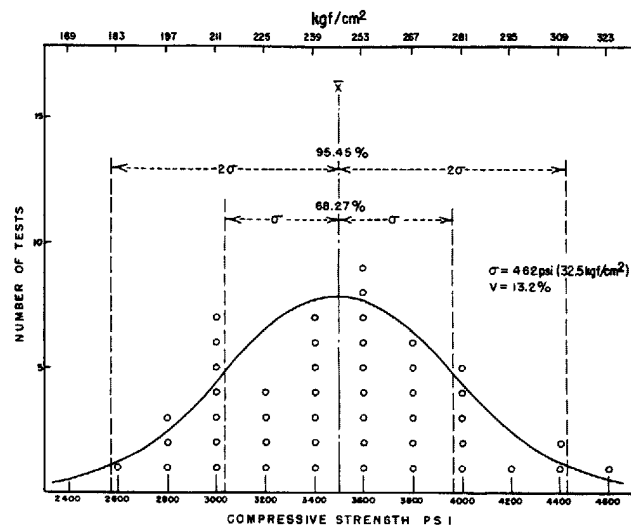


Fig. 2.4—Frequency distribution of strength data and corresponding normal distribution.

are inevitable, but an occasional low test should not be of major concern provided the result is not too low (more than 500 psi below the specified strength) or the low test does not represent a portion or member of the structure deemed critical by the designer. On the other hand, a few tests falling above the specified strength is not necessarily proof of adequate-quality concrete throughout the entire structure, as it is quite possible that lower-strength concrete was placed somewhere in the structure but has not been included in the tests. What is of concern is that the quantity of standard cylinder test results falling below f'_c is not more than allowed by the contract documents. Typically, the contract documents require that the average of all sets of three consecutive test results equal or exceed the specified strength. If the test results do not meet this criterion, changes to the mixture proportions or improvement of quality-control procedures must be made. Further, if the test result is more than 500 psi below the specified strength, the in-place concrete is in question and appropriate actions must be taken. See the chapter on criteria in ACI 318.

Although not pertinent to statistical evaluation as such, tests of standard concrete control specimens during construction provide the basis for evaluation of the potential strength of the concrete delivered to the placing site. Placing, consolidation, and curing techniques will affect the quality of the hardened concrete in the structure.

The quality of concrete can best be evaluated by analysis of at least 30 standard tests from a given mixture.

STATISTICAL TOOLS

Results of concrete compressive strength tests are plotted to form a histogram, or frequency distribution, for which the normal distribution curve can be computed. More importantly, the results are tabulated and $\bar{X}$ and s computed, to provide background data to use in selecting a required average strength f_{cr} for future concrete construction. This required average strength must be selected so as to provide actual concrete strength test results that will meet the specified concrete

Table 2.2—Standards of control of concrete compressive strength, from ACI 214

Class of operation	Standards for concrete control				
	Excellent	Very good	Good	Fair	Poor
Overall variation, standard deviation, psi (kgf/cm ²)					
A. General construction testing	Below 400 (below 28.1)	400 to 500 (28.1 to 35.2)	500 to 600 (35.2 to 42.2)	600 to 700 (42.2 to 49.2)	Above 700 (above 49.2)
B. Laboratory trial batches	Below 200 (below 14.1)	200 to 250 (14.1 to 17.6)	250 to 300 (17.6 to 21.1)	300 to 350 (21.1 to 24.6)	Above 350 (above 24.6)
Within-test variation, coefficient of variation, %					
A. Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
B. Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

strength f'_c within certain specified tolerances. This strength is statistically computed, based on the average $\bar{X}$ and the standard deviation s of the past results. Appendix 3 of this chapter shows examples of how to compute s and f_{cr} for given data.

Normally, the concrete inspector will not be concerned with plotting frequency distribution curves for concrete strength tests. The inspector can determine the mean value and the standard deviation, or coefficient of variation, for a set of concrete test results from previous construction records, without plotting the curve.

Usually a technician employed by the concrete producer or contractor will determine the required average concrete strength f_{cr} and proportion the mixture to meet this requirement. An average strength higher than the required minimum strength is needed to ensure that the in-place concrete will be accepted when results of concrete control tests on the upcoming job are compared with the criteria of the contract documents.

If the concrete inspector is required to check the f_{cr} value computed by the contractor or concrete producer, the inspector must use data computed from previous testing of concrete produced by the same concrete plant or contractor, particularly the standard deviation.

The criteria most commonly referenced in contract documents are those of ACI 318. The ACI Building Code requires that, where a concrete production facility has a previous record based on at least* consecutive strength tests that represent similar materials and conditions to those expected in the new work, the concrete mixture shall be proportioned for a required average compressive strength f_{cr} , which shall be the larger of the values computed by the following formulas

$$f_{cr} \geq f'_c + 1.34s$$

$$f_{cr} \geq f'_c + 2.33s - 500$$

where

f'_c = specified compressive strength of concrete, psi;
 f_{cr} = required average compressive strength of concrete, psi; and

*Allowance for using as few as 15 consecutive strength results by using factors that increase the sample standard deviation used in the above equations. These factors are: 1.16 for 15 tests, 1.08 for 20 tests, 1.03 for 25 tests, and 1.00 for 30 or more tests.

s = standard deviation, psi (modified if less than 30 tests are used to determine the sample standard deviation) (McMillan and Tuthill 1987).

All of these required levels of overdesign are based on statistical assumption so that the concrete produced for the new construction can be expected to meet specification requirements when concrete control cylinders are tested during construction. These levels of overdesign are also based on the assumption that specification requirements are the same as those contained in the ACI 318 Building Code, which require that the average of all sets of three consecutive strength tests equals or exceeds the required f'_c and that no individual strength test (average of two cylinders) falls below the required f'_c by more than 500 psi.

Actually, the standard deviation of results of tests for compressive strength of concrete, or any other test results, is made up of components that are standard deviations of several sub-items. The main components are deviations due to sampling errors, deviations due to testing errors, and deviations due to actual variation in the material itself. A chart showing the relationships among these subitems on several different concrete projects is shown in Fig. 2.5. Note that these items are not additive; instead the relationship consists of

$$s_o^2 = s_s^2 + s_t^2 + s_m^2$$

where s_o is the overall standard deviation, s_s is the standard deviation of sampling, s_t is the standard deviation of testing, and s_m is the standard deviation of the actual material properties.

Typical values for standard deviation of concrete strength tests, for various standards of control and for type of testing, are shown in Table 2.2. Refer to ACI 214 for possible revisions.

Control charts

Although frequency distributions themselves are used primarily to establish a proposed average compressive strength of concrete before commencing work, control charts are the primary statistical tools used for evaluation of test results on the concrete and concrete materials during construction.

Control charts are, in essence, horizontal line charts. The horizontal lines (for single test result or for "average" type charts) generally consist of a central line at the specified average and an upper line at the specified upper acceptance limit and a lower line at the lower acceptance limit (if both are applicable)—for an "acceptance" control chart. A line

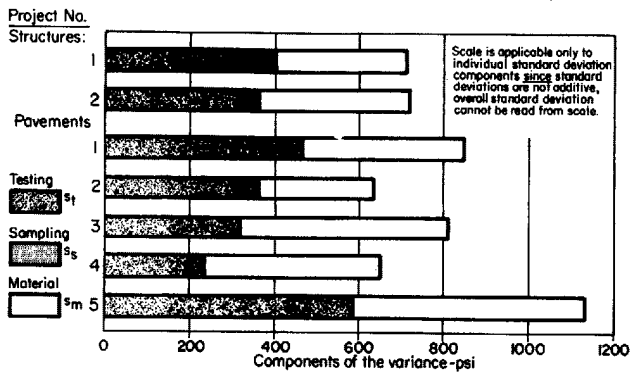


Fig. 2.5—Portland cement concrete components of standard deviation, compressive strength.

“control” chart (one used for actual process control) will usually have the center “average” line plus two lower lines and two upper lines. The upper and lower lines closest to the average are termed “warning limits,” or some similar name, and the next lines are termed “action limits,” or some similar name. These warning and action limit lines are placed at some multiple of s , the sample standard deviation, above and below the average value. For the case of concrete tests, only the “below” limits are of concern with the warning line at

$$f'_c \text{ (or } f'_c - 1.34s)$$

and the “action” line at

$$f'_c - 500 \text{ (or } f_{cr} - 2.33s + 500)$$

There are standard statistical procedures for picking the location of these lines, but the inspector will not be involved with this because the limits will be contained in the contract documents. A blank sample of a typical actual process control chart is shown in Fig. 2.6 (Pennsylvania State University, College of Engineering 1974). Note how the control lines are related to a standard distribution curve (shown lying on its side to the left). Also note that the s referred to in this paragraph comes from tests made over short periods of time when the process is “in control.”

Generally, procedures for using actual process control charts require that, when a point (test result value) falls on or outside either warning line, the producer should examine its operation to determine what has caused this variation and attempt to correct it. When a point falls on or outside the action line, the producer must stop its operation and make adjustments necessary to bring the operation under control. Control charts can only indicate that a problem exists, not where it is located.

This type of horizontal line control chart is used to plot both single test results and running averages of a specified number of consecutive test results. Typical charts of this type are shown in Fig. 2.7 (Pennsylvania State University, College of Engineering 1974).

In addition to control charts for single test results and averages, it is common to use control charts to record the variability, or range, of test results, either from a lot or over some

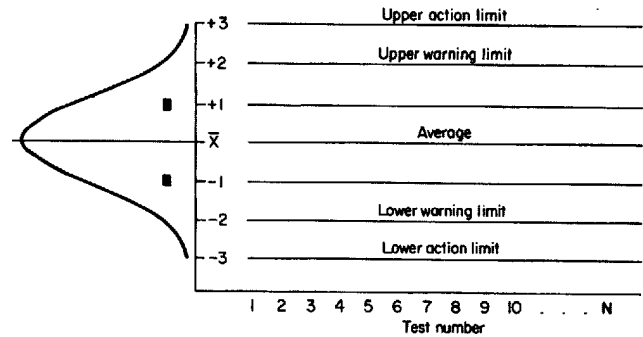


Fig. 2.6—Statistical control chart.

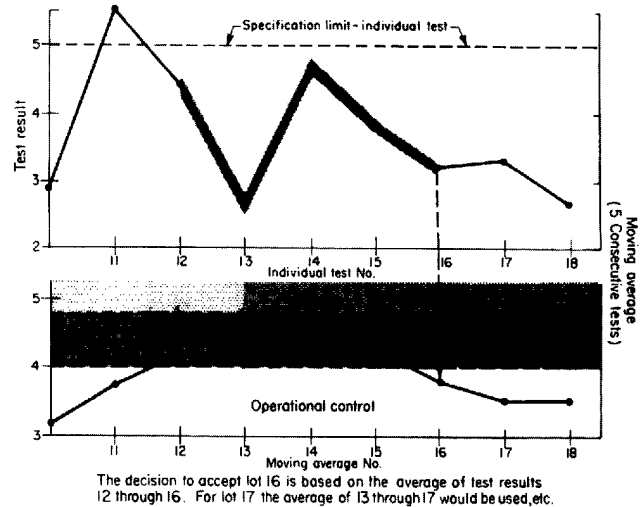


Fig. 2.7—Typical horizontal line control charts.

specified period. These, again, are horizontal line charts, but normally have only a lower and an upper control limit (or only an upper or lower limit).

Control charts for results of tests on concrete

Typical control charts for results of strength test of concrete are shown in Fig. 2.8 from ACI 214. Control charts are commonly required to be maintained for results of tests for air content of concrete. A typical example of such a control chart is shown in Fig. 2.9 (Pennsylvania State University, College of Engineering 1974).

Control charts are sometimes maintained for results of slump tests, and a typical one is shown in Fig. 2.10 (California Department of Transportation 1968). Often these are not required, however, because any batch of concrete whose slump is outside of contract document tolerances should be rejected on the spot.

Control charts for concrete materials

Normally, the only concrete material quality for which control charts are maintained is aggregate gradation, usually for only a few of the sieve sizes. Where aggregate quality is particularly important, however, charts may be maintained on results of certain quality tests, although statistically this may be an improper application. Control charts for aggregate gradation and quality are also shown in Fig. 2.10. Typical control charts for aggregate gradation for individual tests,

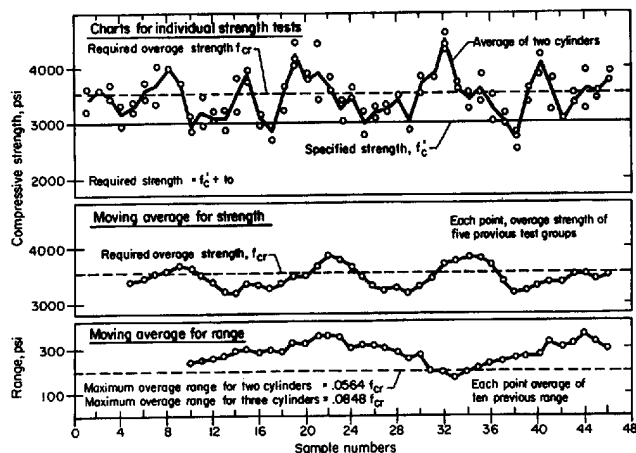


Fig. 2.8—Quality control charts for concrete.

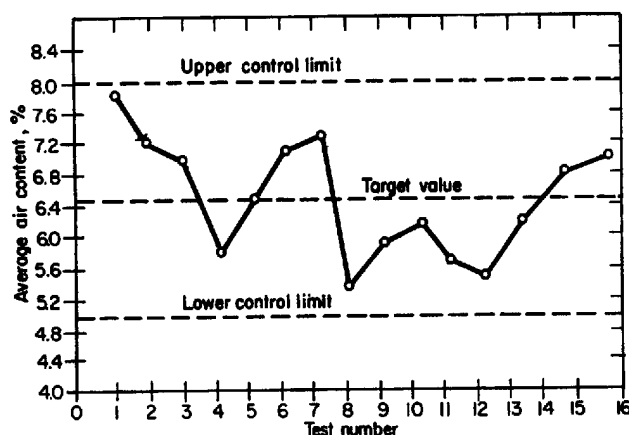


Fig. 2.9—"Bar X" control chart for air content.

range, and sand-equivalent test results are shown in Appendix 4 of this chapter.

CONCLUSION

This chapter gives a background of the underlying concepts for use of statistics in quality-assurance programs for concrete construction, together with examples of the procedures the inspector is likely to encounter. The inspector should study the references noted in this chapter for detailed instruction in the more refined phases of the use of statistics if he or she is involved with them.

This chapter, however, gives only background information and typical uses. The inspector must always follow the requirements of the contract documents.

APPENDIX 1—SAMPLING BY RANDOM NUMBERS Example 1—Sampling by time sequence

Sampling will be done at the place of manufacture. (For example, the manufacture of aggregate, concrete, or precast products.) The task is to select the sample increments by means of a stratified random sampling plan to distribute the sampling over a half or full day, whichever is more applicable.

The contract documents will define the lot size, number of sublots per lot, and the number of sample increments per lot. For this example, assume the contract documents state that

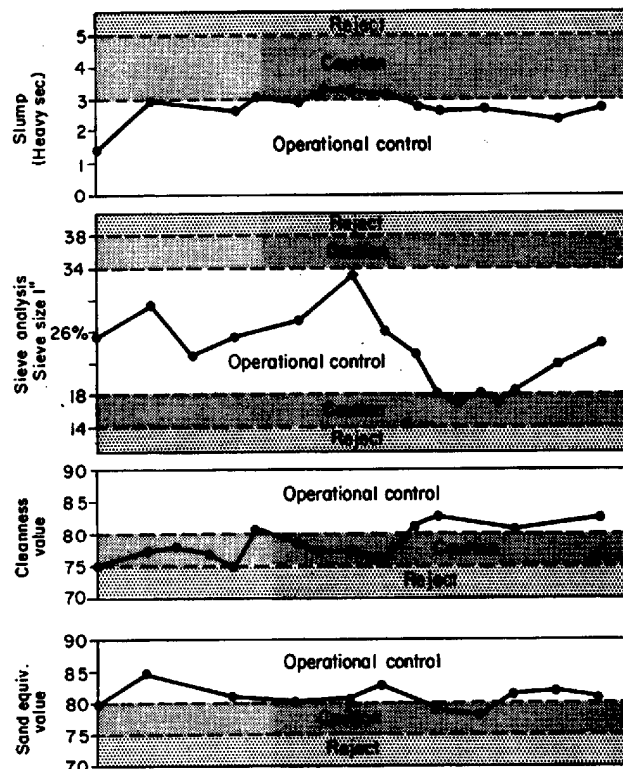


Fig. 2.10—Concrete control chart.

the lot size is a day's production, that five sublots are required from each lot, and that one sample increment per sublot must be obtained. The plant operates for 9 h (from 7:30 a.m. to 4:30 p.m.) to accomplish one day's production. Assume that the plant is running continuously through the lunch period. (Alternatively, one might assume a sampling time to coincide with the actual hours of production.)

Solution:

1. *Lot size*—The lot size is a day's production of 9 h because the plant starts at 7:30 a.m. and stops at 4:30 p.m.
2. *Sublot size*—Divide the lot into five equal sublots by selecting five equal time intervals during the 9 h that the plant is operating. The time interval for each sublot is

$$\text{sublot time interval} = \frac{(9 \text{ h per lot}) (60 \text{ min per h})}{5 \text{ sublots per lot}}$$

$$= 108 \text{ min per sublot}$$

The division of the 9 h of production time into five equal sublots is shown diagrammatically in Fig. A1-1, which indicates that Sublot No. 1 begins at 7:30 a.m. and ends at 9:18 a.m. Sublot No. 2 begins at 9:18 a.m. and ends at 11:06 a.m., etc.

3. *Sample increments*—Until now, nothing has been randomized. One sample increment per sublot is required but the exact time within each sublot when the sample increment should be taken is unknown. The times when the sample increments are to be obtained must be selected on a random basis.

Use the table of random numbers (Table A1-1) to randomize the timing of sample increments. Choose consecutive random

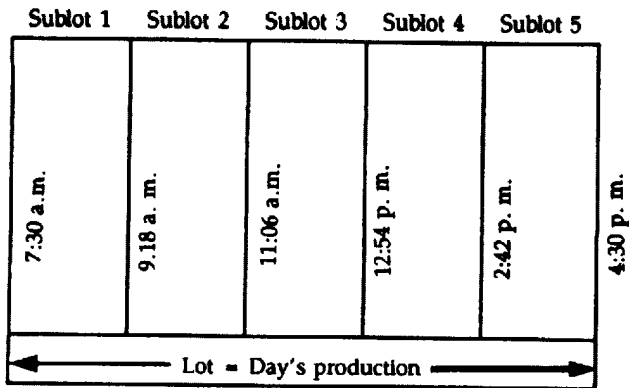


Fig. A1-1—Relationship between lot and sublots, time interval.

numbers from either the X or Y columns. The particular column to use may be specified by the inspector's supervisor.

For this example, use Column X to obtain the timing of five sample increments. Note that Column Y could have been used instead and that any five consecutive values could be selected by starting at any point in the table.

Choosing the first five numbers from Column X, the numbers are 0.471, 0.6936, 0.6112, 0.7930, and 0.0652. To randomize the sampling time within each subplot, use the time interval (108 min) computed in Step 2. This time interval is multiplied by each of the five random numbers selected previously.

Sublot No. 1: 0.4721	×	108	=	51 min
Sublot No. 2: 0.6936	×	108	=	75 min
Sublot No. 3: 0.6112	×	108	=	66 min
Sublot No. 4: 0.7930	×	108	=	86 min
Sublot No. 5: 0.0652	×	108	=	7 min

The computed times are added to the starting times for each subplot. This results in the randomized time at which the sample increment is to be obtained. The sampling times can be summarized as follows:

Sublot No.	Sampling time
1	7:30 a.m. + 51 min 8:21 a.m.
2	9:18 a.m. + 75 min 10:33 a.m.
3	11:06 a.m. + 66 min 12:12 p.m.
4	12:54 p.m. + 86 min 2:20 p.m.
5	2:42 p.m. + 7 min 2:49 p.m.

The first sample increment is obtained from Sublot No. 1 at 8:21 a.m. The second sample increment is not drawn until 10:33 a.m., when Sublot No. 2 is in production. The remaining sample increments are obtained during the time when each of the last three sublots is in production.

The five sample increments constitute a sample of size $n = 5$, taken from five sublots of a day's production (that is, the lot). Each increment of this sample of size $n = 5$ must be tested. The data would be employed to estimate the properties of the lot. In other words, the average, the sample standard deviation s , the coefficient of variation V , or any other statistic can be computed

Table A1-1—Table of random numbers

Random positions in decimal fractions, four places					
	X	Y		X	Y
1.	0.4721	R 0.2091	51.	0.6985	L 0.8636
2.	0.6936	L 0.3182	52.	0.3410	L 0.5636
3.	0.6112	R 0.2909	53.	0.5937	R 0.3727
4.	0.7930	R 0.8908	54.	0.6912	R 0.4545
5.	0.0652	L 0.4818	55.	0.0318	R 0.7272
6.	0.04604	L 0.2091	56.	0.1303	R 0.8090
7.	0.0167	L 0.3727	57.	0.6893	R 1.0000
8.	0.0077	R 0.6181	58.	0.3886	R 0.7817
9.	0.6777	R 0.8636	59.	0.0312	R 0.8090
10.	0.8010	L 0.8362	60.	0.0166	R 0.5909
11.	0.3027	L 0.3454	61.	0.4609	L 0.4000
12.	0.9831	L 0.2364	62.	0.0893	L 0.9726
13.	0.7159	R 0.6181	63.	0.4542	L 0.1545
14.	0.3609	R 0.6454	64.	0.9363	R 0.1000
15.	0.8915	L 0.2636	65.	0.8183	R 0.5636
16.	0.6442	R 0.3182	66.	0.9401	L 0.5091
17.	0.1904	R 0.1818	67.	0.5967	L 0.9726
18.	0.6074	R 0.8908	68.	0.7547	R 0.2636
19.	0.7522	R 0.9181	69.	0.0101	R 0.2909
20.	0.7041	L 0.8362	70.	0.2896	L 0.8362
21.	0.5102	R 0.2364	71.	0.8011	R 0.6454
22.	0.2471	L 0.3182	72.	0.6718	L 0.6454
23.	0.5693	L 0.5636	73.	0.5567	L 0.1818
24.	0.8583	R 0.4545	74.	0.0481	L 0.2636
25.	0.3093	R 0.1818	75.	0.4266	L 0.9454
26.	0.9144	R 0.9181	76.	0.3941	R 0.5636
27.	0.7944	L 0.5909	77.	0.9876	L 0.7545
28.	0.8725	R 0.2636	78.	0.6313	R 0.7272
29.	0.0135	R 0.8908	79.	0.6803	R 0.3182
30.	0.2044	R 0.7272	80.	0.7955	L 0.9726
31.	0.2517	L 0.2909	81.	0.7399	R 0.8080
32.	0.2763	L 0.8090	82.	0.9328	L 0.5909
33.	0.0314	R 0.4818	83.	0.1507	L 0.4000
34.	0.9560	L 1.0000	84.	0.3087	R 0.3182
35.	0.4622	R 0.4000	85.	0.7513	L 0.1818
36.	0.1327	L 0.7817	86.	0.6469	R 0.4818
37.	0.6922	L 0.5636	87.	0.2536	R 0.7545
38.	0.0010	L 0.1273	88.	0.1488	R 0.1818
39.	0.7609	R 0.2091	89.	0.9411	L 0.5636
40.	0.5957	L 0.1000	90.	0.0571	R 1.0000
41.	0.3115	R 0.4000	91.	0.4797	R 0.9454
42.	0.3377	R 0.8362	92.	0.0866	R 0.4272
43.	0.5651	L 0.1545	93.	0.2889	R 0.1273
44.	0.4742	R 0.6727	94.	0.4783	L 0.7000
45.	0.9483	L 0.4000	95.	0.0304	R 0.9181
46.	0.2951	R 0.6451	96.	0.8945	R 0.4515
47.	0.0441	L 0.1273	97.	0.4499	R 0.2081
48.	0.9143	L 0.1273	98.	0.9209	L 0.9454
49.	0.5723	L 0.8362	99.	0.5827	L 0.5636
50.	0.6069	R 0.4000	100.	0.4560	L 0.8908

Note:

X = decimal fraction of total length measured along road from starting point (or decimal fraction of other units).

Y = decimal fraction of road from outside edge toward centerline (or decimal fraction of other units).

R = measurement from right edge.

L = measurement from left edge.



Documents

Document Sharing Hub

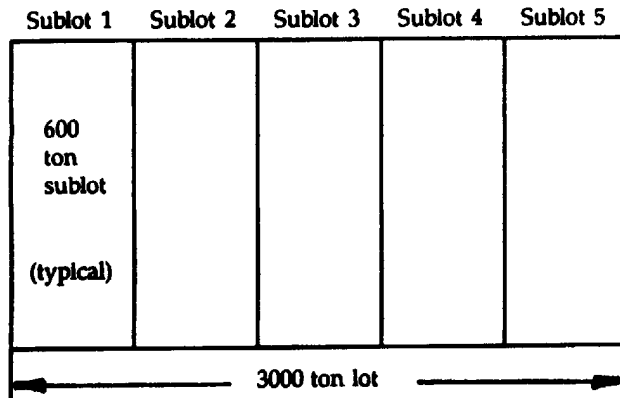


Fig. A1-2—Relationship between lot and sublots quantity interval.

to reflect the statistical property of the lot when it is offered by the contractor or material supplier for acceptable sampling.

Example 2—Sampling by material weight

Assume that the contract documents specify a lot size of 3000 tons with five sublots per lot and that one sample increment per subplot must be obtained. In addition, assume that the total tonnage required for the project is 15,000 tons. The sampling will be done from the hauling units at the manufacturing source.

Solution:

This solution follows the same basic pattern as the solution given for the previous example. First identify the lot size and then determine the number of lots, subplot size, and finally the point at which to obtain the sample increments.

1. *Lot size and number of lots*—Because there are 15,000 tons required for the project and the lot size is 3000 tons, the total number of lots is:

$$\text{Number of lots} = \frac{15,000 \text{ tons}}{3000 \text{ tons per lot}} = 5 \text{ lots}$$

2. *Sublot size*—The subplot size is:

$$\text{Sublot size} = \frac{3000 \text{ tons per lot}}{5 \text{ sublots per lot}} = 600 \text{ tons per subplot}$$

The relationship between lot and subplot size is shown in Fig. A1-2.

3. *Sample increments*—The contract documents require one sample increment per subplot, but which load should be sampled is unknown because the sample increments have not been randomized yet. Referring to Table A1-1, choose five random numbers from Column Y starting with Number 17 for this randomization process. These numbers are then multiplied by each of the five sublots as follows:

Sublot no.	Random number	Sublot size, tons	Ton to be sampled
1	0.1818	600	109th
2	0.8908	600	534th

3	0.9181	600	551st
4	0.8362	600	502nd
5	0.2364	600	142nd

Obtain the first sample increment at the 109th ton of the first subplot. Then wait until the first subplot of 600 tons is completed before selecting the second sample increment at the 534th ton of the second subplot. Follow the same procedure for obtaining the remaining three sample increments.

If a cumulative log of the tonnage being produced is kept, it would appear as follows. The sampling sequence for the lot (3000 tons) should be:

Sublot no. 1:		109th ton
Sublot no. 2:	600 + 534	= 1134th ton
Sublot no. 3:	1200 + 551	= 1751st ton
Sublot no. 4:	1800 + 502	= 2302nd ton
Sublot no. 5:	2400 + 142	= 2542nd ton

In actual practice when sampling the subplot, the hauling units containing the 109th ton, 1134th ton, 1751st ton, etc., would be sampled.

Example 3—Sampling depth of concrete pavement

The depth of concrete pavement in a roadway must be sampled for acceptance purposes. Assume that the contract documents require a lot size of 5000 lin ft, each lot divided into five sublots, and one sample increment per subplot. In addition, assume that the pavement width is 12 ft and the project begins at Station 100 + 00 and ends at Station 300 + 00.

Solution:

1. *Lot size and number of lots.*

$$\text{Lot size} = 5000 \text{ lin ft}$$

The distance from Station 100 + 00 to Station 300 + 00 is 20,000 ft. The number of lots is:

$$\text{Number of lots} = \frac{20,000 \text{ ft}}{5000 \text{ ft per lot}} = 4 \text{ lots}$$

2. *Sublot size*—The first lot begins at station 100 + 00 and ends at Station 150 + 00. Divide the distance between these stations into five equal sublots.

$$\text{Sublot size} = \frac{5000 \text{ ft per lot}}{5 \text{ sublots per lot}} = 1000 \text{ ft per subplot}$$

Fig. A1-3 indicates how this lot is divided.

(Note that random numbers starting somewhere else in the table, either list X or list Y, could have been used. The inspector should select the starting point at random to avoid making the time or location of the sample increment predictable.)

3. *Sample increments*—The point at which each sample increment will be obtained must be randomized in both the longitudinal (X) direction and the transverse (Y) direction.

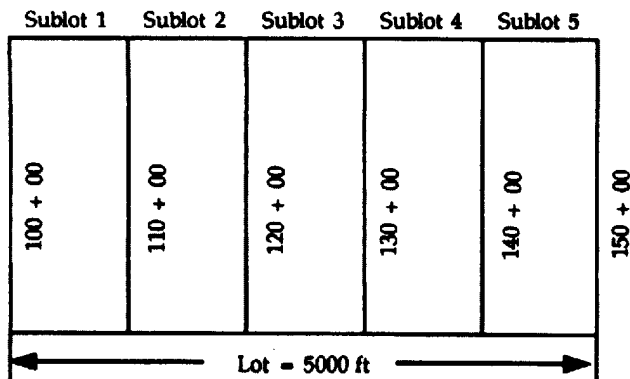


Fig. A1-3—Relationship between lots and sublots, distance interval.

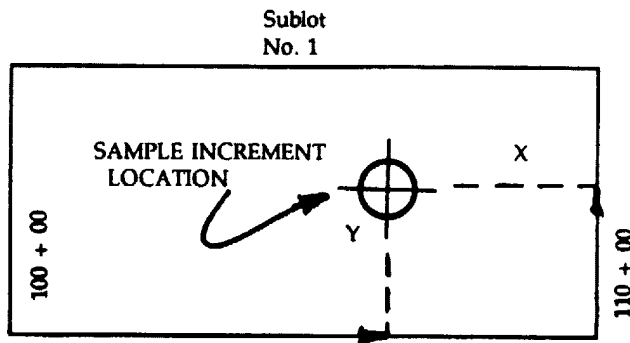


Fig. A1-4—Coordinate system for paved sublot.

location by X-Y coordinates is illustrated in Fig. A1-4, in which both the station and the offset are chosen in separate randomizing operations.

Referring to the table of random numbers (Table A1-1), use five consecutive random numbers from Column X and five from Column Y starting with number 43. Multiply these X numbers by the length of each sublot, and multiply the Y numbers by the 12 ft width of the roadway wearing surface.

Sublot No.	Longitudinal random number	Sublot size, length, ft	Sample location, ft, from start of sublot	Sample location, ft, from start of lot
1	0.5651	1000	565.1	565.1
2	0.4742	1000	474.2	1474.2
3	0.9483	1000	948.3	2948.3
4	0.2951	1000	295.1	3295.1
5	0.0441	1000	44.1	4044.1

Sublot no.	Transverse random number	Sublot size, width, ft	Location of sample, ft, from edge of roadway
1	L 0.1545	12	1.8 from left edge
2	R 0.6727	12	8.1 from right edge
3	L 0.4000	12	4.8 from left edge
4	R 0.6451	12	7.7 from right edge
5	L 0.1273	12	1.5 from left edge

Coordinates from beginning of lot and from right edge of roadway are:

Sublot No. 1 $X = 565.1$ ft $Y = 10.2$ ft

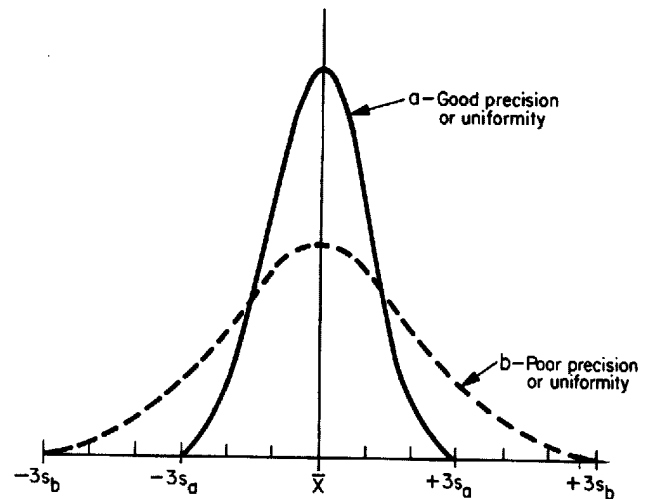


Fig. A2-1—Coordinate system for paved sublot.

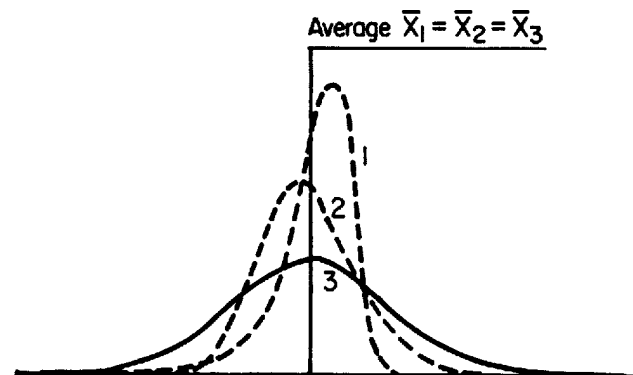


Fig. A2-2—Quite different distributions may have the same average.

Sublot No. 2	$X = 1474.2$	$Y = 3.9$
Sublot No. 3	$X = 2948.3$	$Y = 7.2$
Sublot No. 4	$X = 3295.1$	$Y = 4.3$
Sublot No. 5	$X = 4044.1$	$Y = 10.5$

APPENDIX 2—NORMAL DISTRIBUTION CURVES

Fig. A2-1, A2-2, A2-3, and A2-4 show examples of normal distribution curves and how they vary but are interrelated.

The sample standard deviation s and the related term V , coefficient of variation, are measures of the scatter or variability of data. As illustrated in Fig. A2-1 through A2-4, when the frequency distribution is long and flat, s (or V) is large, indicating wide variation. When the variability is small, s (or V) is small and the data are closely packed. Fig. A2-4 also shows that a high value of f_{cr} is required when the variation is wide.

Fig. A2-5 illustrates the proportion of the total area under a standard normal distribution curve for each successive step of distance s from the average (mean). These proportional areas for deviations of $1s$, $2s$, and $3s$ form the basis for statistically based tolerances for test values. For a standard normal distribution, approximately 68% of all test values fall within one standard deviation ($1s$) on each side of the average. More importantly, approximately 95% of all test values fall within two standard deviations ($2s$) on each side of the average.

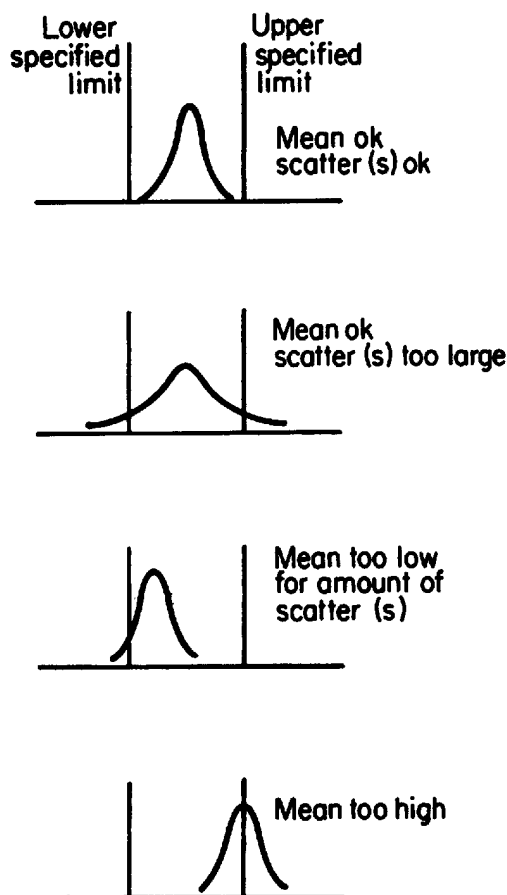


Fig. A2-3—Process control related to specification limits.

2s of the average, and almost no test values (less than 0.3%) will be found outside the 3s limits.

APPENDIX 3—COMPUTING STANDARD DEVIATION AND REQUIRED AVERAGE CONCRETE STRENGTH

The sample standard deviation s is defined as the “root mean square deviation” of test results from their average and is computed by the following equation:

$$s = \sqrt{\frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n - 1}} \quad (1)$$

where X_1, X_2, X_n are individual strength test values. Or, in a simpler form:

$$s = \sqrt{\frac{1}{n - 1} \left(\sum (X_i^2) - \frac{(\sum X_i)^2}{n} \right)} \quad (1a)$$

where $\sum (X_i^2)$ is the sum of the squares of all individual tests, and $(\sum X_i)^2$ is the square of the sum of all individual tests.

Note that $(n - 1)$ is used here rather than the theoretical value n , which is applicable for an unlimited number of tests. The reason is that $(n - 1)$ increases the value of s and tends to compensate for the lesser reliability of a small number of tests.

Examples of calculating deviation s

Example 1—Compute s by Eq. (1a)

Compressive strength tests of concrete cylinders		
Test no.	X value, psi	X ² value
1	3315	10,989,255*
2	3090	9,548,100
3	3510	12,320,100
4	2900	8,410,000
5	3690	13,616,100
6	3310	10,956,100
7	3100	9,610,000
8	3490	12,180,100
9	3295	10,857,025
10	3500	12,250,000
11	2910	8,468,100
12	3700	13,690,000
13	3110	9,672,100
14	3790	14,364,100
15	3300	10,890,000
16	3290	10,824,100
17	3105	9,641,025
18	2800	7,840,000
19	3305	10,923,025
20	3495	12,215,025
	$\sum X_i = 66,005$	$\sum (X_i^2) = 219,264,225$

*Although squared values have been written herein for illustration, this is unnecessary if calculator permits each squared number summed in memory as computed.

$$n = 20 \text{ (number of test results)}$$

$$\frac{(\sum X_i)^2}{n} = \frac{66,005^2}{20} = 217,833,000$$

$$s = \sqrt{\frac{\sum (X_i^2) - [(\sum X_i)^2 / n]}{n - 1}}$$

$$= \sqrt{\frac{219,264,225 - 217,833,000}{19}}$$

$$s = \sqrt{75,327} = 274 \text{ psi}$$

Calculation of required average strength f_{cr}

After the standard deviation has been computed, valuable information is available based on the theoretical normal probability curve. Fig. A3-2 shows a typical theoretical bell-shaped curve with the values for s indicated graphically. Regardless of the shape of the theoretical curve and the value of s , the area under the curve between $(\bar{X} + s)$ and $(\bar{X} - s)$ will always be 68.2% of the total area under the curve, and the area under the curve between $(\bar{X} + 2s)$ and $(\bar{X} - 2s)$ will be equal to 95.4% of the total. Considering only the half of the curve representing values less than $\bar{X}$, 34.1% of the total area will fall between $\bar{X}$ and $(\bar{X} - s)$, and that leaves 15.9% of the area under the curve for values less than $(\bar{X} - s)$.

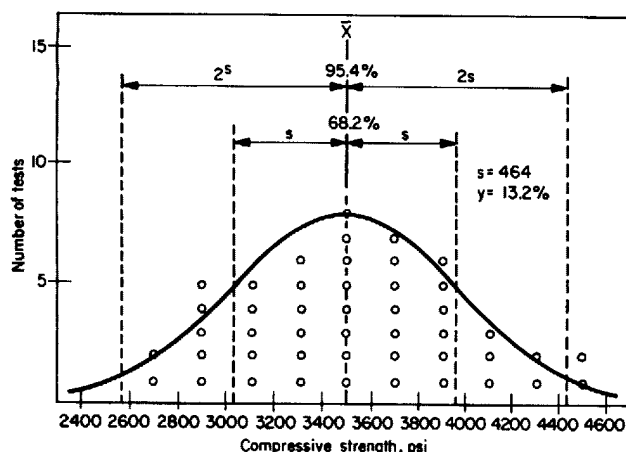


Fig. A3-1—Normal frequency distribution of test results.

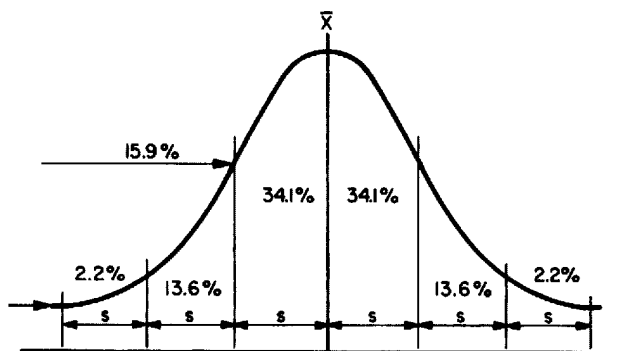


Fig. A3-2—Division of the area under the normal frequency distribution curve based on deviations from "bar X" in multiples of s.

These same percentages will apply for the number of tests involved, as well as for an area. Therefore, 15.9% of the tests for any normal curve will fall below $(\bar{X} - s)$.

Table A3-1 is an adaptation of a table from a math handbook (the normal probability integral) altered to show the percentage of concrete strength tests falling below f'_c as a function of the required average strength f_{cr} . For example, just as Fig. A3-2 shows that 15.9% of the tests will fall below $(\bar{X} - s)$, Table A3-1 shows that if

$$f_{cr} = f'_c + s$$

then 15.9% of the tests will fall below f'_c .

Table A3-1 is useful in establishing the required average strength and also in determining the probability of low tests occurring when s is known. With s computed from project data and f'_c established, Table A3-1 can be used to compute the required average strength f_{cr} . For example, assume that a designer would like to limit the probability of tests falling below 3000 psi to 5% and the expected standard deviation of the concrete is 560 psi. What average strength should the concrete be designed for?

From Table A3-1 for 5% low tests:

$$f_{cr} = f'_c + 1.65s \text{ (by interpolation)}$$

Table A3-1—Expected percentages of test lower than f'_c

Required average strength f_{cr}	Percent of low tests	Required average strength f_{cr}	Percent of low tests
$f'_c + 0.1s$	46.0	$f'_c + 1.6s$	5.5
$f'_c + 0.2s$	42.1	$f'_c + 1.7s$	4.5
$f'_c + 0.3s$	38.2	$f'_c + 1.8s$	3.6
$f'_c + 0.4s$	34.5	$f'_c + 1.9s$	2.9
$f'_c + 0.5s$	30.9	$f'_c + 2.0s$	2.3
$f'_c + 0.6s$	27.4	$f'_c + 2.1s$	1.8
$f'_c + 0.7s$	24.2	$f'_c + 2.2s$	1.4
$f'_c + 0.8s$	21.2	$f'_c + 2.3s$	1.1
$f'_c + 0.9s$	18.4	$f'_c + 2.4s$	0.8
$f'_c + s$	15.9	$f'_c + 2.5s$	0.6
$f'_c + 1.1s$	13.6	$f'_c + 2.6s$	0.45
$f'_c + 1.2s$	11.5	$f'_c + 2.7s$	0.35
$f'_c + 1.3s$	9.7	$f'_c + 2.8s$	0.25
$f'_c + 1.4s$	8.1	$f'_c + 2.9s$	0.19
$f'_c + 1.5s$	6.7	$f'_c + 3.0s$	0.13

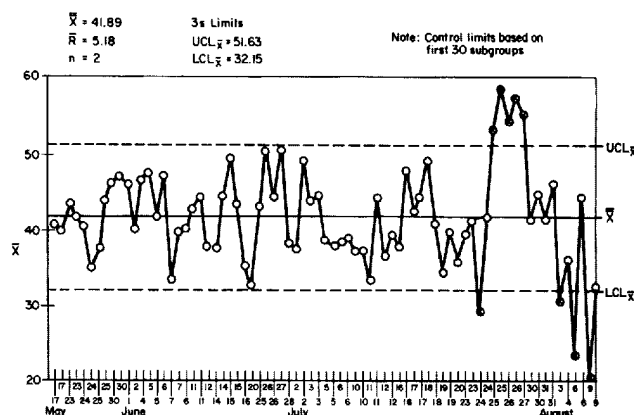


Fig. A4-1—Control chart for average ($\bar{X}$) 3/8 in. sieve, % passing.

$$= 3000 + 1.65(560)$$

$$= 3000 + 925 = 3925 \text{ psi}$$

APPENDIX 4—CONTROL CHARTS ON CONCRETE MATERIALS

Normally the only concrete material property for which control charts are maintained is aggregate gradation, usually for only a few of the sieve sizes. Where aggregate quality is particularly important, however, charts may be maintained on results of certain quality tests although statistically this may be an improper application. Typical control charts for aggregate gradation for individual tests and for range are shown in Fig. A4-1 and A4-2 (Pennsylvania State University, College of Engineering 1974). Plot gradation in individual percent retained on the particular sieve.

Example calculations and control charts for moving average (five tests) for sand-equivalent test results and for coarse aggregate material passing the 1-in. sieve are shown in Examples 1 and 2, which are taken from California Department of Transportation Highway Research Report No. M&R631 (35Q-68).

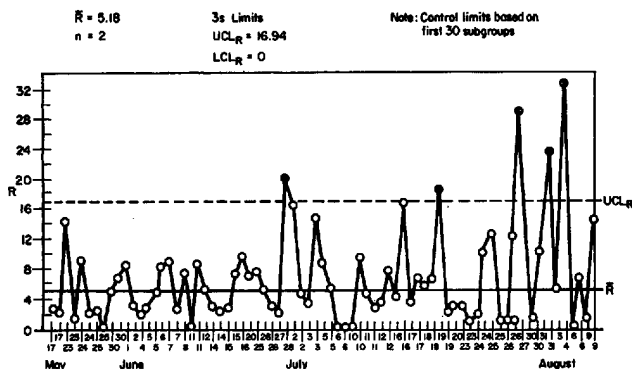


Fig. A4-2—Control chart for range (R) 3/8 in. sieve, % passing.

Example 1 calculations				
Test no.	Date	Individual test result (minimum 73)	Moving average*	
			Sum† divided by number of results (minimum 75)	Rounded to
1	8-11-91	79‡	—	—
2	8-14-91	85	$164 \div 2 = 82.0$	82
3	8-16-91	84	$247 \div 3 = 82.7$	83
4	8-18-91	72	$320 \div 4 = 80.0$	80
Waived and accepted by engineer				
5	8-22-91	80	$400 \div 5 = 80.0$	80
6	8-24-91	75	$396 \div 5 = 79.2$	80
7	6-25-91	74	$385 \div 5 = 77.0$	77
8	8-28-91	68	$369 \div 5 = 73.8$	—

Materials rejected and results not shown on control charts.
Operation discontinued and significant steps taken by contractor to correct deficiency before additional material accepted.

9	8-29-91	79	—	—
10	8-31-91	80	$159 \div 2 = 79.5$	80
11	9-5-91	81	$240 \div 3 = 80.0$	80
12	9-7-91	83	$323 \div 4 = 80.7$	81

*Results rounded up to next whole number using same number of significant figures as in individual test result.

†Sum of five most recent individual test results, including current test result.

‡Show test as first value on moving average control chart.

Example 1—Calculations to determine moving averages for sand-equivalent test (See Fig. A4-3 for plot of data)

Assume the contract documents require an individual test of not less than 73 and a moving average not less than 75. The caution zone for this example was arbitrarily set between 75 and 80. The data tabulation and calculation are shown below. The operation was discontinued and significant steps were taken by the contractor to correct the deficiency before additional material was accepted.

Example 2—Calculations to determine moving averages for 1-1/2 x 3/4 in. concrete aggregate (maximum variation of percentage of material passing 1 in. sieve) (See Fig. A4-4 for plot of data)

The contractor's proposed average (job formula) is 26% passing the 1 in. sieve. Assume that the contract documents allow an individual test variation of 14% and a moving average variation of 12% from the average submitted by the con-

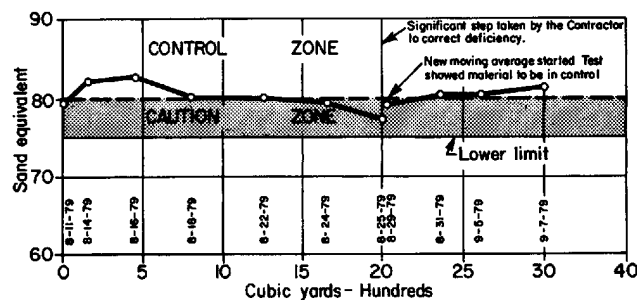


Fig. A4-3—Control chart of moving averages for sand equivalent.

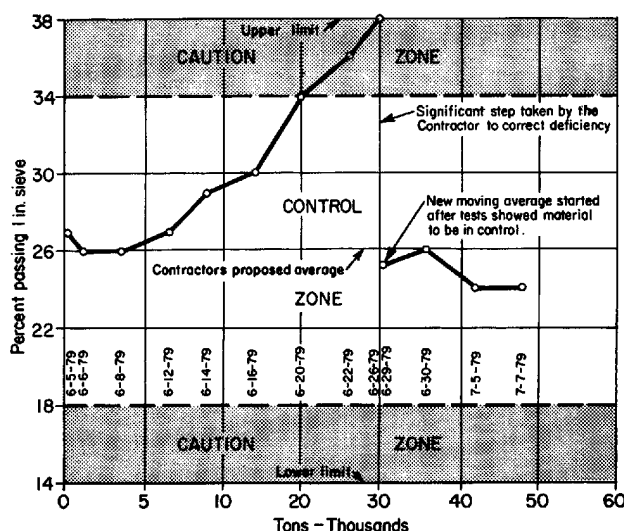


Fig. A4-4—Control chart for moving averages for grading analysis.

Example 2 calculations				
Test no.	Date	Individual test result (limits 12 to 40%)	Moving average*	
			Sum† divided by number of results (limits 14 to 38%)	Rounded to
1	6-5-91	27‡	—	—
2	6-6-91	24	$51 \div 2 = 25.5$	26
3	6-8-91	28	$79 \div 3 = 26.3$	26
4	6-12-91	29	$108 \div 4 = 27.0$	27
—	6-14-91	35	$143 \div 5 = 28.6$	29
—	6-16-91	34	$150 \div 5 = 30.0$	30
—	6-20-91	42	$168 \div 5 = 33.6$	34
Waived and accepted by engineer				
8	6-22-91	38	$178 \div 5 = 35.6$	36
9	6-26-91	40	$189 \div 5 = 37.8$	38
10	6-27-91	42	$196 \div 5 = 29.3$	—

Materials rejected and results not shown on control charts.
Operation discontinued and significant steps taken by contractor to correct deficiency before additional material accepted.

*Results rounded up to next whole number using same number of significant figures as in individual test result.

†Sum of five most recent individual test results, including current test result.

‡Show test as first value on moving average control chart.

tractor. The caution zone for this example was arbitrarily set between 4% higher than the lower limit and 4% lower than the upper limit. Data tabulation and calculations follow.

CHAPTER 3—INSPECTION AND TESTING OF MATERIALS

Materials are inspected and tested to see that they meet contract document requirements and that they are properly stored, handled, and used in the work. If materials are inspected for acceptance before being shipped to the job, their condition should be checked for degradation that may have occurred during shipment and storage. The contractor's records pertaining to shipments and quality of materials should be made available to the inspector. Standard methods of testing concrete are discussed in Chapter 19.

CEMENT

Five standard types of portland cement are used in concrete as specified in ASTM C 150 (U.S. Federal Specification SS-C-192):

Type I—A cement for general use when the special properties of other cements are not needed.

Type II—A cement for general use that has moderate sulfate resistance and moderate heat of hydration.

Type III—A cement for use when high early strength is desired.

Type IV—A cement for use when low heat of hydration is necessary, such as for mass concrete.

Type V—A cement for use when sulfate resistance is required, such as for structures in contact with soils or ground water having a high sulfate content and for concrete in contact with concentrated domestic sewage.

ASTM C 150 also includes specifications for air-entraining cement, that is, cement containing an air-entraining agent. Some users prefer this arrangement for introducing the agent into the concrete; others find that they are able to control air content of concrete better by adding the air-entraining agent at the mixer. (See discussion in Chapters 6 and 19.) ASTM C 150 specifies three types of air-entraining cement—Types IA, IIA, and IIIA, corresponding to Types I, II, and III listed earlier.

Other cements

Other cements, both blended and unblended, are available in certain localities. These are generally used for economic reasons. Such cements include: slag cement; portland blast-furnace slag cement; portland pozzolan cement, and others as given in ASTM C 595.

Pozzolans are often used to replace a portion of the portland cement in the mixture. These materials react with the free lime always present as a product of the hydration of portland cement to form cementitious compounds of slow strength gain. Pozzolans are often used for economic reasons in areas where they are cheaper than portland cement.

Most pozzolans, used as partial replacement of the portland cement, will produce a concrete mixture with less heat generation (of great advantage in massive structures); prevent or minimize alkali-aggregate reaction; and, except for Class C, will usually produce a more sulfate-resistant concrete. The three general classes of pozzolans covered by ASTM C 618 are as follows:

Class N—Natural materials such as diatomaceous earth and certain clays and shales, either calcined or not.

Class F—Normal fly ashes usually produced by burning bituminous coals.

Class C—High-lime fly ashes that are partially cementitious, usually produced from burning lignite or sub-bituminous coals.

Optional requirements

ASTM C 150 contains additional optional requirements for “low-alkali,” “false-set,” 28-day compressive strength, heat of hydration, and sulfate resistance, to be applied at the option of the purchaser.

When the aggregates to be used contain elements known to be destructively reactive with sodium or potassium oxides, the minor alkalies found in cements, then the durability and serviceability of concrete are better ensured if low-alkali cement or an acceptable pozzolan is used. The use of low-alkali cement will often, but not always, ensure that concrete will be free of objectionable alkali-silica expansion. By definition, low-alkali cement contains not more than 0.60% of these oxides computed as sodium oxide. Petrographic examination of the aggregate is a reliable method of identifying reactive aggregate (ASTM C 295). An indication of the potential alkali reactivity of cement-aggregate combinations can be determined by the mortar bar test (ASTM C 227) and, less reliably, by the quick chemical method (ASTM C 289). Low alkali content will not render a cement sulfate-resisting as is sometimes thought. ACI 116R defines false set as “the rapid development of rigidity in a freshly mixed portland-cement paste, mortar, or concrete without the evolution of much heat, which rigidity can be dispelled and plasticity regained by further mixing without addition of water. ...” Flash set (or quick set) is defined as “the rapid development of rigidity in a freshly mixed portland-cement paste, mortar, or concrete, usually with the evolution of considerable heat, which rigidity cannot be dispelled nor can the plasticity be regained by further mixing without the addition of water. ...” The presence of false set and flash set may be determined by ASTM C 359 (mortar method) or ASTM C 451 (paste method).

Although both of these properties are objectionable, flash set is the most detrimental. Considerable water must be added to regain plasticity, with consequent loss in strength and greatly increased plastic and drying-shrinkage cracking. Cement with flash-set properties will usually fail the requirements for time of set in ASTM C 150. Flash-setting cement should not be used in typical concrete construction. False setting of cement will generally have no deleterious effects on the quality of concrete, particularly when transit mixing is employed, as the longer mixing time will restore the plasticity without water addition (and often without personnel being aware that false set has occurred). With short mixing times, however, severe false setting may require addition of slightly more mixing water, and consequent reduction of strength and increased drying shrinkage. With very short mixing times,

false set may occur after the concrete has been dumped from the mixer, in this case causing considerable difficulty.

Job delays and too much time from mixing to placing are the causes of most slump loss problems. They can, however, be aggravated by fast-setting cement, cement-admixture incompatibility (particularly in hot weather), cement having false-setting tendencies, loss of water caused by high temperatures of fresh concrete, loss of water to unusually absorptive aggregates or subgrade, or loss of water to drying in sun and wind. In cold weather, a fast set may be caused by overheating of materials or by too much calcium chloride.

So-called "hot cement" (cement delivered from the mill before it has cooled to approximately atmospheric temperature) is considered the cause of false set due to driving off some of the water molecules in the gypsum that is added to control the set.

Sampling and testing

Testing cement for acceptance is essentially a laboratory matter. It is discussed briefly herein. Usually the cement is sampled and tested by the mill, which then issues mill test results and certifications. Cement remaining in bulk storage at the mill, prior to shipment, for more than 6 months after completion of tests should be retested as indicated in ASTM C 150. Large users, such as state highway departments, will often either engage an independent laboratory or perform the work of sampling and testing each silo themselves. Many other owners will obtain samples from incoming shipments and have the cement tested by an independent laboratory as they feel necessary. The field inspector checks incoming shipments against the notices of acceptance, and examines the cement for any signs of loss, contamination, or exposure to moisture during the shipment. Inspectors should be sure that seals on bulk shipment cars are unbroken.

If the cement is sampled at the job, secure a representative sample of the portion in question in accordance with ASTM C 183. Take samples for testing of at least 10 lb each (or at least 5 lb each when they are to be combined into a 10 lb sample). If the cement is in bags, take a small quantity from one bag for each 100 bags or fraction thereof; mix these amounts well and choose a sample with a sample splitter or by the quartering method.

If the cement is shipped in bulk, take samples either: 1) with a slotted sampling tube; or 2) by drawing off a considerable quantity of cement at the discharge opening. From the quantity secured, blend a composite sample as described previously.

Place the cement sample in a clean, dry waterproof container, and close the cover tightly to exclude air and moisture. Duct tape around the seam of a slipcover can make an excellent seal. Completely identify the sample both inside and outside the can, giving the date, name of job, name of inspector, car or lot number, brand of cement, quantity represented by sample, part of work in which cement is used, temperature when sampled, authority or reason for sampling, and tests desired.

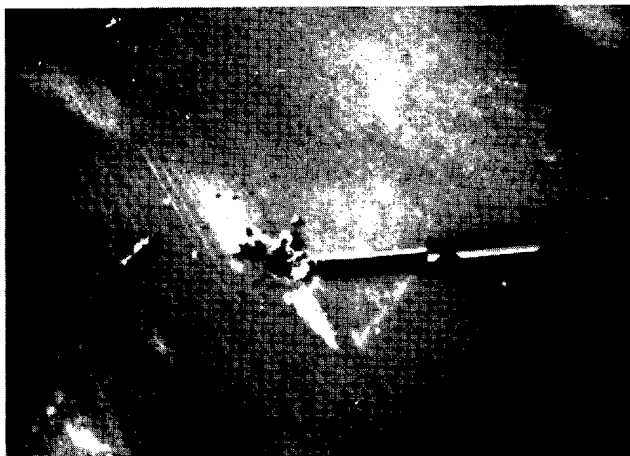


Fig. 3.1—Lightweight chert can cause popouts.

AGGREGATES

In general, inspection consists of examining and testing aggregates for acceptability, making necessary control tests, seeing that the aggregates are properly stored and handled, and checking the operations of batching. Minimizing variation in the aggregates as batched is important.

Specifications

Standard specifications for aggregates include ordinary aggregates (ASTM C 33), recommended stock sizes of aggregate for highway construction (ASTM D 448), and lightweight aggregates (ASTM C 330 and C 332). In general, aggregates must be clean, hard, sound, and durable, and sizes of particles must be graded within stated limits. Recent specifications usually require that the chosen grading of fine aggregate be maintained reasonably uniform by restrictions on the range of fineness modulus (see the following discussion under "Tests for Grading") of various shipments. Various deleterious substances are restricted to small percentages.

The following is a list of deleterious substances listed in ASTM C 33, showing the reason for restricting amounts of the material in the final aggregate product.

Clay lumps and friable particles—Unsound particles in the concrete; may increase water demand if they break down during mixing.

Material finer than No. 200 (75 μ m) sieve—Increases the mixture water demand.

Coal and lignite—Detrimental to surface appearance and cause difficulty in air entrainment.

Soft particles—Reduce performance of heavy-duty floors and other concrete where surface hardness is required.

Lightweight chert (with specific gravity less than 2.40)—Reduces durability of concrete and is a cause of "popouts" (Fig. 3.1).

Sampling

Select samples of processed aggregate for testing that are representative of the run of the material as it will be when batched; that is, from bins that discharge directly into the mixer. Use sampling methods conforming to the requirements of ASTM D 75. In quality concrete production, aggregates

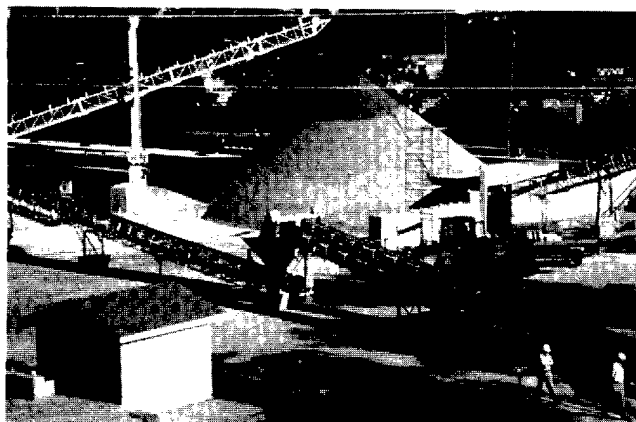


Fig. 3.2—Fine aggregate stockpile.

gate sampling may be the weakest link; therefore, it should receive close attention.

Expect some local variation in the aggregate source and select samples so that the effects of local variations are neither over- nor under-emphasized. In judging test results, consideration may be given to the statistical distribution of the amount of undesirable material and the quality-control charts of previous samplings (Chapter 2). For example, a single clay lump in one sample does not in itself justify rejection of an entire carload of aggregate, unless the sample is obviously representative and is supported by a degradation trend. In judging test results, accept or reject aggregate in accordance with the contract documents for the project.

Samples may be taken from conveyors, bins, cars, barges, or stockpiles (Fig. 3.2). Methods of sampling from belts, bins, and stockpiles are outlined in Chapter 19. Preferably, sampling should be from conveyors or from the discharge opening of bins (Fig. 3.3). Stockpiles are most difficult to sample properly and should be avoided if possible. ASTM D 75 does not recommend sampling stockpiles, but if it is necessary, take samples at three or four points along the length and about mid-elevation of the pile. See the Appendix of ASTM D 75 for additional guidance. Avoid segregated surface material. A satisfactory method of sampling stockpiles is to use a front-end loader to scoop material from the stockpile and then remove sample material from the front of the scoop. Select a quantity greater than the desired sample at various intervals or at various places, and then blend these quantities thoroughly. Obtain the sample from this total quantity as described later.

The most representative sample possible is that from a conveyor belt. For fine aggregate, take scoopfuls as the belt goes by until a bucketful is obtained from which the test sample can be split or quartered (ASTM C 702). For coarse aggregate, take samples from the belt only if it is practicable to stop it while all material on a short length of belt is removed. If arrangements cannot be made to stop the belt, or if there are no belt conveyors on the job, other means must be used. The next best method is to take the entire momentary discharge of coarse aggregate from a chute or bingate. Take at least several ft^3 of material and quarter the test sample from this amount.

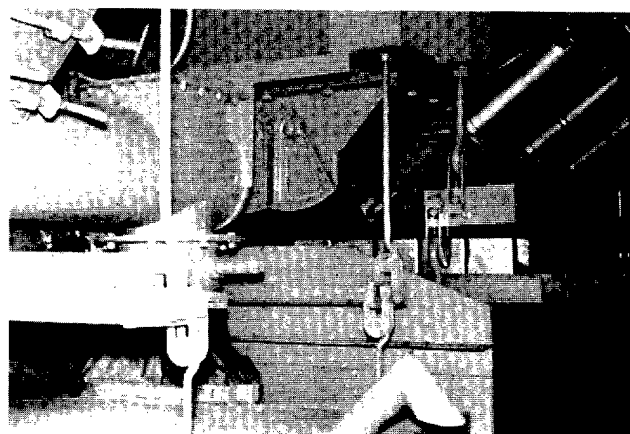


Fig. 3.3—Where access is convenient and safe, material may be sampled from hopper or bin outlet.

Such samples are most representative when it is possible to quarter them from material taken from the first, middle, and last of the material to be tested.

Make up samples taken from surface aggregate in a bin, car, barge, or stockpile by taking portions at several separated points. Avoid an excess of unrepresentative material such as fines in the center, coarse sizes toward the edges, and surface materials wetter or drier than average. All material, however, should be properly represented in the sample. Sometimes a sample from under the surface is obtained by using a board held in the surface of sloping material to prevent it from running down.

When possible, take fine aggregate samples from damp material to avoid the segregation that occurs in dry sand. Select samples from below the surface, preferably by means of a sampling tube driven into the sand at several separated points. When sampling for moisture content, allow for non-uniform moisture distribution. For example, a mass of wet sand will be wetter toward the bottom a few hours after water has been applied.

If two or more types of sand or coarse aggregate are to be batched separately and blended in the mixer to produce a specified grading, sample and test each type separately and compute the results for the blended aggregate from the proportions of each type. If necessary, adjust the proportions to obtain the required grading. The computation method for combining two such aggregates into a desired grading is identical with that illustrated in Table 3.1, even though that table illustrates the overall grading of fine and coarse aggregates.

The size of sample depends on the type and number of tests to be made. Samples of fine aggregate should contain not less than 25 lb, and samples of coarse aggregate of maximum size up to 1 in. should contain not less than 165 lb. Requirements for sieving of samples are discussed as follows under "Tests for Grading."

Some federal specifications for airport pavements require much tighter limits on the amount of deleterious substances in fine and coarse aggregates than those of ASTM C 33. Such tighter restrictions may range from 0.1% for soft particles and chert to 0.5% for material passing the No. 200 (75 μm) sieve. To provide meaningful results and achieve statistical

Table 3.1—Typical computations of fineness modulus

% coarser than sieve number	Sand	No. 4 to 1-in. coarse aggregate	Mixture 40% sand and 60% coarse aggregate*
	Cumulative % by weight retained		
3 in.	—	0	0
1-1/2 in.	—	3	2
3/4 in.	—	49	29
3/8 in.	—	77	46
No. 4 (3/16 in.)	4	96	59
No. 8 (3/32 in.)	15	100	66
No. 16 (3/64 in.)	37	100	75
No. 30 (3/128 in.)	62	100	85
No. 50 (3/256 in.)	85	100	94
No. 100 (3/512 in.)	98	100	99
Total	301	725	555
Fineness modulus	3.01	7.25	5.55

*0.40 × % of sand plus 0.60 × % of coarse aggregate.

control of tests (Chapter 2) for compliance with these tight specifications, take much larger size samples. To obtain a representative sample of aggregate from a large sample for test, use either a sample splitter or the method of quartering (ASTM C 702).

Unless the particular test calls for an exact amount of material, take the nearest approximate amount resulting from quartering or from the use of the sample splitter. Adjusting the amount to obtain exactly some arbitrary quantity by adding or removing material may change the average characteristics of the sample and should never be done except when specifically required by the test method.

If samples are to be shipped to a laboratory for test, use a clean container because even a small amount of some materials (such as sugar or fertilizer) may cause serious contamination. Close the container tightly to prevent either contamination or loss of fines. Identify the sample clearly, inside and outside the container, including the date, kind of aggregate, quantity represented by sample, location and other conditions of sampling, authority or reason for test, and kind of test desired.

Principal tests on aggregates

Concrete inspection is concerned with three types of test on aggregates:

1. Initial laboratory acceptance tests for suitability as to grading, cleanness (silt and organic impurities), soundness and durability, abrasion resistance, deleterious materials, foreign substances, and mineral composition.
2. Secondary laboratory tests on approved samples to determine physical properties used in mixture proportioning, such as absorption, specific gravity, density, voids, and bulking.
3. Field tests for secondary acceptance or control, such as grading, cleanness, deleterious materials, and moisture content.

The significance of the various tests on aggregate is discussed in ASTM STP 169-C (1994).

Tests for grading (ASTM C 136)

Sieve analysis of aggregates provide the basis on which gradation is controlled and by which compliance with specified grading requirements is checked. Use sieve analysis of

coarse aggregates to determine proportions of each type required to produce a combination most nearly having the desired grading.

Select the amount of the test sample to use for a sieve analysis in accordance with ASTM C 136. To avoid segregation, reduce the sample of fine aggregate to the desired size before drying. Separate the sample into the various sizes with the specified series of sieves, preferably mounted on a mechanical shaker. Use a combined lateral and vertical motion of the sieve, accompanied by a jarring action that keeps the sample moving continuously over the surface of the sieve. Do not manipulate fragments on the sieves by hand. Do not add slugs to the sieves as sieving aids. Keep sieves, particularly the small sizes, clean and unblinded by use of a good quality brush.

The fineness modulus is an index number that is roughly proportional to the average size of particles in a given aggregate; that is, the coarser the aggregate, the higher the fineness modulus. It is computed by adding the cumulative percentages coarser than each of the following U.S. standard sieves and dividing the sum by 100: 3, 1-1/2, 3/4, and 3/8 in.; and No. 4, 8, 16, 30, 50, and 100, as shown in Table 3.1. Although it gives no idea of grading and does not distinguish between a single-size aggregate and a graded aggregate having the same average size, it does indicate whether one graded aggregate is finer or coarser than another. It is used for specification and record purposes and finds particular use as a means for controlling grading and uniformity. It is used in one computation method of proportioning aggregates (PCA 1994). ASTM specifications require that the fineness modulus of a shipment of fine aggregate shall not vary more than a certain amount (in some cases, 0.20) either way from the fineness modulus of an acceptably representative preliminary sample.

Perform a sieve analysis only with standard sieves as defined by ASTM C 136. With the aid of a conversion chart, it is possible to convert a sieve analysis made using one series of sieves to an analysis using another series of sieves (perhaps having round instead of square openings, or the reverse). However, the conversion is only approximate, and in case of dispute, use only the actual sieves required by the contract document.

Aggregates, particularly coarse aggregates, vary considerably within stockpiles and bins; hence, any single test is of limited significance. Average each new test with at least two immediately preceding tests on the same material to obtain a more representative analysis of its general run and use the average to adjust the mixture proportioning or to determine if grading requirements are met.

The number of sieve analysis to be made for acceptance of aggregates depends chiefly on the homogeneity of the supply and to some extent on the quantity being used and the shipping units. In general, on a job of moderate size, make a sieve analysis once or twice each day, and at any other time when it appears that changes in grading have occurred.

Tests for material finer than No. 200 sieve

The extremely fine mineral material (clay, silt, dust, or loam) occurring in most aggregates requires relatively large increases in the amounts of mixing water; it tends to work out

the surface of concrete and to cause checking due to shrinkage upon drying. If the fines adhere to the larger aggregate particles, they also tend to interfere with bond between the aggregate particles and cement-water paste. Specifications limit the amount of such material to a small percentage.

For specification and test purposes, material finer than the No. 200 sieve was formerly termed "silt." The test for percentage of fines in aggregate is described in Chapter 19 and in ASTM C 117. Wash the fine material through sieves from a weighed sample of oven-dry aggregate. Oven-dry the remaining aggregate again and weigh it to find the amount of fines removed. See ASTM D 2419 for a standard field test for fine mineral material in sand.

A simpler sedimentation test for the approximate amount of fines in sand is often used in the field as follows (USBR, 1981). Do not dry the test sample because drying may result in loss of fines. Fill a clear glass jar or bottle, preferably a 32 oz graduated prescription bottle, approximately half full with the sand. Add clear water until the contents reach a level approximately twice that of the inundated sand.

Vigorously shake the container and allow the contents to settle for 1 h. Measure the depth of the layer of fines on top of the sand, and if this exceeds a permissible percentage of the depth of the sand and fines, test the sand by the more accurate method specified. Roughly 2% by volume (depth) is the equivalent of 1% by weight.

Determine the amount of clay lumps or other friable particles by the methods of ASTM C 142. As described in Chapter 19, this method uses the material retained on the No. 16 sieve of the ASTM C 117 test. For fine aggregate, dry the material, soak it in distilled water for 24 h, and then break the friable particles by squeezing and rolling between the thumb and forefinger. In the case of coarse aggregate, dry the material and separate it into the four sizes from No. 4 to 1 in. Then soak the different sizes for 24 h in distilled water and break the friable particles as for fine aggregate. Separate the residue from each sample by wet-sieving over prescribed sieve sizes, and compute the amount of friable material as percentage of the sample weight.

In coarse aggregate, fine minerals or crusher dust in objectionable quantities is usually clearly apparent to the eye. ASTM C 33 limits materials passing the No. 200 sieve to 1% by weight. This limit is increased to 1.5% if the fine material does not consist of clay or shale materials. Other criteria also apply as specified in ASTM C 33.

Make routine tests (perhaps once each day or so) for material finer than a No. 200 sieve when statistical analysis is desired and at any other time when there is reason to believe, from the appearance or from the sieve analysis, that the permissible amount of fine materials is being exceeded.

Tests for organic impurities in fine aggregate

A small amount of some kinds of organic material in fine aggregate may delay or prevent hardening of concrete, and may drastically reduce concrete strength. Organic matter in sand usually occurs in the form of decayed vegetable matter. Tannic acid from certain pine tree roots in certain locations occurs as deposits on the particle surfaces and is not removed by washing.

A color comparison test for the presence and approximate amount of organic material is described in detail in ASTM C 40. Use a slightly damp sample for test because an excess of surface moisture weakens the testing solution, and because dried aggregate may lose some of the organic material in handling or by burning off. Immerse the sample in a 3% (by weight) solution of sodium hydroxide in a clear glass bottle. After vigorous shaking, allow the sample to stand for 24 h. Note the color of the supernatant liquid and compare it with a standard color solution prepared according to ASTM C 40. If the solution is clear or lighter than the standard solution, the fine aggregate is satisfactorily free from organic matter. If the solution is darker than the standard solution, the presence of organic impurities is indicated and it may then be necessary to make comparison strength tests of mortar containing the fine aggregate with and without the organic impurities in accordance with ASTM C 87. Coal or lignite particles in fine aggregate may indicate a dark color in the color comparison test; however, such particles are permissible in fine aggregates, provided the amounts do not exceed the allowable limits in ASTM C 33.

The frequency of testing for organic matter depends on the condition and homogeneity of the fine aggregate and on the requirements of statistical evaluation (Chapter 2). The color comparison test may be made daily, although for washed fine aggregate with a satisfactory record, it may be made as infrequently as once each week. Make additional determinations if the amount of organic matter is near the permissible limit, or if the supply is changed, or if at any time the concrete hardens more slowly than normal.

Tests for moisture and absorption

Make tests for moisture content and absorption of aggregates for these reasons:

1. To determine the amount of water contributed to, or absorbed from, a concrete mixture by the aggregates. An increase of 1% in moisture content of fine aggregate, for example from 4 to 5%, if not compensated, will increase slump of concrete as much as 1 in. and decrease the compressive strength of concrete as much as 300 psi.
2. To determine the necessary adjustment in weight or volume to secure uniform quantities of equivalent saturated, surface-dry aggregates in the batches. If measurement is by volume, the bulking factor must be known.

With regard to moisture, aggregates may be in any of four states, as shown by Fig. 3.4:

- Oven-dry, that is, completely dry and fully absorbent;
- Air-dry, that is, dry at the surface but containing some interior moisture less than the amount required to saturate the particles (called the "absorption capacity"), and hence somewhat absorbent;
- Saturated and surface-dry, an ideal condition in which the aggregate neither contributes water to, nor absorbs water from, the paste; or
- Moist, containing an excess of moisture on the surface of the particles.

A clear understanding of these definitions is necessary for proper proportioning and batching of the aggregates.

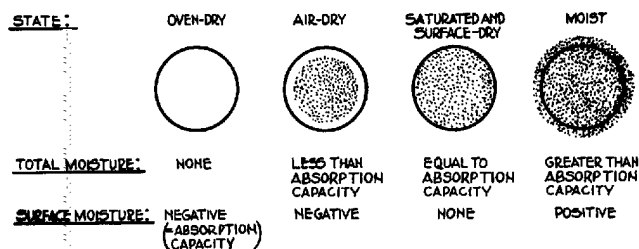


Fig. 3.4—Range of moisture content in aggregate.

Base all computations on aggregate in a saturated, surface-dry condition. It is impracticable to secure aggregates for construction in this ideal condition; but by simple arithmetic the measurements on damp or dry aggregates may be converted into terms of the equivalent amounts of saturated, surface-dry aggregate. It is necessary only to know the total moisture content and the absorption capacity of the aggregate. The relationship is given by this equation:

$$\text{Surface or free moisture} = \text{total moisture} - \text{absorption capacity}$$

If the total moisture is less than the absorption capacity (as in the case of air-dry aggregate), the surface moisture will be negative, and the aggregate will absorb some of the mixing water.

Tests for the determination of moisture content and absorption of aggregates are described in detail in *Design and Control of Concrete Mixtures* (PCA, 1994) and in ASTM C 70, C 127, C 128, and C 566. The significance of these tests is discussed in ASTM STP 169-C (1994). For laboratory purposes, make the tests with a precision that will yield results accurate to the nearest 0.1%. Base the percentages on the oven-dry weight rather than on the saturated, surface-dry weight or air-dry weight; however, the percentages of moisture and absorption generally are so small that these differences in bases make little difference in the numerical results.

For job determinations of moisture content of fine aggregate, speed is more important than refinement of test and results. Unless information on changes in moisture content is available in time to make appropriate adjustments in batching, the tests serve little purpose. Electrical and nuclear equipment for indicating moisture is available that immediately reflects significant changes in moisture content of fine aggregate.

Absorption—For practical purposes, the total absorption capacity of a given aggregate does not vary. In hard, dense natural aggregates, it usually amounts to 1% or less of the weight of aggregate, but this amount may be exceeded with some natural aggregates. For blast-furnace slag, it may be as much as 5%. For a given type of aggregate on small jobs, the value of absorption is often assumed, but, where careful control is desired, the absorption should be accurately determined.

Determine the coarse aggregate absorption using the procedure in ASTM C 127 with deletion of the weighing under water if specific gravity is not to be determined also. To measure absorption, bring a damp sample to the saturated and surface-dry condition, weigh it, completely dry it by heating, and reweigh it. The loss in weight after heating represents the absorption capacity. Obtain the surface-dry condition by wiping the particles with absorbent cloth.

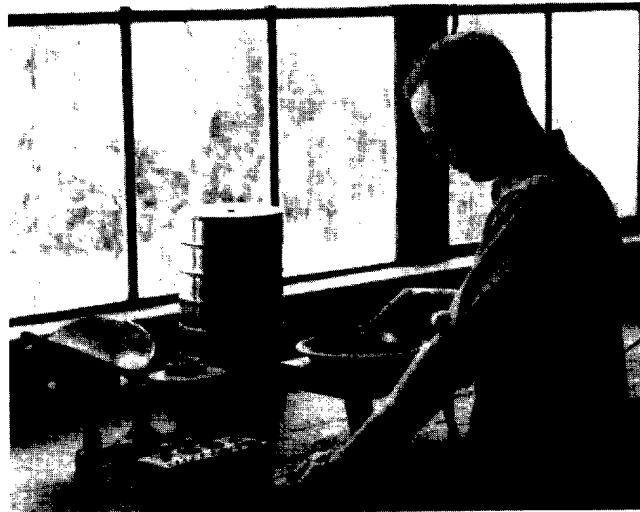


Fig. 3.5—Drying sand on hot plate to determine total moisture.

Determine fine aggregate absorption by using ASTM C 128 with deletion of the use of the flask if specific gravity is not measured. Bring a damp sample to the saturated and surface-dry condition, weigh it, oven-dry it, and reweigh it. Determine the surface-dry condition using the cone test described in ASTM C 128, as follows:

From time to time, lightly tamp a portion of the fine aggregate that is being dried (by evaporation or a gentle current of warm air) into a small conical mold open at top and bottom, then lift the mold vertically. If the pile of fine aggregate retains the shape of the mold, surface moisture is present. At the point in the series of tests when the pile begins to slump, the sand is saturated and surface-dry.

Another indication of the point at which drying sand becomes saturated and surface-dry is when it just ceases to adhere to a clean glass rod or jar. Neither of the tests for the saturated surface-dry condition is fully satisfactory for very coarse fine aggregate or for certain very angular fine aggregate.

Moisture—The surface moisture in fine aggregate can be determined by means of the Chapman flask (ASTM C 70). For this test, the specific gravity of saturated, surface-dry aggregate must be known.

For either fine or coarse aggregate, determine surface moisture directly by weighing a damp sample, air-drying it to the saturated and surface-dry condition as previously described in the case of absorption, and reweighing. A more rapid method described in Chapter 19 and in ASTM C 566 consists of weighing the damp sample, drying it by means of heat, and reweighing (Fig. 3.5). The loss in weight represents the total moisture from which the absorption capacity is subtracted to obtain the surface moisture. Aggregates that appear to contain no surface moisture should be tested by this method of heating because the surface "moisture" in this case is either zero or negative (indicating that the aggregate will absorb mixing water). Other common methods of determining surface moisture involve weighing the aggregate in air and then under water, or the use of a pycnometer. These methods are described in *Concrete Manual* (ACI, 1991).

The frequency of testing for moisture content depends on the uniformity of the supply and the requirements for statistical analysis (Chapter 2). Test twice a day ordinarily, and make additional tests, particularly of fine aggregates, whenever conditions change appreciably. To minimize the effect of inaccuracies in sampling and weighing, use as large a sample for moisture test as can be conveniently handled within the time available.

From experience with fine aggregate and routine moisture tests, and by observing the concrete slump and workability, the inspector should soon be able to judge with reasonable accuracy any significant changes that may occur between tests, and make appropriate adjustments in the batch.

Tests for specific gravity

To convert a given weight of aggregate into terms of solid volume for computing yield, or to convert solid volume to weight for purposes of batching, it is necessary to know the specific gravity of the aggregate. Specific gravity is the ratio of the weight of a given solid volume of the material to the weight of an equal volume of water. The specific gravity of most aggregates is approximately 2.65, although limestone may have a specific gravity as low as 2.50 or less, and traprock may have a specific gravity of 2.75 or greater. For a given aggregate, the value is substantially constant, and for most purposes it may be taken as constant without serious error. As a routine check, make determinations of specific gravity about once each week to detect any change or to confirm that there has been none.

Perform a test to determine specific gravity of coarse aggregate (ASTM C 127) by weighing a saturated, surface-dry sample in air, weighing the aggregate under water (by placing the sample in a wire basket that is suspended from a scale and immersed in water), oven-drying the sample, and reweighing it. The sample should weigh in pounds at least 10 times the maximum size in inches; therefore, a 5 lb sample would be the minimum required for 1/2 in. aggregate.

Solid (bulk) saturated, surface-dry specific gravity = $B/(B - C)$

Solid (bulk) oven-dry specific gravity = $A/(B - C)$

in which

A = oven-dry weight of sample;

B = saturated, surface-dry weight of sample; and

C = immersed weight of saturated sample.

Perform a test (ASTM C 128) to determine the specific gravity of fine aggregate by weighing a water-filled calibrated flask, weighing the same flask filled with water and a known weight of saturated, surface-dry fine aggregate, drying the aggregate sample with heat, and reweighing the dried sample. The specific gravity of fine aggregate may also be determined by weighing it in air and then in water as described for coarse aggregate. A special device developed by the U.S. Bureau of Reclamation is convenient for tests to determine moisture, absorption, and specific gravity. This and other methods of de-

termining specific gravity are described in *Design and Control of Concrete Mixtures* (PCA 1994).

For use with saturated, surface-dry aggregates, base the specific gravity on the surface-dry condition; for materials that will be batched on an oven-dry basis, base the specific gravity on the oven-dry condition. For aggregates containing other than these two quantities of moisture, express the aggregate weight in terms of either of these given conditions (plus excess water), and use the corresponding dry or saturated, surface-dry specific gravity. Many engineers prefer to base recommended mixture proportions on saturated, surface-dry aggregates. ACI 211.1 uses the oven-dry basis for determination of the dry-rodded volume of coarse aggregate. Convert the dry volume to weight with the measured, dry-rodded density, and obtain the saturated, surface-dry weight of coarse aggregate by adding the amount of water absorbed in 24 h (ASTM C 127) (see Chapter 6).

Tests for voids

$$\text{percentage of voids} = 100 \left(\frac{1 - \text{weight, lb/ft}^3}{\text{specific gravity} \times 62.4} \right)$$

The percentage of voids in aggregate is usually computed from the specific gravity and density, as follows:

Always state the condition of the aggregate regarding moisture content and compactness when reporting the amount of voids. For dry-rodded aggregate, the method of determining voids is described in ASTM C 29. A formerly used method of determining voids by measuring the amount of water required to fill a container of aggregate is subject to error caused by entrapped air.

Tests for density

The weight per unit volume of aggregates is used in computing the amount of voids in aggregate, in computing proportions of materials, and for conversion of bulk volume quantities to weight, or vice versa.

The density of a given type of aggregate as used in the work varies with the degree of compaction and with the moisture content. In fine aggregate, the "bulking" or fluffing apart of particles by films of surface moisture may lessen the density as much as 25%.

To provide a uniformly reproducible basis of measurement of ordinary aggregates, ASTM has adopted a standard method of test for density of aggregate (ASTM C 29). This test consists of compacting the dry aggregate into a cylindrical container and weighing the aggregate. In one method of compaction, fill the container in three layers, rod each layer 25 times, then strike off the excess aggregate level with the top of the container. The standard sizes of container are as follows:

Container			
Maximum size of aggregate	Capacity, ft ³	Inside diameter, in.	Inside height, in.
1 in. or less	1/3	8.0	11.5
1-1/2 in.	1/2	10.0	11.0
4 in.	1	14.0	14.2



Documents

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For aggregate of maximum size greater than 1-1/2 in., compact the layers of aggregate by jiggling the container instead of by rodding. Although not specifically stated in the standard method, the term "dry" should be interpreted as either saturated, surface-dry or oven-dry, depending on which basis of mixture computation is employed.

ASTM C 29 also provides for measurement of the density of dry loose or damp loose aggregate. Determine such density by filling the standard container heaping full in one layer. Then strike off the excess aggregate level with the top of the container without downward pressure, and weigh the aggregate.

Determine lightweight aggregate's density only by the shoveling procedure in ASTM C 29. Test the aggregate in an oven-dry condition. Although density tests may be made with greater accuracy, values of density of aggregates are generally considered to be accurate only within 1 or perhaps 0.5%.

Test for density of aggregate when mixture proportions are made on the density basis, and whenever it is observed that the type or grading of the aggregate has changed.

Bulking

Except when using volumetric batching and mixing equipment conforming to ASTM C 685, avoid batching of aggregates by volume whenever possible, because of the large fluctuations that occur (PCA 1994). When volume batching is unavoidable, contract documents should state whether the basis of measurement is damp loose, dry loose, or dry-rodded volume. To compute the number of ft³ of damp loose aggregate corresponding to 1 ft³ of dry-rodded aggregate (a ratio called the "bulking factor"), determine the density under both conditions and determine the moisture content of the damp aggregate. Then:

$$\text{bulking factor} = \frac{\text{density of surface-dry rodded aggregate}}{\text{density of damp loose aggregate}}$$

$$= \frac{\text{weight of surface moisture in unit volume of damp loose aggregate}}{\text{weight of damp loose aggregate}}$$

Undesirable substances and properties of aggregates

ASTM tests for undesirable substances and properties, which may be required by contract documents for aggregate, are: C 123 (Note: include coals and lignite), C 142, C 88, C 131, C 535, C 295, C 227, C 289, C 586, C 666, and C 40.

Substances in aggregate that have a deleterious effect on quality concrete are discussed in detail in ASTM STP 169-C (1994). Cherts, "chocolate bars," and clayey limestones, are subject to considerable changes in volume during wetting and drying or freezing and thawing. Spalling can be detected by petrographic examination supplemented by visual inspection, sorting, and weighing. These materials also often cause high losses in the sodium or magnesium sulfate soundness test and in the freezing and thawing tests.

Lightweight chert in coarse aggregate (specific gravity less than 2.40) contributes to "popouts" at concrete surfaces.

ASTM C 33 limits such chert to 3 to 8%, depending on exposure conditions. Flat or elongated particles, which are considered undesirable under some conditions, likewise can be sorted out of a sample and weighed to determine the percentage. Petrographic examination will also identify elements that occur in some aggregates and that are undesirably reactive with alkalis in cement. Some of these elements are opal, chalcedony, tridymite, and acid or intermediate volcanic glasses. Lightweight materials that, along with soft and weak materials, usually detract from concrete strength and quality may be quickly separated by flotation in a heavy liquid as described in ASTM C 123. Deleterious substances adversely affecting the chemical activity (setting) of the cement are usually organic and can be detected by means of the colorimetric test.

WATER

Potable water is usually satisfactory for mixing water and is the quality criterion usually specified. Ordinarily, the presence of harmful impurities such as alkalis, acids, decayed vegetable matter, oil, sewage, or excessive amounts of silt will be known. Submit water of doubtful quality for laboratory analysis; or, if time is available, test specimens of concrete or mortar made with the doubtful water for comparative strength and durability with respect to control specimens made with water known to be satisfactory. ASTM C 94 allows the use of mixer wash water in subsequent batches if the quantity can be measured accurately.

ADMIXTURES

The standard specification for chemical admixtures (water-reducing, retarding, and accelerating) for concrete is ASTM C 494. This specification considers seven types of admixtures with various purposes as follows:

Type A—Water-reducing admixtures

Type B—Retarding admixtures

Type C—Accelerating admixtures

Type D—Water-reducing and retarding admixtures

Type E—Water-reducing and accelerating admixtures

Type F—Water-reducing, high-range admixtures

Type G—Water-reducing, high-range, and retarding admixtures

Also, ASTM C 1017 covers "Chemical Admixtures for Use in Producing Flowing Concrete."

The standard specification for air-entraining admixtures is ASTM C 260. These standards provide methods of testing in the laboratory, but the tests are not intended to simulate job conditions. The inspector should verify that admixtures used on the job comply with all requirements of the contract documents and that proper storage and dispensing are provided on the job.

ACI 116R defines an admixture as "a material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of concrete or mortar, and added to the batch immediately before or during its mixing." Contract documents may require or permit an admixture to be used in concrete for one or more of the following purposes:

1. To increase workability without increasing water content or to decrease the water content at the same workability.

2. To accelerate the rate of strength development at early stages;
3. To increase the strength;
4. To either retard or accelerate initial setting;
5. To retard or reduce heat evolution;
6. To modify the rate of, or capacity for, bleeding, or both;
7. To increase durability or resistance to severe conditions of exposure, including application of ice-removal salts;
8. To control expansion caused by reaction of alkalis with certain aggregate constituents;
9. To decrease capillary flow of water;
10. To decrease the permeability to liquids;
11. To produce cellular concrete;
12. To improve penetration and pumpability of grouts and pumpability of concrete;
13. To reduce or prevent settlement, or to create slight expansion, in concrete or mortar used for filling blockouts or other machinery, column or girder spaces, or for filling post-tensioning cable ducts or voids in preplaced aggregate;
14. To increase bond of concrete to steel;
15. To increase bond between old and new concrete;
16. To produce colored concrete or mortar;
17. To produce fungicidal, germicidal, and insecticidal properties in concrete or mortars;
18. To inhibit corrosion of embedded corrodible metal; and
19. To decrease the unit cost of concrete.

See ACI 212.3R and ACI 212.4R for more detailed information.

As a part of acceptance of admixtures, either perform a laboratory analysis or rely on the manufacturer's statements. Inspection of admixtures includes seeing that they conform to appropriate specifications; that they are stored without contamination or deterioration; that they are accurately measured; that they are introduced into the batch as specified; and that they perform as expected so far as can be determined from the concrete as mixed and tested. For example, contract documents should require that calcium chloride (if allowed) be dissolved before being added to the batch, to ensure uniform distribution and uniform acceleration of hydration throughout the mixture.

If at all possible, make routine quality-control tests of admixtures for specific gravity and solids (residue by drying).

STEEL REINFORCEMENT

Steel for concrete reinforcement is usually purchased under one of the ASTM specifications listed in Chapter 22. (See Chapter 17 for discussion of prestressing steel.) Standard practice with regard to purchase and handling of reinforcement is given in the *Manual of Standard Practice* (CRSI 1997b). In general, purchase specifications cover the method of manufacture, certain chemical requirements, tests in tension and in bending, finish of surface, coating for corrosion protection, marking (for size, grade, and point of origin), and permissible variations in weight. Usually, the reinforcement is inspected for acceptance at the mill, and is shipped to the job in bundles marked with tags. The inspector should check each shipment to see that it has been covered by mill inspection, that the specified grade has been delivered, and that the reinforcement is not damaged or ex-

cessively rusted. If at any time it appears that the reinforcement does not meet the contract document requirements, it is recommended to send samples to a laboratory for check tests. A light film of red rust is not objectionable on ordinary reinforcement (in fact, its roughness improves the bond), but a heavy coating consisting of flakes or scales that fly off when the bar is bent or is struck with a hammer should be removed. Reinforcement should be clean, and oil or nonadherent mortar that has been spilled on it should be cleaned off. Epoxy-coated reinforcement should be produced and installed as provided by ASTM A 775.

Occasionally, high-strength reinforcement of Grade 60 or 75 is cracked or broken, especially in cold weather. Of course, cracked and broken reinforcement must be rejected. Inspection of cutting, bending, storing, handling, and placing reinforcement is described in Chapter 8.

CURING COMPOUNDS FOR CONCRETE

Membrane-forming concrete curing compounds are often specified in place of water curing or to provide final curing following a short period of water curing. Curing compounds include clear (with or without a fugitive dye) and white or gray pigmented materials. ASTM C 309 provides standard specifications and references for testing methods for curing compounds.

Base acceptance of curing compounds on certification by reliable manufacturers or on laboratory testing, to ensure compliance with contract documents. Inspection consists of seeing that the material is properly labeled and is not contaminated, diluted, or altered in any way before application; that the compound is mixed thoroughly before and during application; that it is applied when concrete surfaces are still damp and full of moisture; that formed concrete is saturated with water before application; that the specified coverage rate is attained; and that the compound film remains unbroken for the specified length of curing. See further discussion of curing in Chapters 10 and 12.

JOINT MATERIALS

Joints create openings that usually must be filled or sealed to prevent intrusion of dirt, water, or other unwanted substances. For many years, oil-based mastics or bituminous compounds and metallic materials were the only joint sealants available. Fillers available were resilient materials such as fiber board, wood, rubber, or cork. All of these materials are still used in some instances.

To overcome the drawbacks of the traditional joint sealants, many new materials of the elastomeric type have been developed in recent years. The behavior of these materials is largely elastic rather than plastic, and they are flexible rather than rigid at normal service temperatures. Elastomeric materials may be either field-molded or preformed. The inspector must become familiar with the description and detailed use of such materials provided in ACI 504R. This reference lists the many types of elastomeric materials and their properties.

Test and approve joint materials before they are shipped to the job, where the inspector will check shipments to see that the material is not damaged or contaminated, and that

it is properly labeled, stored, prepared, and installed. If laboratory testing is required, prepare representative samples before shipping to the laboratory.

Instructions for sampling liquid and dry components of a job-mixed mastic joint filler are given in the *Concrete Manual* (USBR 1981). Thoroughly mix the liquid component before a sample is taken because it is susceptible to separation. Obtain a sample of dry component by using a sample splitter or by "quartering." Refer to ASTM C 702 for procedures. Ship samples in tightly sealed containers.

The successful performance of any joint sealant will depend greatly on proper installation. Each step in the con-

struction and preparation of the joint to receive the sealant requires careful workmanship and thorough inspection. The contract documents for the work should state the type of sealant, the method of installation, and special features required in construction and preparation of the joint to receive it. Inspection of each joint for cleanness and dryness is essential prior to placing back-up materials, primers, or sealants. Check joint widths and concrete temperatures against the design assumptions if they are stated in the contract documents. In the absence of specified restrictions with respect to temperature, avoid installation at above 90 F and below 40 F.



CHAPTER 4—HANDLING AND STORAGE OF MATERIALS

The quality of concrete produced depends on the quality of the ingredients used. Contaminated, poorly graded aggregates or old cements contribute to poor-quality concrete. Problems such as high or low yield, low strength, and deterioration can often be traced to poor handling and storage of materials. Comprehensive recommendations for transporting and handling are found in ACI 304R.

CEMENT HANDLING AND STORAGE

Bulk storage of cement

For storage of bulk cement, weatherproof and properly ventilate the bin to prevent moisture accumulation. Use a bin with smooth interiors shaped to allow removal of all cement. Inverted truncated cones at the bottom are preferred. Air-diffuser flow pads, installed before filling, are an excellent means of loosening cement that has settled tightly in a silo. Avoid clogged bin vents. Incorrect weights may be indicated on the cement scale if a tanker is transferring cement and pressurizing the bin during batching.

Equip each bin or compartment with a gate and conveyor system for batching. Isolate the conveyor system from the elements.

On large jobs, empty the silos periodically and inspect them for a buildup of cement, which must be removed before refilling. Make this inspection whenever a new supplier's cement or a new type of cement is put into an existing silo.

At all times, expose the cement as little as practical to air because moisture in the air causes partial hydration. If cement becomes slightly lumpy during storage, its use may be permitted if most lumps are sufficiently soft to be crushed between the thumb and fingers. If harder lumps exist, they should be removed by screening, provided that this is not prohibited by the contract documents. If an excessive number of lumps are encountered, the cement should be tested.

Bulk hauling of cement

Cement is typically transported in bulk tanker trucks, rail cars, or barges. The equipment used to haul cement should be maintained leakproof and containment free. The loading chutes or boots for loading the transport vehicles should be regularly inspected. The boot should extend into the truck or compartment to minimize loss of cement.

Bagged cement

Bagged cement normally is used only on relatively small jobs. If bagged cement is used, protect it from both ground moisture and the elements. The preferred method of storage is in an enclosed building and on pallets above the floor. If exterior storage is used, all coverings must be watertight. When removing bagged cement from storage, use the oldest cement first. If the cement has developed warehouse set, the bags should be rolled on a hard surface to regain flowability.



Fig. 4.1—Aggregate piles must be kept clean and separate. Minimize segregation.

Cement with lumps that do not break down easily should be tested prior to use.

AGGREGATE HANDLING AND STORAGE

Keep the grading and moisture content of aggregates as uniform as possible and protect them from contamination. Recommendations for handling and measuring materials are given in ACI 304R and illustrated in Figs. 4.1, 4.2, 4.3, and 4.4.

Avoiding contaminants in vehicles

Vehicles used for transporting aggregate must be tight. Do not use straw, hay, sacks, or large pieces of aggregate to patch vehicles for aggregate shipment. Thoroughly clean and wash the vehicles to rid them of all contaminants before hauling aggregates.

Aggregate stock piles

If aggregates are stored in piles on the ground, either pave the area, lay planks, or leave a bottom layer of aggregate, several inches deep, undisturbed. Regardless of the method used, level and roll the ground first. Do not allow a crane bucket containing other aggregates or materials to swing over the aggregate pile. Build up piles of coarse aggregate in layers to prevent segregation of sizes and reclaim in such a manner that aggregate does not run down the slopes at the edge of the pile. Excessive handling will cause segregation and degradation. Definitely separate adjacent piles, either by ample space or by substantial partitions. Do not mix or store aggregates from different sources in the same pile, because this practice may cause objectionable variation in the concrete. Use each aggregate until it is gone, and make appropriate adjustment in proportions for the next aggregate if required. Separate batching is much preferred over attempts to blend materials by means of clam buckets or bulldozers. Results by the latter methods are seldom sufficiently consistent and dependable.

Do not allow aggregate to fall from a height so that larger particles will be thrown beyond the smaller particles, or that the sizes will be separated by wind. If the height of drop of aggregate is great, use baffles or rock ladders (Fig. 4.2) to break

ADMIXTURE STORAGE AND HANDLING

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CHAPTER 5—FUNDAMENTALS OF CONCRETE

The inspector should “know concrete,” that is, one should know why as well as how things are done. This chapter presents some of the basic features of concrete that affect the work of inspection. For detailed study of principles and practice, see *Manual of Standard Practice* (CRSI 1997b), ASTM STP 169-C (1994), *Concrete Construction Handbook* (Waddell), USACE Manual No. 1110-2-2000 (1994), and ACI 224.1R.

GENERAL CLASSIFICATIONS OF CONCRETE CONSTRUCTION

Most concrete construction can be divided into formed work, slabs on grade, and mass concrete. Within these general divisions, subdivisions can be made, and later chapters will detail inspection requirements for these subdivisions. The fundamentals of concrete, however, apply to all types of construction, and the three general divisions will suffice for presentation of the common fundamentals. Formed work such as beams, columns, walls, arches, and some tunnel linings is usually reinforced; the space for placing concrete is restricted; and, for some, a surface treatment may come after the forms are removed. Pavement and floor slabs have a relatively large, exposed horizontal surface that must be finished and protected soon after placing. Mass concrete in dams, piers, and foundations has relatively low surface-to-volume ratio, but the bond between different lifts and the rise in temperature due to heat of hydration of the cement must be considered.

CONCRETE REQUIREMENTS

The principal requirements of hardened concrete are that its constituents be evenly dispersed; that it have the required strength; that it be watertight and resistant to weather, wear, and other destructive agents to which it might be exposed; and that it not shrink excessively on cooling or drying. The hardened concrete may be required to have a particular architectural finish or appearance. It may be required to have high resistance to abrasion, high resistance to aggressive chemicals, or impermeability to water or other liquids. For some uses, concrete must meet special requirements; it may be required to be fire resistant, or to be light in weight, or to be especially smooth, or to have a purposely textured surface finish. Fundamental knowledge of the essentials of concrete enables the designer to fulfill the requirements so far as possible and better enables the inspector to see that these requirements are obtained.

NATURE OF CONCRETE

In freshly mixed concrete, all of the granular solids, including cement, are temporarily separated by thin layers of water. This separation of the particles and the lubricating effect of the water layers, together with certain inter-particle forces, make the mixture workable.

It is convenient to think of concrete in terms of its two major components: paste (or binder) and a mineral aggregate, with the individual particles of the aggregate being embed-

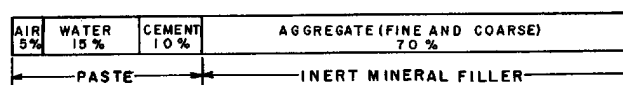


Fig. 5.1—Volumes of components of typical concrete mixture containing an air-entraining admixture.

ded in and separated by this paste. The paste is a mixture of cement, air, and water, as shown in Fig. 5.1. The volume of the whole mixture is equal to the solid volume of the cement, water, and aggregate, plus the volume of the entrained or entrapped air, or both. The concrete may or may not contain one or more admixtures.

All concrete will contain some air, known as “entrapped air,” no matter how thoroughly the concrete is consolidated during placing. The amount of entrapped air in thoroughly consolidated, normalweight concrete is usually less than 2% by volume. With the mixture proportions and aggregate characteristics fixed, the entrapped-air content is greater with stiffer consistency and with smaller aggregate. The air entrapped in concrete normally exists as scattered voids, usually having sizes comparable with the larger grains of sand. Such voids are characteristic of concrete, and their occurrence is neither harmful nor avoidable.

In addition to entrapped air, concrete may contain voids introduced intentionally by means of an air-entraining admixture. Such admixtures cause the formation of a large number of small spherical voids within the cement paste during mixing. These voids are comparable in size with the larger cement grains and the finer sizes of sands.

Air voids aid the paste in making the mixture workable. The surface tension and the surface-active agent absorbed at the void boundaries of entrained-air voids impart added “body” and cohesiveness to the paste. Entrained air, as produced by an air-entraining admixture, is essential to obtain freeze-thaw resistance where the hardened concrete is highly saturated and has little opportunity to dry out before being exposed to freezing temperatures. Entrained air in concrete will also substantially increase the resistance to the effects of freezing and thawing, reduce surface scaling of pavements, add to the workability and cohesiveness, slightly increase resistance to sulfate attack by reducing permeability, and reduce segregation and bleeding. Recommended practices regarding the use of air-entrained concrete are given throughout this manual.

Settlement

In undisturbed, newly placed, and consolidated concrete, the solids will slowly settle through the fluid portion of the concrete, usually leaving a layer of clear water at the surface. This is known as bleeding or water gain. As a result of settlement, the solids at the bottom of the concrete member become more closely packed. During the process, the compacted zone gradually increases in thickness until it extends to the surface, or until settlement is stopped by the set-

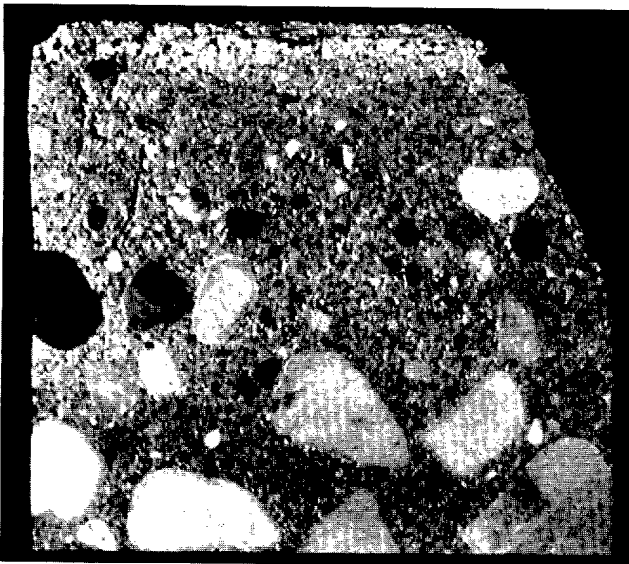


Fig. 5.2—Concrete cross section displays aggregate settlement.

ting of the cement paste. In the latter case, the upper part of the concrete remains less compact than the lower part; that is, its water and void content remains higher. Because of this settlement and resultant bleeding, the space occupied by the hardened concrete is slightly less than when it was freshly placed. (In estimating yardage from a batch count, this should be taken into consideration.) The amount of settlement and resultant bleeding is influenced by friction against the forms, by temperature, and by handling, and is influenced greatly by the mixture proportions, air entrainment, consistency, and the consolidation procedures. Correctly proportioned mixtures and those with low slump settle less than incorrectly proportioned or high-slump mixtures.

When entrained air is present, the process of settlement is altered, and the rate and amount of settlement is usually materially reduced (Fig. 5.2).

During hot, dry weather, bleeding may aid in prevention of excessive surface drying and plastic shrinkage, but ordinarily the elimination of bleeding is desirable. Bleeding delays proper finishing, because floating and troweling operations should not be performed on a wet surface. Unless the concrete is revibrated just before it sets, bleeding is likely to form layers of water and fissures under the aggregate particles and reinforcing steel, and result in losses in strength and impermeability. Although, theoretically, bleeding reduces the w/cm , which should improve concrete quality, the foregoing considerations suggest that bleeding is not advantageous. Air entrainment will often reduce bleeding by approximately half. Use of other cementitious materials or pozzolans, such as silica fume, also reduces bleeding appreciably and has other effects on the concrete, depending on the product used.

Under severe drying conditions, bleeding may continue below the surface of flatwork, because the surface stiffens sufficiently from drying to permit floating and troweling before the lower concrete has hardened. Under such conditions, the surface may later scale if the lower plastic concrete

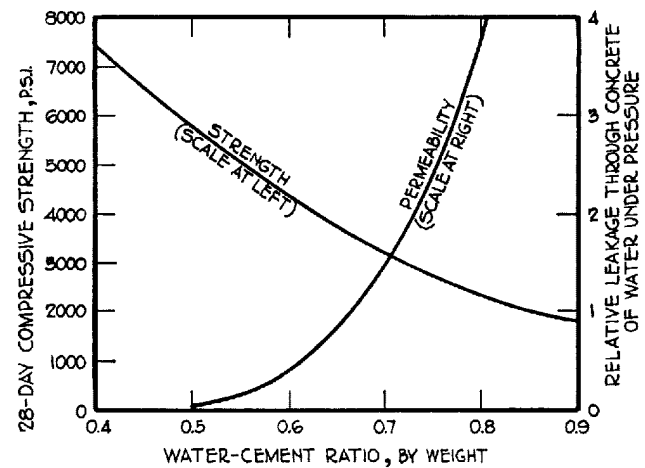


Fig. 5.3—Concrete of lower water-cementitious materials ratio (w/cm) is stronger and more nearly watertight. For illustration only, to show trends; values will differ with materials and conditions of test.

continues to bleed to form a thin layer of water under the hardened surface. When placing flatwork under conditions of severe drying, apply either plastic sheeting or a fine spray from fog nozzles to prevent the surface from hardening faster than the interior, and delay finishing as long as possible. This same problem can also occur in cold weather when a concrete slab is placed on extremely cold subgrade while the surface is subjected to artificial heating.

Composition of paste

Because the paste surrounds and separates the individual aggregate particles, the strength of the concrete is limited by the weakest of:

- The strength of the paste;
- The strength of the aggregate; and
- The strength of the bond developed between paste and aggregate.

With the paste between, aggregate interlocking does not contribute appreciably to the compressive strength of hardened concrete. It does contribute to flexural strength, which is important in pavements. With satisfactory aggregates, percolating water must act on or pass through the paste. Some of the constituents of the hardened paste are water soluble, and the rate of leaching of these soluble constituents is greatly diminished with denser paste. Hence, it is desirable that the paste be dense and have a low w/cm when the concrete will have prolonged contact with soft water or with water that contains aggressive chemicals such as chlorides, sulfates, or acids.

The strength and density of the paste depend primarily on w/cm (Fig. 5.3), and on the extent to which the cement becomes hydrated. Upper limits on w/cm and ample curing are required to ensure a sufficient degree of cement hydration. See Chapter 6 for a discussion of cementitious materials

Hardening process

The principal reaction product of the hardening process has a gel configuration, formed from water and there acted con-

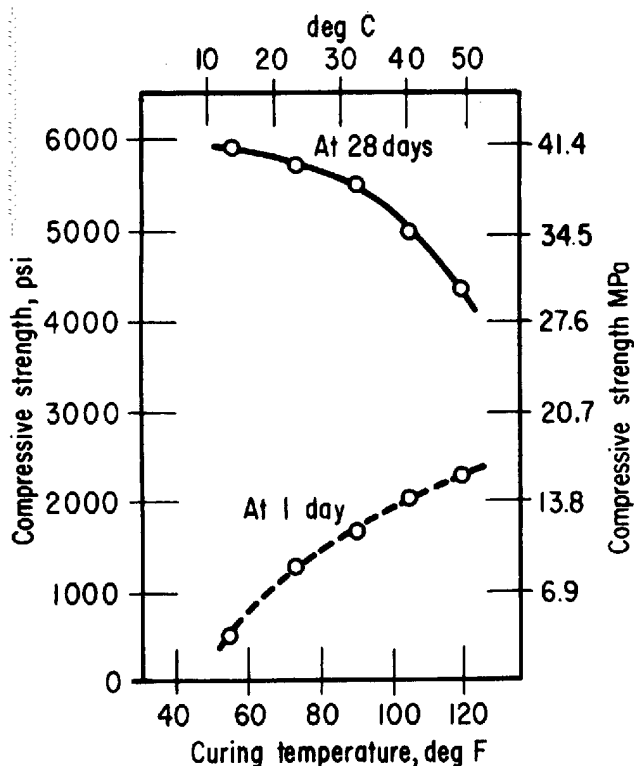


Fig. 5.4—One-day strength increases with increasing curing temperature, but 28-day strength decreases with increasing curing temperature. Reference: "Structural and Physical Properties of Cement Pastes," (Verbeck and Helmuth, Proceedings, Fifth International Symposium on the Chemistry of Cement, V. 3, 1968, p. 9).

stituents of the cement grains. This process of hydration of cement and formation of gel continues at a diminishing rate as long as moisture is available. If the paste is not kept moist, cement hydration ceases when the evaporative water escapes from the paste, showing the importance of adequate curing.

After adequate initial curing, the time during which hydration of cement will continue varies with the ambient temperature, and the accessibility of an external water supply. When concrete of the type commonly used is cured for 1 month under moist laboratory conditions, more than 80% of the cement will become hydrated. The percentage of hydration is influenced by the grind of the cement with the finer cements reaching more complete hydration. Under field conditions, however, the concrete in thin sections and surface concrete may become partially dry within a few days. Thereafter, the cement may have an opportunity for continued hydration only by slow migration of water from any subgrade contact or from moisture obtained during rainy periods or other wetting conditions. Therefore, only under favorable moisture conditions will the hydration of cement continue for many years.

Rates of strength development are somewhat different from, but related to, rates of hydration. At normal temperature, the earliest stages of hydration produce relatively little strength. Under standard laboratory conditions, about one-half of the ultimate compressive strength of concrete will be reached during the first week, and about three-fourths during the first month, when Type I cement is used. Because

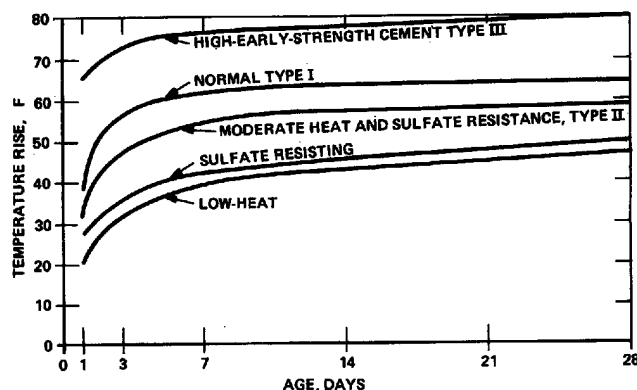


Fig. 5.5—Temperature rise of concrete when no heat is lost, for various types of cement; 376 lb cement per yd³.

the gain in strength is due to an increase in the degree of cement hydration, drying impedes the development of strength as it does the progress of hydration. In cold seasons, however, after lengthy water curing, some drying before exposure will be advantageous because saturated concrete is damaged more readily by freezing.

Increasing the ambient temperature increases the rate of hydration and modifies the physical characteristics of the hydration products. The higher the ambient temperature, the greater the modification, particularly at early ages. The modification of the gel produced by early high temperatures will lower the ultimate strength of the concrete (Fig. 5.4, adapted from ACI 308-92, Fig. 2).

Heat of hydration

The reaction between the constituents of portland cement and water is accompanied by liberation of heat. Part of this heat escapes through the surface of the concrete, but some is retained and the concrete gets warmer. Excessive temperature rise is undesirable because it may reduce the strength and it produces stresses that may cause cracks as the temperature drops later. This is particularly true where temperature differentials exist between parts of the mass and where it is partially restrained. In most concrete structures, temperature rise is small and of little consequence. In heavy mass concrete where the heat escapes slowly, the temperature rise will be somewhat as shown in Fig. 5.5. As shown, the temperature rise depends on the type of cement. Also, it is roughly proportional to the cement content of the concrete.

To control the temperatures in mass concrete, various measures have been adopted, such as using a lean mixture, using a low-heat type of cement, replacing some of the cement with a pozzolan (see ASTM C 618), using a water-reducing admixture to further reduce cement requirements, precooling materials, or replacing a portion of mixing water with ice. Other measures include scheduling placements during cooler periods of the day or during cooler seasons, scheduling the placement so as to allow one layer to cool before placing the next, and removing heat by means of embedded pipes through which cool water is circulated.

Curing and protection

The period of positive curing provided for in the contract documents is required to ensure attainment of potential

strength and to prevent surface crack formation. This cracking is caused by rapid loss of water and resultant shrinkage while the concrete is still low in tensile strength and unable to resist the shrinkage stresses. Hydration of cement in thin-section beams, columns, and slabs, not in contact with moist earth or water, is reduced so as to become insignificant at and near the surface soon after termination of curing.

If a member is sheltered from rain or other free water, hydration can proceed at significant rates (in the portion of concrete that has dried) only when the relative humidity of ambient air is well above 80%. On the other hand, members with thin sections in contact with moist earth or other free water, such as retaining walls and pavement slabs, will continue hydration at a significant rate. The principal purpose of specified curing is to prevent rapid early removal of water by initially dry subgrades or by sun and wind, so as to ensure the early attainment of specified strength and to reduce the effects of shrinkage. Hydration of cement beyond that needed for specified strength is highly desirable for the added margin of quality it produces.

Self-desiccation (removal of available water in the concrete by hydration of the cement) of very rich mixtures may become important when curing formed concrete by means of commercial membrane-forming curing compounds. The compounds available only retard the water loss. They do not provide perfect seals, nor do they supply water. When applied promptly and properly to mixtures of ordinary proportions, however, they may retain the evaporable water sufficiently long for the concrete to reach its specified strength within an acceptable period, but little more.

More detailed information on curing is provided in Chapter 10. That chapter also provides information on the necessary protection of concrete during cold, normal, and hot weather conditions.

FREEZE-THAW RESISTANCE

Among the natural agencies that can disintegrate exposed concrete structures, the action of freezing and thawing is the most common, particularly if the concrete is saturated at the time of freezing. Under some circumstances, both the hardened cement paste and the aggregate particles are vulnerable.

Nature of freeze-thaw damage

Normal cement paste is vulnerable because, when saturated, expansion of its freezable water content produces a volume increase in the paste exceeding the amount of expansion that the paste can withstand without damage. Some aggregate particles with pore sizes large enough to allow slow entrance of water, but not large enough to allow rapid exit and pressure relief when freezing commences, can contain more freezable water than they can accommodate when freezing occurs. Even aggregate particles not otherwise affected by freezing can have water virtually sealed into the pores of the aggregate by the surrounding dense cement paste so that freezable water in the particles must either burst the stones or paste, or both, and will cause damage if freezing occurs while pores are full or nearly so.

Under most conditions, exposed concrete does not remain saturated. For example, a pavement or retaining wall with one

side in contact with moist earth and the other in contact with air generally is not in a water-saturated state, because during most of the time the rate of evaporation exceeds the rate of replenishment of moisture. The lower the porosity of the paste, the greater the freeze-thaw resistance of the concrete.

Protection by entrained air

Because the paste in concrete normally contains freezable water, it cannot long withstand the action of freezing after it becomes saturated. If the paste has a large number of small, closely-spaced air voids produced by an air-entraining admixture, however, freezing does not damage the paste, even though the paste surrounding the voids is water saturated. To be effective, the induced voids must be so numerous that the calculated spacing factor of air voids is a maximum of 0.008 in.

Such spacing does not normally occur naturally and must be produced by use of air-entraining agents. In general, the amount of air-entraining admixture required for concrete subject to severe exposure is that which will produce the following total percentage of air (all based on achieving the previously mentioned spacing of voids).

Coarse aggregate, maximum size, in.	Total air, %
3/8	7-1/2 ± 1-1/2
3/4	6 ± 1-1/2
1-1/2	5-1/2 ± 1-1/2
3	4-1/2 ± 1-1/2
6	4 ± 1-1/2

ACI 318 and ACI 301 permit a 1%-point reduction for concrete over 5000 psi. Refer to Chapters 6 and 7 for discussion of other aspects of air entrainment.

SHRINKAGE AND SWELLING

Concrete shrinks when it dries and expands when it is moistened. When concrete is kept continuously damp, it slowly expands for several years, but both the total amount and the rate of expansion are normally so small that the volume is considered to remain constant. Usually concrete is not kept continuously damp and hence is subject to water loss and subsequent shrinkage rather than expansion. Also, some of the shrinkage on initial drying is irreversible; hence, under ordinary conditions, the volume when initially hardened is the largest that will occur during the life of the concrete.

After concrete has dried to constant water content under ordinary atmospheric conditions, a drop in humidity will cause it to lose water or an increase will cause it to gain water because hardened cement paste is hygroscopic. The paste and the concrete of which it is a part will shrink or swell with each such change in water content.

On changing from a saturated to a dry state [50% relative humidity (RH) or less], an average concrete will shrink approximately 2/3 in. per 100 ft, or approximately 0.06%. This is approximately the amount of contraction caused by a temperature drop of 100 F.



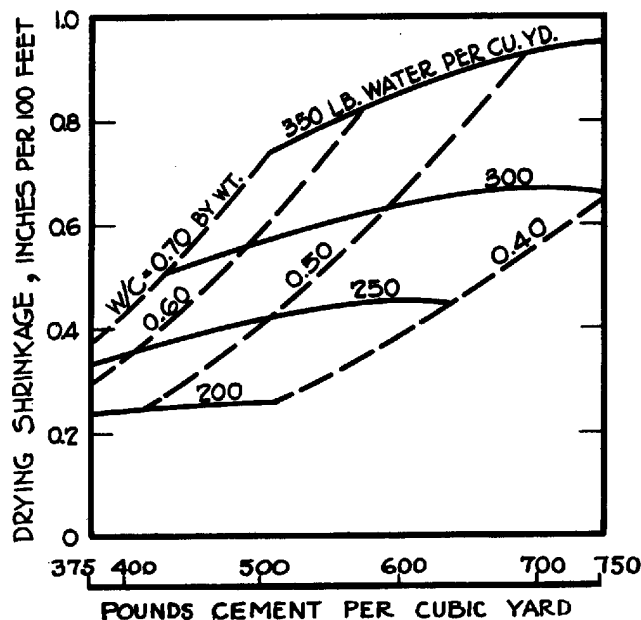


Fig. 5.6—Interrelation of shrinkage, cement content, water-cementitious materials ratio (w/cm), and water content of concrete. For illustration only, to show trends; values will differ with materials and drying conditions.

Many different factors (such as the particular cement or aggregate or porosity in the concrete) influence the amount of shrinkage under given drying conditions, but the most important factor is the total amount of water in the original mixture. A good correlation between total water content of fresh concrete and drying shrinkage of hardened concrete has been found (Fig. 5.6) for different mixtures made with the same materials. Note that the effect of total water content is large.

If a concrete member is restrained against shrinkage by the subgrade, reinforcement, or structural connections with other members, it will tend to crack as a result of drying shrinkage or the combined effects of thermal and drying changes. Further, when the surface of the hardened concrete in a structural member dries more rapidly than the interior, differential stresses are set up that may cause the formation of a network of shallow cracks on the surface. Unequal drying of opposite surfaces of thin slabs with little or no reinforcement, such as pavements, may cause them to "curl," most noticeably at edges and corners. Curling is sometimes described as "warping," but the latter term is more properly used to express similar displacements caused by subgrade movements.

Although drying shrinkage is a primary cause of cracking, other factors such as tensile strength, stress-strain-time characteristics, and moisture-diffusion characteristics of the concrete must be considered along with shrinkage to account for differences in cracking of different concrete structures.

Volume changes of concrete due to temperature changes are as important to the behavior of structures as is drying shrinkage. The relative magnitudes are previously given (100 F temperature drop causes approximately same contraction as drying from saturated to dry state). Restraint of thermal contraction may cause cracking in structural members or in slabs. Therefore, measures must be taken to minimize thermal cracking. In reinforced concrete construction, the reinforcement used for load resistance will generally do this. In slabs with light or no reinforcement, however, joints of proper spacing and depth must be formed or sawed into the slabs to provide stress relief at planned locations and to prevent uncontrolled cracking. In members requiring no structural reinforcement, light "temperature steel" is often designed simply to control thermal cracking by producing many small insignificant cracks instead of a few large objectionable cracks.

CHAPTER 6—CONCRETE MIXTURES: PROPORTIONING AND CONTROL

It is necessary to consider a number of items in proportioning concrete mixtures. Durability and strength (compressive or flexural) as required in the contract documents, will set the w/cm for given materials. Durability requirements will also indicate the need for air entrainment or extra-high-strength and dense concrete. Placeability (workability and consistency) will be dictated to a great extent by the proposed concrete placing methods (buckets, buggies, pumps, and conveyors), the placing conditions (form depth and dimension, reinforcement, and accessibility), and the method of consolidation (spading, internal or external vibration). Appearance, such as that of architectural concrete, may require consideration of color and type of the coarse aggregate, type of cement, and fine-to-coarse aggregate, particularly in the case of exposed aggregate concrete.

Adjustments of the concrete's setting characteristics or water requirement may require chemical admixtures for water reduction or for retardation or acceleration of set. Other cementitious materials (pozzolans such as fly ash or silica fume, and ground, granulated blast-furnace slag) may also be required or permitted in addition to portland cement and blended cements.

The required properties of the concrete are governed by its use. Such properties are often, but not always, reflected in the contract documents for the job. A discussion of the factors to be taken into consideration and certain general principles employed when proportioning concrete mixtures will be presented in this chapter. Detailed mixture proportioning procedures are covered in ACI 211.1, ACI 211.2, and ACI 211.3. Proportioning of concrete mixtures containing one or more admixtures is discussed in ACI 212.4 R. Lightweight concrete mixture proportioning is also discussed in Chapter 16 of this manual.

METHODS OF SPECIFYING CONCRETE PROPORTIONS

Generally, contract documents require that the concrete develop a certain strength at a given age within a limiting range of consistency (slump). A maximum w/cm or minimum cement content is often specified as an additional precaution to ensure the necessary durability, impermeability, or workability.

Strength specification

Often the specified strength is designated as a "minimum strength," and literal interpretation leads to confusion and argument over the occasional low-strength tests that can occur even though satisfactory concrete mixture proportions are used. Such argument may result in unnecessary modifications to the mixture proportions or increased test requirements. The evaluation of the results of strength tests of concrete takes into consideration that the production of concrete is susceptible to variations of ingredients, variations in batching, and testing. Modern codes for structural design permit occasional lower individual tests as much as 500 psi

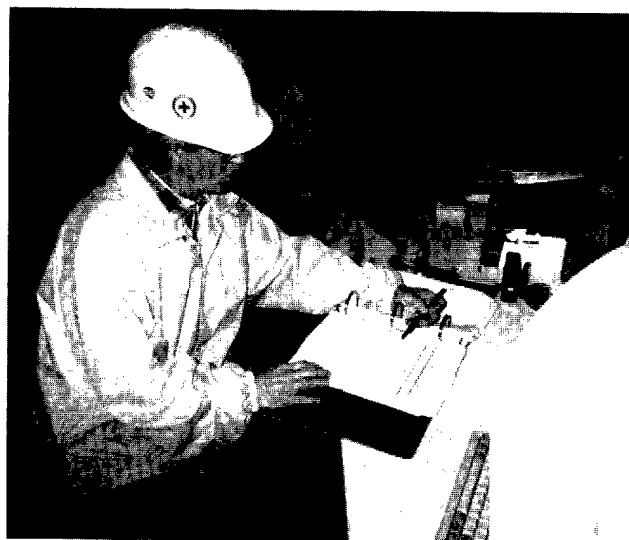


Fig. 6.1—Concrete inspector viewing mixture proportions.

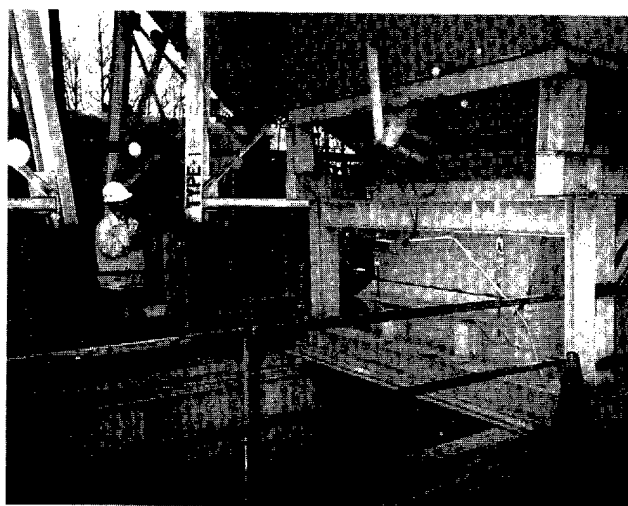


Fig. 6.2—Concrete inspector inspecting the batch plant weight scale area.

below the specified (design) strength. The recommended consideration of occasional low strengths is discussed in detail in Chapter 2 of this manual and in ACI 318 and ACI 301.

Because of variability in concrete, as well as variability in test specimens and in test results (see ACI 214), it is necessary to proportion concrete for an average strength far enough above the specified f'_c that all but a small proportion of the concrete will equal or exceed f'_c . The amount of "over-design" for strength in trial mixtures should be statistically based on the previous record of concrete production. Some contract documents require up to 1500 psi overdesign when the data from previous records indicate extreme variability in production or when no previous data are available. In the absence of such contract document requirements, prepare the design as discussed in Chapter 2. As a history of field strengths is accumulated using the established mixture pro-

portions, and proper control of field operations is attained, it may be possible to adjust mixture proportions.

The same approach is used for pavement concrete except that, in this case, concrete strength may be evaluated as flexural strength of standard test beams instead of compressive strength.

Proportion specification

A specification may govern the proportions of materials by one of the following methods:

1. A fixed or a minimum amount of cement (and admixture, if specified) per volume of concrete;
2. A fixed or a maximum w/cm ;
3. Fixed proportions of cementitious materials, fine aggregate, coarse aggregate, and admixtures; and
4. Limits on the proportion of fine-to-total aggregate, for example, 35 to 50%.

Requirements 1 and 2 are often combined and are more typical than Requirements 3 and 4. The consistency (slump) is also typically specified. For air-entrained concrete, it is usual to specify the range of total air in the concrete mixture. If the specified slump range cannot be obtained with the minimum cementitious materials content and maximum w/cm specified, several changes will remedy the situation. For example, the cementitious materials content can be increased, the aggregate types can be changed (angular to rounded), or the relative proportions of fine-to-coarse aggregate can be changed. The desired slump may also be achieved by using a water-reducing admixture. When using Requirements 1, 2, and 4 together, specify values, including strength, that are consistent with respect to each other. Specify a range for slump.

METHOD OF PROPORTIONING FOR SPECIFIED STRENGTH OR WATER-CEMENTITIOUS MATERIALS RATIO (w/cm)

Cement

The type of cement to be used is usually stated in the contract documents. For ordinary uses, employ a normal portland cement (ASTM C 150, Type I) or a blended cement (ASTM C 595); for special cases, use moderate heat (Type II), high early-strength (Type III), or sulfate-resisting (Type V) cements. When other than Type I or Type III is used, a choice of type will usually be dictated by considerations other than strength. However, even under such conditions, a minimum concrete strength at each specified age is usually required. (See discussion on cement in Chapter 3.)

Whatever the type of cement to be used, proportioning determines the quantity of cement for a unit volume of concrete that will produce hardened concrete of specified strength and durability if proper curing occurs. The quantity of cement needed depends on the following factors:

1. Type and quality of cement;
2. Quantity and quality of pozzolan or other cementitious material;
3. Maximum w/cm or water-cement ratio (w/c);
4. Consistency of mixture;
5. Use of admixtures, including air-entraining admixtures singly or in combination;
6. Maximum size and grading of the aggregate;

7. Other characteristics of the aggregate, such as particle shape and surface texture; and

8. Rate of strength gain desired.

CONCRETE WITH POZZOLAN AND OTHER CEMENTITIOUS MATERIALS

The use of pozzolans as additions or as replacement of a certain portion of the portland cement in concrete is not a new development. Pozzolans have been widely used in massive structures such as dams since the late 1940s. Since that time, pozzolans (particularly fly ash) have also found considerable use in structural concrete. Pozzolans can improve workability (Fig. 6.5), reduce heat of hydration, decrease permeability, improve sulfate resistance and reduce expansions caused by reaction between certain aggregates and the alkalis in cement. Importantly, the use of pozzolans can result in greater economy of concrete, particularly if compressive strength is specified at ages greater than 28 days.

In the 1980s, an ultra-fine pozzolan called silica fume gained attention as a mineral admixture, contributing to the development of a new generation of high-strength concretes, ranging upward from 12,000 psi in strength. Silica fume, a byproduct of the industrial manufacture of ferrosilicon and metallic silicon, has particles approximately 1/100 the size of portland cement grains. Consult ACI 234R for detailed information.

The use of pozzolans generally reduces the rate of early strength development so that concrete strengths at early ages may be less than those of comparable mixtures with only portland cement, but strengths at later ages will be nearly equal or higher. Class N pozzolans may increase mixing water requirements, and thus, at least theoretically, drying shrinkage, but no difference is evident in field structures. Class F (fly ash) pozzolan reduces mixing water requirements more often than it increases them. To properly assess the advantages and disadvantages of using pozzolans, conduct laboratory studies of proposed concretes using actual job materials. When the aggregates are potentially reactive, alkalis in the pozzolans as well as those in the cement should be considered in evaluating the cement-pozzolan combination. The concrete color may vary depending on the color of the pozzolans. Detailed information on the use of pozzolans in concrete is given in *Concrete Manual* (USBR 1981), USACE Manual No. 1110-2-2000 (1994), and ACI SP-132 (1992).

Materials

ASTM C 618 provides requirements for three classes of pozzolans as follows:

Class N—Raw or calcined natural pozzolans, such as some diatomaceous earths, opaline cherts, shales, tuffs, volcanic ashes or pumicites, and some clays and shales.

Class F—Fly ash that is a finely divided residue resulting from the combustion of ground or powdered anthracite or bituminous coal.

Class C—Fly ash produced from burning lignite or sub-bituminous coal and generally having sufficient lime content to have some cementitious properties.

Requirements for ground granulated blast-furnace slag (GGBF) are provided in ASTM C 989. GGBF slag is class-

fied by that specification as either Grade 120, 100, or 80, based on compressive strength results of the slag activity index test with portland cement.

Requirements for silica fume are provided in ASTM C 1240.

Mixture proportioning and control

Follow the recommendations of ACI 211.1 for trial mixture proportioning of concrete containing pozzolans and other cementitious materials using the established specific gravity of each material in appropriate calculations.

Carefully identify batching and storage equipment to differentiate between portland cement and fly ash, as the color of these may be nearly the same.

The dry weights of portland cement, pozzolans, and other cementitious materials are generally combined to determine the total cementitious content of a mixture, and subsequently, the w/cm .

Silica fume is sometimes combined with water in a slurry solution to facilitate handling and batching during mixing operations. The amount of water added to the batch as part of a slurry solution must be determined and properly accounted for in calculating the w/cm .

Because selection of pozzolans and other cementitious materials is often based on the desire to create concrete having unique or enhanced properties before use, it is desirable to test resulting mixtures for these properties.

Water-cementitious materials ratio (w/cm)

If aggregate of approximately the same grading and maximum size and from the same source is used, and other materials remain the same, the potential compressive strength of concrete is nearly constant when the w/cm is held constant. For a desired slump and strength, however, the necessary w/cm will vary somewhat for different aggregates and for different gradings (particularly in regard to maximum size of aggregate) and may be modified substantially with the use of one or more admixtures. Nevertheless, average relationships of w/cm and strength are usually sufficiently representative for proportioning a trial or starting mixture. Estimate the necessary w/cm from a published table of w/cms and corresponding strength values.

Table 6.1 (adapted from ACI 211.1) gives approximate strengths for different w/cm , using average aggregates with and without an air-entraining admixture. Strengths obtained from these w/cm will generally be on the conservative side. If there is a history of usage of given materials, a review of available test information can provide useful data, particularly as to water requirement and strength level of the concrete.

Aggregate

The nominal maximum size of aggregate usually is specified, or limited by the placing conditions, dimensions of structural member, and reinforcing steel spacing. Well-graded aggregate of large maximum size has less total volume of voids than smaller-sized aggregate. Therefore, concretes with the larger-sized aggregates that are properly graded require less mortar, and thus less water, per unit volume of concrete. Generally, and for "average" strength requirements, the max-

Table 6.1—Relationships between water-cementitious materials ratio (w/cm) and compressive strength of concrete

Compressive strength at 28 days, psi*	Water-cementitious materials ratio, by weight	
	Non-air-entrained concrete	Air-entrained concrete
6000	0.41	—
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

*Values are estimated average strengths for concrete containing not more than the percentage of air shown in Table 5.3.3 of ACI 211.1. For constant w/cm , strength of concrete is reduced as air content is increased. Strength is based on 6 x 12 in. cylinders moist-cured for 28 days, in accordance with Section 7.3 of ASTM C 31.

Note: Relationship assumes maximum size of aggregate = 3/4 to 1 in.; for a given source, strength produced for given w/cm will increase (as will cement content) as maximum size of aggregates decreases. See Section 3.4 and 5.3.2 of ACI 211.1.

imum size of aggregate should be the largest that is economically available and consistent with the dimensions of the structural elements and placing conditions. When high-strength concrete (more than 6000 psi) is desired, best results may be obtained with reduced maximum aggregate sizes, usually 3/4 or 1/2 in., because concretes with these aggregates normally have higher strengths at a given w/cm . Smaller aggregate, however, will require more water and thus more cementitious material.

Whenever mixture proportioning studies and concrete tests are made for evaluation of materials, use each material to the best advantage. Best results from each aggregate are likely to be obtained with different gradings, especially the proportion of fine-to-coarse aggregate. Keep the amount of pea gravel or flat and elongated small coarse aggregate at a minimum to enhance finishability and pumpability. Nevertheless, whatever aggregates are selected, determine the most favorable combination of fine with coarse aggregate to provide the required concrete properties. Generally, keep the percentage of sand as low as practical but still provide the needed fine sizes for good workability and minimum bleeding. Low sand content usually minimizes the water requirement of the concrete and gives the most economical proportions provided a gap-grading doesn't occur due to lack of intermediate sizes. Water requirement, however, increases only by approximately 1% for each percentage point increase in the sand-aggregate ratio. A strict minimization of the proportion of fine aggregate is not always advisable, particularly if concrete with more fine aggregate is noticeably easier to place, consolidate, and finish. Low sand contents are desirable in low-slump concrete to maximize strength, but higher sand contents are needed to minimize segregation in higher-slump concretes.

Other factors being the same, aggregates composed of angular particles require more paste than equal proportions of smooth, rounded particles. When concrete strength is the criterion, however, the rounded aggregates are not always preferable because crushed aggregates normally give higher strengths at a given w/cm . When durability requirements do not govern the w/cm , it is sometimes permissible, on the basis of test data, to use a w/cm higher with crushed material than would be required for rounded material. In other words,

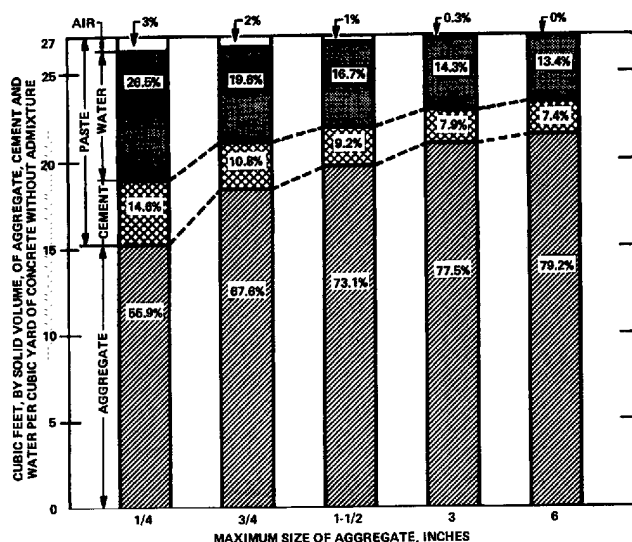


Fig. 6.3—The larger the maximum size of graded aggregate, the smaller the amount of paste required to make the concrete workable. $w/cm = 0.58$ by weight, medium consistency (3 to 5 in. slump); natural sand and gravel. Non-air-entrained concrete; air content shown is entrapped air.

with a different aggregate, a different w/cm may sometimes be used to achieve the same strength. For concrete designed on the basis of flexural strength for pavements, angular aggregates are usually preferable if available.

After determining the w/cm , the next step is to find the aggregate proportions that will provide a workable mixture with a minimum amount of paste. Whenever possible, the mixture should be based on trial mixtures using job materials. All mixtures must be workable. The data to be obtained from trial batches are strength (flexural or compressive), slump, % air, and density.

When these tests cannot be made, use recommendations based on experience, such as those of ACI 211.1 and 211.3 as well as *Design and Control of Concrete Mixtures* (PCA 1994). These recommendations do not explicitly take into account differences in strength that may arise from differences in aggregate or cement characteristics; however, they are sufficiently conservative to provide safe results. Adjust the initial mixture proportions as necessary based on test results and observations during production.

Air entrainment

For normal concrete of a given w/cm , without adjustment of slump increase, the entrainment of air will reduce strength approximately 5% for each percentage point of added air. With air entrainment, however, less mixing water will be required to provide the same slump because the small air bubbles provide "lubrication" to the mixture. Therefore, if slump and cement content remain constant, a lower w/cm results, which will partly compensate for the strength loss in ordinary mixtures. Usually, the coarse aggregate proportions are the same for air-entrained concrete as for non-air-entrained mixtures, but less fine aggregate is needed because the air increases the volume of mortar and helps provide workability. With some lean mixtures (low

cement content), use of air entrainment with consequent reduction in w/cm may actually increase compressive strength.

Quality of cementitious material

Concretes containing equal amounts of cement from different sources (or perhaps the same source at different times) will not necessarily have the same strength. If high-strength concrete is required, use portland cement meeting the optional physical requirements given in Table 4 of ASTM C 150. The same considerations apply to blended cements and other cementitious materials. Further, do not use air-entraining cement unless it is needed for durability. As stated in Chapter 3, cement remaining in bulk storage at the mill for more than 6 months after completion of tests should be retested as indicated in ASTM C 150.

Quantity of paste

With given materials, the optimum mixture proportions use the least amount of total water per unit volume of concrete to obtain the required slump and workability. With a fixed w/cm , material costs are reduced by using mixtures having the least paste. The cementitious material in the paste is typically the most costly ingredient of the concrete; therefore, using more paste than required adds unnecessarily to the cost of the concrete. When using extremely high-priced aggregates, however, balance the cost of paste against the aggregate cost.

Also, minimizing the paste is desirable because water in the paste is the primary cause of shrinkage as the concrete hardens and dries. The more water (that is, the more paste), the greater the drying shrinkage. Also, cement produces heat as it hydrates. Therefore, high cement contents may produce undesirable temperature rise and crack-producing temperature differentials. The quantity of paste required in a unit volume of concrete depends on the following factors:

1. w/cm of the paste;
2. Consistency of the fresh concrete;
3. Grading of the aggregate (including chemical content, in some cases);
4. Shape and surface texture of the aggregate particles;
5. Amount of entrained air;
6. Chemical and mineral admixtures;
7. Nominal maximum size aggregate;
8. Proportion of fine aggregate to total aggregate;
9. Characteristics of the cement; and
10. Amount, type, and quality of other cementitious materials.

Nominal maximum size of well-graded aggregate is the principal feature that determines paste requirement. A typical relationship is shown in the following table and in Fig. 6.3.

Nominal maximum size of aggregate, in.	Paste fraction in unit volume of concrete	Cement, lb/yd ³ *
3/8	0.40	750
3/4	0.30	565
1-1/2	0.26	490
3	0.22	415
6	0.21	395

* $w/cm = 0.58$ by weight.

