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**ANALYSIS OF INITIAL CONCRETE TESTING
IN RELATION TO
EXPECTED PERFORMANCE**

By

VINCENT RACANELLI

**Lieutenant Commander
Civil Engineer Corps
U. S. Navy**

A research paper submitted
in the partial fulfillment of the requirements
for the degree of

Master of Science in Civil Engineering

University of Washington

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CHAPTER 1 - INTRODUCTION

Portland cement concrete is unique among most construction materials in that its properties change substantially from when delivered to the job site to when the final product made from the concrete is put to use. When delivered, the concrete must exhibit uniformity and workability sufficient to place and consolidate the fresh concrete. After sufficient curing the concrete must have strength and durability. Quality control testing must therefore consider both fresh and hardened properties to evaluate the acceptability of the concrete for its intended application.

Standard quality control testing performed at the job site includes slump, air content, unit weight and yield. Typically, these tests are performed by the agencies as the concrete is delivered to the job site. Results are available within minutes after completing the testing. The information derived from the tests is believed to provide inspectors with an initial indication of the expected short and long term performance of the concrete. Standard practice is to accept or reject the load of concrete based on the test results.

The aspect of timely results for quality control testing at the job site is an important advantage over strength test results which are not available for several days after the concrete has set. The initial quality control testing provides information at the beginning of the process to permit corrective action during placing operations. By the time strength results are available it is usually too late to correct the situation without a great deal of effort and expense and in some cases the only feasible solution may be to take contract deductions for low strength.

The purpose of this research was to investigate the policies and procedures of various agencies for quality control testing at the job site and to determine the influence of one of many important parameters affecting portland cement concrete, fine aggregate gradation, on the test results. Results of this investigation were used to make an

assessment of the adequacy of current job site procedures and to develop recommendations for improvement and identify areas requiring further research effort.

A dual approach was taken to address the adequacy of current job site procedures. Interviews were conducted with various agencies to analyze the procedures being employed in the field. The agencies consulted for this research included two public agencies, the U. S. Navy, and the Washington State Department of Transportation. In addition, an interview was conducted with a commercial concrete prefabrication manufacturer, the Concrete Technology Corporation. The interviews focused on the typical scenario for testing and examined the current specification requirements, testing procedures, and variations in the testing to assess how the agencies used the test results to gauge expected performance. The interviews helped to establish how these organizations view the adequacy of these tests as acceptance and rejection criteria. Laboratory testing was performed to analyze how variations in the concrete mix, in particular, the sand fineness modulus and water requirements, would affect the test results. This analysis provided insight into the ability of the test results to detect variations that have an affect on expected performance.

Together, the results of the interviews and laboratory testing along with a literature review helped to establish whether the current quality control procedures for testing ready-mixed concrete at the job site provide adequate enough indication of expected performance for acceptance and rejection criteria. A complete description of the research effort and analysis of the results are provided in this report.

CHAPTER 2 - BACKGROUND

2.1 INTRODUCTION: Concrete consists of a "heterogeneous mixture" of ingredients that include portland cement, water, and aggregates as described by Smith [1]. The cement and water make up the paste that surrounds the aggregate. The mixture may also include other cementitious materials such as flyash, and air entraining and water reducing admixtures to facilitate production, placement, and improve the quality of the final product. Concrete performance is directly influenced by the "proportioning and control" of these ingredients according to the ACI Manual of Concrete Inspection [2]. Proper selection and proportioning of materials will ensure the necessary performance characteristics including placeability, strength, and durability for the desired function to ensure short term and long term performance [3]. The typical properties associated with short term performance (placeability) are uniformity and workability of freshly mixed concrete. These properties also affect the long term performance characteristics of strength and durability after the concrete has attained a hardened state. The typical tests that are performed on the fresh concrete in the field to demonstrate the required performance traits are the slump test, air content test, and determination of unit weight and yield. Though, there are many applications for ready-mixed concrete, this research effort concentrated primarily on concrete mixes for structural applications. [1][2][3][12]

2.2 PERFORMANCE FACTORS: The ACI Manual of Concrete Inspection [2] indicates that the essential performance factors for quality concrete are related to the nature of concrete as it exists during its lifetime: freshly mixed and hardened concrete. Freshly mixed concrete must have uniformity and workability [1]. Hardened concrete must have sufficient strength to withstand the loads that may be applied to the structure based on its intended function [4]. The hardened concrete must also be durable enough to withstand

deterioration due to a variety of adverse actions such as abrasion, weathering, freeze - thaw conditions, and aggressive chemical reactions for long term performance per ACI 201.2R-77 "Guide to Durable Concrete" [5]. A description of the important characteristics and an explanation of the requirements for performance are summarized in the following paragraphs.

2.2.1 Uniformity means that the concrete does not have variations in required proportions, appearance, or other important properties within a batch or in successive batches. Uniformity is important to the performance as variations have been shown to affect both the short term performance including workability and ability to place the concrete as well as the long term performance of the hardened concrete, i.e. strength and durability. In order to ensure uniformity, control must be maintained over potential variations including mix proportions, gradation and moisture of the aggregate, sources of the materials, quality of the water, cement, batching and mixing equipment, and ambient conditions for placement. [1]

There are several characteristics that affect or are affected by the uniformity of concrete and may be used as measures of this property [1]. These characteristics include consistency, air content and unit weight. Consistency is defined by Kosmatka and Parnarese [6] as the ability of concrete in the fresh state to flow. The slump of concrete is used as a measure of consistency. Variations in consistency as indicated by variations in slump may indicate lack of complete mixing, or lack of uniformity of the ingredients within a batch [1]. The consistency as measured by slump should remain fairly constant throughout a batch for uniform concrete. The slump should also be similar from batch to batch if the water content, water - cement ratio, other proportions, and aggregate gradation are uniform. Air content affects a variety of factors including workability, strength and durability. Concrete should contain a certain amount of air for workability. The air content

should not vary by more than 1 percent for a uniform batch of concrete. Variations in the unit weight of concrete as slump and air content are held constant may indicate a lack of uniformity in the quantity of ingredients, especially the weight of the aggregate. This variation in aggregate weight may be caused by a variations in gradation, moisture content and density. Uniformity is maintained through consistent production procedures including batching, mixing, transporting and placing. [1][6][3][7]

2.2.2 Workability has been defined in many standard specifications and publications as well as by many other knowledgeable sources. This property is briefly defined in ASTM C 125-92 "Standard Terminology Relating to Concrete and Concrete Aggregates" as "that property determining the effort required to manipulate a freshly mixed quantity of concrete with minimal loss of homogeneity." Mehta and Monteiro [8] indicate that the term "manipulate" refers to the placement, compaction, and finishing of fresh concrete. ACI 211.1-91 "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete" [3] describes workability as a property that establishes how well fresh concrete can "be placed and consolidated properly without harmful segregation." Workability is also defined as how easily fresh concrete can be placed, consolidated and finished into the final form. [8][4][6]

Workability is considered to be the "composite" of two primary characteristics: consistency and cohesiveness [8]. Consistency is closely related to the property of workability according to ACI 211.1-91 [3]. It is defined as "the ability of freshly mixed concrete to flow" or as "the relative mobility of concrete", or "flowability" of fresh concrete [6][3][8]. It influences the amount of work necessary to compact concrete [8]. Slump is a measure of consistency of concrete [1][8]. However, consistency only provides a partial indication of the workability of the freshly mixed or ready-mixed concrete delivered to the project site. Consistency is indicative of the "wetness of concrete measured

by slump" [1]. However, a wetter mix may not be workable because the mix may experience the adverse affects of segregation if too wet. Also, slump is only a measure of the consistency of concrete and not a complete measure of workability [8]. Smith [1] indicated that it is generally agreed that fresh concrete "should have the driest consistency" possible for effective placement and compaction. ACI 211.1-91 [3] and ACI 301-89 "Specifications for Structural Concrete for Buildings" [9] recommend fresh concrete have a standard slump of 4 inches for structural work. Cohesiveness refers to the effort needed to consolidate the fresh concrete without adversely affecting its stability or its ability to hold water instead of bleeding and the ability to hold coarse aggregate [8]. These two characteristics, consistency and cohesiveness, fully cover the meaning of the ability to manipulate fresh concrete. [8][4][6][1][9]

Numerous factors affecting workability have been identified as having varying affects on consistency and cohesiveness of freshly mixed concrete [1][8]. Factors include water content, cement content, aggregate gradation, air entrainment and factors affecting slump loss. ACI 211.1-91 [3] suggests that a higher consistency as measured by slump is achieved by an increase in the water content for a given size and shape of coarse aggregate. However, freshly mixed concrete with too high consistency may lead to bleeding and segregation, whereas low consistency may be difficult to place or compact and exhibit segregation [8]. A low cement content can tend to make the mix harsh and not easily finished. Variations in fine aggregate gradation impact the consistency of concrete as more water is required for finer gradation to maintain slump [1]. Coarser fine aggregate can lead to finishing problems. Consistency improves from an increase in the paste volume when air is entrained in the concrete [8]. Air entrainment also enhances the cohesiveness by reducing bleeding and segregation problems during placement. Slump loss is defined as the "loss of consistency in fresh concrete with elapsed time" [8]. This problem is often resolved in the field by "retempering" the concrete; adding water and remixing just prior to

placement [8]. ACI 304-89 "Guide for Measuring, Mixing, Transporting and Placing Concrete" [7] clearly indicates that the addition of water at the job site should not exceed the "proportioned water - cement ratio." This requirement is essential because an excessively high water - cement ratio may lead to segregation, and may increase drying shrinkage cracking that may adversely affect long term performance (strength and durability). [1][8][4][7][2]

Workability is affected by physical characteristics and the aspects of construction process including mixing, placing and consolidation [1]. In terms of construction operations, fresh concrete is workable if it can be placed and easily moved in the forms and then consolidated without causing harmful bleeding or segregation [8].

2.2.3 Compressive Strength is a critical property of hardened concrete in that the strength is directly related to the ability of the structure to withstand the loads associated with its intended function. This property is used as an indication of the quality of concrete including its ability to resist deterioration. Strength is defined as "the ability to resist stress without failure" [8]. The compressive strength is often specified in the design of concrete structures because of its direct relationship with structural capability and overall performance. [4][8][6]

The strength of concrete is affected by a variety of factors, the most important being the water - cement ratio and the age of the concrete [6]. Neville [10] indicates that in addition to water - cement ratio, strength is also affected by compaction as both (water - cement ratio and compaction) affect the void volume of the concrete. Concrete strength may also be impacted significantly by gradation changes and air entrainment [8]. Mixing and uniformity have been known to have a marked influence on strength. [6][10][8][1]

Strength performance is achieved by effective material selection and proportioning [8]. The water - cement ratio is the most important factor. Strength

increases as the water - cement ratio decreases. Water - cement ratio may also have an impact on the influence of other factors. Though, an increase in air voids by incomplete compaction or intentionally by entrainment of air will decrease the strength, the water - cement ratio and cement content may impact the amount of strength reduction. Mixes with high cement contents show a significant loss of strength with an increase in entrained air, while mixes with lower cement contents may experience minimal strength reductions from air entrainment [10][8]. A gain in strength with air entrainment at the lower cement contents may be experienced when there is a simultaneous reduction in water content for workability. [8][10]

Aggregate grading can impact concrete strength when it causes a change in consistency and bleeding. Mehta and Monteiro [8] report the results of testing in which the ratio of coarse to fine aggregate and cement content were increased to raise the consistency from 2 inches to 6 inches under a constant water - cement ratio of 0.6, resulting in a 12 percent reduction in strength. However, with the proper ratio of fine to coarse aggregate, a "wide range" in fine aggregate grading within ASTM C 33-90 "Standard Specification for Concrete Aggregates" requirements may be employed without adversely affecting strength. [8][6]

Compaction (consolidation) is an important factor to the strength performance of concrete as indicated in ACI 309R-87 "Guide for Consolidation of Concrete" [11]. Strength is significantly affected by the extent of compaction [10]. Voids from entrapped air or from spaces remaining after the removal of excess water cause a weakening of the concrete. Strength is improved by a reduction in voids through proper consolidation. The property of workability is also essential to strength performance as the concrete requires adequate consistency or mobility for proper compaction.

2.2.4 Durability is defined as the ability of hardened concrete to resist deterioration from adverse conditions including weathering, attack by aggressive chemicals, and freezing and thawing conditions as described by ACI 201.2R-77 [5]. Concrete is considered to possess durability if it can hold its original shape, and continue to exhibit "quality and serviceability" after being exposed to the environment [5]. For performance in this area, concrete must have the necessary properties to prevent or as a minimum limit the extent of the damage that may occur over time.

In general, deterioration is the result of various causes [10][8]. Water is a major culprit leading to concrete deterioration. It can be the direct cause of physical deterioration or may serve as the medium for transporting harmful and aggressive chemicals. Water as a primary component of the concrete mix is within the substructure from the beginning. The ACI Manual of Concrete Practice [2] indicates that the water in the paste of fresh concrete is the major cause of drying shrinkage and cracking as the concrete hardens. Reductions in drying shrinkage cracking are achieved by minimizing the water content to a quantity sufficient for workability. [10][8][2]

Penetration of water with or without harmful chemicals in the concrete may adversely cause deterioration of the substructure. Water can move within the substructure causing disruptive volume changes. Aggressive chemicals dissolved in the water can lead to decomposition. A principle factor affecting penetration and internal movement of water is the permeability of concrete. Concrete with a low permeability is desired for durability performance to limit penetration of water into the substructure and limit the flow of water within the structure. Low permeability may be achieved by minimizing the capillary voids through a low water - cement ratio, sufficient cement content, minimizing water content, along with effective compaction and curing. [8][10]

Damage from freezing and thawing conditions is a significant problem responsible for deterioration of concrete especially in northern climates as indicated in

ACI 201.2R-77 [5]. This condition affects the hardened cement paste and the aggregate in different ways. Damage in the hardened cement paste can be prevented through air entrainment as the air bubbles will provide a place for the unfrozen water to migrate to vice the frozen capillaries. Absorption of water in the aggregates with fine pore structure is responsible for damage from the freezing and thawing conditions. Requirements necessary to ensure durability for concrete expected to be exposed to freeze-thaw conditions include low - water cement ratio of 0.45 for exposed structures, air entrainment, and appropriate materials.

Surface wear such as abrasion is another form of deterioration resulting in a loss of mass from the concrete surface [8]. Resistance to this action may be achieved through sufficient strengths, low water cement - ratio, proper gradation, and minimum air content needed for the exposure conditions.

2.3 TESTS AT THE JOB SITE: The initial tests of ready-mixed concrete at the project site are performed at the time of placement of the concrete according to ASTM C 94-92 "Standard Specification for Ready-Mixed Concrete." The primary tests include slump, air content, unit weight and yield. In addition, temperature and strength specimens are usually taken in conjunction with these tests. The initial tests, termed "acceptance tests", are used to show that the fresh concrete complies with the project specifications [12]. This research project focused on the initial tests for concrete to assess their reliability as acceptance or rejection criteria. Descriptions of the tests and an assessment of their reliability are summarized in the following paragraphs.

2.3.1 Sampling Procedures:

General procedures for sampling freshly mixed concrete at the project site from revolving drum mixers (typical delivery method) are specified in ASTM C 172-90

"Standard Practice for Sampling Freshly Mixed Concrete". ASTM C 94-92 contains specific sampling procedures for uniformity tests (slump, air content, unit weight and yield) of ready-mixed concrete delivered to a project site. According to ASTM C 94-92, separate samples of about 2 cu. ft. each are obtained for uniformity tests after the mixer discharges about 15 percent and 85 percent of its load. The samples are obtained within about 15 minutes and prepared, including remixing of the samples to "ensure uniformity" before testing per ASTM C 172-90. However, instead of combining the samples (as required by ASTM C 172-90), ASTM 94-92 requires the samples to remain separate in order to be representative of points in the batch. Uniformity tests should be performed within 5 minutes after obtaining the last sample.

Samples for strength specimens are obtained according to ASTM C 172-90. The minimum sample size is 1 cu. ft. Fresh concrete is to be sampled at regular intervals from the middle portion of the batch as the truck is discharging the load. Samples are to be obtained and combined within 15 minutes. Strength specimens should be made within 15 minutes after producing the composite sample.

ASTM C 172-90, ASTM C 94-92, ACI 304-89 [7] and the ACI Manual of Concrete Inspection [2] identify important aspects about sampling that affect the tests. All of the water must be added to the mixer prior to sampling to ensure uniform mixing. If water is added at the job site, sufficient time should be permitted for additional mixing of at least 30 drum revolutions so the water can be adequately incorporated into the mixture. The concrete should be discharged within 1 1/2 hours or 300 drum revolutions after the initial introduction of water to the batch. This requirement will minimize "grinding of aggregates, loss of slump, and wear on the mixer" [7]. Enough personnel should be at the site to perform the tests within the specified time. Fresh concrete should be sampled and handled properly to avoid segregation. Remixing of each sample is necessary prior to testing for uniformity. Project specifications usually identify locations for taking samples,

i.e. point of discharge or point of placement. However, sampling at both the mixer discharge and point of placement should be performed under certain placement methods such as pumping due to possible changes in the concrete from the particular placement method. [7][2]

2.3.2 Slump Test: This test is performed per ASTM C 143-90a "Standard Test Method for Slump of Hydraulic Cement Concrete." As summarized in the ACI Manual of Concrete Inspection [2], procedures require a metal cone shaped mold (8 inch dia. base, 4 inch dia. top, 12 inch height) to be dampened and placed on a wet, flat, nonabsorbing surface. The mold is filled with fresh concrete in three layers of equal volume rodded 25 times each, and the excess concrete is struck off the top. The cone is lifted off the surface and the concrete slump is measured to the nearest 1/4 inch. The "slump of concrete" is a measure of how far the unsupported cone of fresh concrete slumps down after removal of the metal mold [8]. ASTM C 94-92 recommends tolerances for slump measurements as follows:

For specifications indicating a "Maximum or not to exceed requirement":

The tolerance is - 1 1/2 inches for specified slump of 3 inches or less.

The tolerance is - 2 1/2 inches for specified slump of more than 3 inches.

For specifications that are "not written as a Maximum or not to exceed requirement":

The tolerance is $\pm 1/2$ inch if the specified slump is 2 inches or less.

The tolerance is ± 1 inch if the specified slump is greater than 2 inches to 4 inches.

The tolerance is $\pm 1 1/2$ inch if the specified slump is over 4 inches.

Concrete should be within the required slump range for 30 minutes after arrival of the truck, or after water is added at the job site. The test is not appropriate for extremely wet or

dry concrete. The ACI Manual of Concrete Inspection [2] advises that a single slump test should not be used as the only basis for rejection because of the potential variation, especially from inadequately trained technicians. The test may be inconsistent as reported measurements from different test operators may differ by as much as 1/2 inch [1]. A "shear slump" that is falling apart to one side is not suitable because one can not determine the point to measure the slump [1]. According to ASTM 143-90a, there should be no more than a 0.83 inch difference in two tests performed by different operators in the same laboratory on the same concrete. The slump range (1.5 inches to 2.76 inches) for this precision statement is considered to be limited. [2][8][1]

2.3.3 Air Content Test: Air content is typically measured at the project site by the procedure defined in ASTM C 231-91b "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method." Two types of air meters (types A and B) are employed based on the application of Boyle's law. As summarized in the ACI Manual of Concrete Inspection [2], general test procedures require calibration of the meter, filling the measuring bowl in three equal layers, rodding each layer 25 times each, striking off excess concrete, placing the meter on top of the bowl, adding water and pressurizing the meter. The measuring bowl should be at least 0.2 cu. ft. The reading on the meter is the total air content in percent that includes air in the voids of the aggregate. An aggregate correction factor (air in the voids of the aggregate) is determined separately and subtracted from the original reading to obtain the actual air content. ASTM C 94-92 recommends tolerances for measured air content of ± 1.5 percent of project specifications. The test is most often used to provide an estimate of the air content of fresh concrete that contains entrained air [13]. An attribute of this test is that parameters such as specific gravity, moisture contents, or batch quantities of the mix are not required to determine the air content. However, inaccurate measurements are possible with porous or unsaturated aggregates [13].

ASTM C 231-91b precision statements indicate that two tests performed by different technicians on the same concrete should differ by no more than 0.8 percent.

2.3.4 Unit Weight and Yield Determination: ASTM C 138-81 "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete" describes the standard test method for unit weight and yield determination. As described by ACI Manual of Concrete Inspection [2] the procedure consists of filling a container with fresh concrete in three layers of equal volume, rodding each layer 25 times each for 1/2 cu. ft. size or less, striking off the excess concrete, and weighing the container. The minimum size of the container is 0.2 cu. ft. The measuring bowl of fresh concrete for the air meter (ASTM C 231-90b) may also be used for this determination. In this case the weight of the bowl with the fresh concrete is measured before conducting the air content test because of disturbances to the concrete from the air content test. The unit weight is defined as the weight in pounds per cubic foot of freshly mixed concrete. The unit weight is equal to the net weight of the fresh concrete divided by the volume. Yield is defined as "the volume of fresh concrete (cu. ft.) produced in a batch" [6]. The yield is calculated by dividing the total weight of batched materials by the unit weight of the fresh concrete. Unit weight test is reliable for controlling yield and evaluating unit weight as required by specifications [13]. Unit weight and yield test establishes the cement factor, and the amount of concrete produced in a batch compared with the batched ingredients. The test may not be conclusive because unit weight is affected by several factors (specific gravity and amount of coarse aggregate, air content, and proportions of water, sand and cement), resulting in variations that are difficult to ascertain. [2][6][13][1]

2.3.5 Interrelationship Between the Tests: The three tests are interrelated in many respects. According to the ACI Manual of Concrete Inspection [2], slump is affected by

variations in air content, and conversely, air content is sensitive to slump variations. An increase in entrained air of about 5 percent may increase the slump by about 1/2 inch to 2 inches [10][20]. An additional 10 lbs. of water per cubic yard of concrete may increase slump by 1 inch, causing a 1/2 percent to 1 percent increase in air content [6]. Increasing the volume of air should result in a lower unit weight [13]. Therefore, testing for air content and unit weight are combined in ASTM C 138-81 or performed in sequence in the field: first ASTM C 138-81 for unit weight, then ASTM C 231-91b for air content using the same sample. Significant variations in slump (greater than one inch) and unit weight (greater than one pound per cubic foot) may indicate a lack of uniformity within a batch per ASTM C 94-92. [2][10][20][6][13]

2.4 RELATIONSHIP BETWEEN TESTS AND PERFORMANCE:

2.4.1 Slump Test: Results of slump tests provide an indication of the concrete uniformity per ASTM C 94-92. The difference between slump tests taken from two locations within a batch should be no more than 1 inch for an average slump up to 4 inches, and no more than 1.5 inches for an average slump over 4 inches. Problems such as lack of mixing and "nonuniform distribution of water or other ingredients" within a batch may be indicated by significant changes in slump (greater than one inch) [1]. A primary function of the test is to provide a "convenient" method for controlling batch to batch uniformity [8]. Variations of slump may indicate changes in the mix proportion, or aggregate gradation or moisture in successive batches [1]. The slump test is an effective measure of the consistency or the flowability of the fresh concrete [8][1]. It does not completely describe all factors related to workability or placeability. Smith [1] points out that tapping the side of the concrete may provide additional insight i.e., concrete sample that falls apart to one side (shear slump) may be harsh with minimal fine aggregate indicating insufficient workability for placement or consolidation. Slump results also

provide an indication of the relationship between consistency and water requirement as slump will increase by 1 inch with about a 3 percent increase in water. Variations in strength may be related to variations in consistency measured by slump for a particular mix as indicated by the ACI Manual of Concrete Inspection [2]. The addition of water to the batch at the project site (retempering) increases the slump to improve the consistency, but may result in a decrease in strength due to an increase in the water - cement ratio. [1][8][2]

2.4.2 Air Content Test: The test in general is used as a control measure and indicates the "adequacy of the air void system" [6]. Variations in entrained air content may indicate variations in workability [1]. Wright [20] and Neville [10] report the results of tests which suggest that over the normal range of air content (up to about 8 percent), an increase in entrained air of about 5 percent may improve the consistency by about 1/2 inch to 2 inches of slump. There may be an even greater effect on consistency as Smith [1] indicates that a 1 percent increase in air entrainment may increase slump by about 1 inch. Entrained air has a greater effect on workability of mixes with low cement contents. Concrete should have a "uniform" amount of air for workability and durability [1]. About 3 percent less air is needed if "only improved workability is desired" than for freeze-thaw durability per the ACI Manual of Concrete Inspection [2]. The test may identify significant reductions in air content causing "loss of workability" [1]. The affect of air content on strength is also documented in the literature [8][10][13][20]. The results of tests reported by Wright [10] and Neville [20] suggest that over the normal range of air content (up to about 8 percent), strength loss is about 5.5 percent per one percent of entrained air under constant water - cement ratio. The test provides an indication of the expected durability of concrete against freeze-thaw damage [13]. Entrained air content of 4 percent to 7 percent in freshly mixed concrete should provide sufficient resistance against frost damage as recommended in ASTM 94-92 and ACI 201.2R-77 [5]. The air content test may also be used to verify that

non air entrained concrete is "normal" as reflected by an air content of less than 1.5 percent [13]. This information is especially important for high strength applications because entraining even modest amounts of air may lead to strength reductions. [6][1][20][10][2][8][13][5]

2.4.3 Unit Weight and Yield Test: Unit weight and yield are measures of batch uniformity with respect to mixture proportioning [1]. The unit weight for fresh "conventional" weight concrete ranges from about 140 lbs./cu. ft. to 150 lbs./cu. ft. [6]. ACI Manual of Concrete Inspection [2] indicates that unit weight and yield determinations are used to verify important mix proportioning and control factors : maximum water - cement ratio and minimum cement content to ensure performance including durability, impermeability, and workability. The purposes of the yield calculations are to determine the actual cement content, or to check the batched volume against the in place volume. The water - cement ratio can be verified if the quantity of water is known. The cement content of a batch can be determined by dividing the weight of cement batched by the yield. The quantity of water and the cement content can then be used to determine the actual water - cement ratio for the batch. The batched volume can be checked by calculating the relative yield which is defined as the "ratio of the actual volume of concrete obtained to the volume as designed for the batch" per ASTM C 138-81. A ratio less than 1.00 indicates the batch being delivered is "short" of the design volume. [1][6][2]

2.5 ACCEPTANCE AND REJECTION CRITERIA AND CONSEQUENCES:

2.5.1 Acceptance and Rejection Determinations: The tests on fresh concrete provide important information about the proportions and properties of the concrete mixture early in the operation prior to placement [12]. The slump test provides an indication of the water content and water - cement ratio of a concrete mix and may be used as grounds for rejecting

excessively wet mixes. The air content test is employed to determine if the mix contains sufficient air entrainment. Unit weight and yield test provides information about batch volume in comparison with proportions of the ingredients and a means of calculating the cement content. The test results are used to make acceptance determinations of the load of concrete before placement because strength results are not available until it would be difficult to take corrective action on the nonconforming hardened concrete. [12][4]

2.5.2 Specification Values at the Job Site:

Specifications of public agencies contain typical values for job site performance. As an example, Washington State Department of Transportation (WSDOT) job site specifications define standard performance criteria [14]. The job site specifications require strict compliance with specified values or the concrete load will be rejected. Tolerances are established to account for mixing and handling variations as well as testing variabilities, but at values that will still ensure quality long term performance.

Per WSDOT Test Method No. 803 "Method of Sampling Fresh Concrete", a sample for acceptance testing is taken at a point representative of the condition of the concrete as placed on the job site. A sample is taken after discharging about 1/2 cu. yd of the load. WSDOT allows a maximum 4 inch slump for structural concrete [14]. The tolerance limit is specified at 1 inch above the maximum specified slump. Reductions in contract price are taken for concrete loads that do not meet the specified slump, but fall within the tolerance limit. Rejection is required for slumps exceeding the tolerances. Air content is specified by WSDOT at 4.5 percent to 7.5 percent for air entrained concrete [14]. The specification establishes tolerances of 1 percent above the maximum specified air content and 1/2 percent below the specified minimum. As with slump, reductions are taken for nonconforming concrete within the tolerance limits. The concrete is rejected if the air content is outside of the tolerances. Other agencies may use similar rejection criteria.

CHAPTER 3 - METHODOLOGY

3.1 OBJECTIVE: The purpose of this investigation was to document the policies of various agencies for quality control testing at the job site and to determine the influence of one of many portland cement concrete parameters. The standard job site quality control tests include slump, air content, unit weight and yield. The parameter selected for the investigation was the sand fineness modulus because, based on the literature, it can have a significant affect on the test results. The methodology for this investigation included interviews with the agencies and laboratory testing. The details of the interview process and laboratory testing are summarized in the following sections.

3.2 INTERVIEWS:

3.2.1 Purpose of the Interviews:

The purpose of the interviews was to analyze the procedures being employed in the field by two public agencies, the U. S. Navy, and Washington State Department of Transportation (WSDOT), and a commercial concrete prefabrication manufacturer, the Concrete Technology Corporation (CTC). Issues were identified from the literature review pertaining to the variations in test results for slump, air content, unit weight and yield of ready-mixed concrete as it is delivered to the project site prior to placement. Based on the literature and laboratory testing, the effect of variations of fine aggregate gradation and water requirement on test results were of primary interest for the interviews.

During the interviews, a review was conducted of the typical scenario for testing at the project site or prefabrication plant. The interviews examined how the agencies handle variations in the test results (particularly from variations in fine aggregate gradation and water requirement). Test requirements of the organizations were discussed in detail to determine how these organizations employ the test results as an indication of expected long

term performance. Ultimately, the interviews provided an insight of the main objective of the report in helping to establish how these organizations view the adequacy of these tests and any limitations of the tests for their applications.

3.2.2. The Organizations Chosen for the Interviews:

The organizations included two public agencies and one commercial prefabrication manufacturer. One of the public agencies selected was the U. S. Navy represented by the Navy Construction Office for the new homeport base in Everett, Washington. This organization was chosen because this researcher has over twelve years of experience with the U.S. Navy Civil Engineer Corps and is very familiar with their procedures. In addition, there is a significant amount of structural work and building construction currently in progress at this base requiring concrete work and associated testing. The other public agency was the Washington State Department of Transportation (WSDOT) represented by the Project Engineer, District 1 in Seattle, Washington. WSDOT was chosen because of the significant construction volume throughout this state and related concrete work. The Project Engineer, District 1 was chosen because of his participation in the development of the current testing and specification requirements for concrete operations within WSDOT.

The commercial prefabrication manufacturer selected to participate was the Concrete Technology Corporation (CTC) located in Tacoma, Washington. A commercial supplier was selected to obtain a perspective from the private sector concerning concrete testing. This particular organization was chosen because of their experience with structural prefabrication work in the local area and their extensive concrete operations.

3.2.3 Preparing the Questions:

After initial contact was made with representatives from the organizations, a

questionnaire was developed for the interviews. Questions were based on the type of organization, types of projects, and inspection procedures. The questions focused on the organizations specifications for ready-mixed concrete, testing procedures, how the organizations use the tests results, and how they view variations in the factors that may affect the test results.

The questions were similar for all of the organizations. The questions for the U. S. Navy Construction Office and the WSDOT Project Engineer, District 1 were exactly the same as these organizations manage construction as customers in a similar manner in that they contract their work to the private sector and then have the work inspected as it progresses to completion. In addition, based on this researchers experience with Navy construction and a preview of WSDOT'S requirements [14], both organizations have extensive specification requirements covering initial concrete testing. The major difference between the two organizations is that the Navy requires the contractor to perform quality control inspection and to perform testing through a certified testing lab. WSDOT is required by law to perform all inspection and testing in house, or may contract directly for testing services in some cases. This difference did not impact the development of the questions, but was reflected in the responses to the questions.

The questions for the Concrete Technology Corporation were modified slightly to account for the organization as a private company supplying concrete products to customers. The questions also took into account that they both produce and place concrete at their plant in the fabrication of their products.

The questionnaire initially addressed specifications for batching, mixing, and placing concrete to identify values for key parameters of the production process important to the organizations. The next series of questions were designed to establish the testing requirements and procedures employed by the organizations. The responses would establish the framework for the testing process based on the types of tests, test procedures

and specified results. The relative importance placed on testing would be determined based on the testing scenario, performance of the tests, and use of the tests results.

After the testing procedures were identified, the next questions specifically dealt with the objective of the laboratory testing and interviews: how variations in fine aggregate gradation and water requirements affect the tests. Results of the laboratory testing were presented to establish the background for the question. The intent was to determine to what extent the organizations consider variations in factors such as gradation that affect the tests to lead to an understanding of the main objective; if the tests adequately relate to expected performance. The final set of questions then addressed the main objective of the report including the relationship and adequacy of the tests as indicators of expected performance. The question forms are contained in Appendix A of this report.

3.2.4 Conducting the Interviews: The interviews were conducted during the period 23-29 June 1993. Initial contact was made the week prior with a representative from each organization. A summary of the organizations and interview details are provided as follows:

U.S. Navy Construction Office, Everett, Washington:

Representatives:

Lieutenant S. Dupes, Civil Engineer Corps, U. S. Navy, Deputy Resident Officer In Charge of Construction.

Mr. T. Lenda, Project Engineer.

Location of interview: Navy base in Everett, Washington.

Date: 24 June 1993

Washington State Department of Transportation (WSDOT):

Representative: Mr. I. Goller, Project Engineer, District 1.

Location of interview: WSDOT District 1 office, Seattle, Washington.

Date: 25 June 1993.

Concrete Technology Corporation (CTC):

Representative: Mr. D. Heizenrader, Concrete Materials Manager.

Location of interview: CTC plant, Tacoma, Washington.

Date: 29 June 1993.

3.3 LABORATORY TESTING:

3.3.1 Purpose of Laboratory Testing: The purpose of the Laboratory Testing was to determine how variations in fine aggregate gradation (sand fineness modulus) would affect the slump, air content, unit weight and yield of freshly mixed concrete. Different gradations were used in laboratory concrete mixes to determine the variation in the amount of mixing water for constant slump. The mixing water amounts were then changed to achieve the target slump of 4 inches commonly used for structural concrete per ACI 301-89 "Specifications for Structural Concrete for Buildings" [9]. Water was added to the mix with low slump to bring the slump up to the standard 4-inch requirement (similar to adding water to a mix in the field that would otherwise be rejected for low slump). Rebatching was performed for the mix with too high a slump by reducing water and cement contents (in keeping w/c constant) to decrease the slump to the standard 4 inches (similar to changes that might be performed at a batch plant). Strength specimens were cast and tested to assess variations in strength from the different gradations and changes in water requirement.

3.3.2 ASTM Gradation Limits: The fine aggregate gradation range of ASTM C 33-90

"Standard Specification for Concrete Aggregates" was selected over the WSDOT Class 1 specification primarily for two reasons. The ASTM limits being wider would cause more pronounced effects over the gradation range making it easier to observe the differences in the test results. The ASTM specification is applicable to a national perspective. The ASTM gradation limits (fine and coarse side) were used in separate mixes. A control mix was established with a fine aggregate gradation at about mid range of the ASTM Specification. This mix was used as a reference point for comparison of test results. The ASTM gradation range is shown in Figure 3-1.

3.3.3 Description of Materials: The concrete mixes for the laboratory testing consisted of four ingredients: portland cement, water, fine aggregate, and coarse aggregate. Admixtures were not used in the concrete mixes. A description of each ingredient is provided in the following paragraphs.

3.3.3.1 Portland cement used in the laboratory is classified as Type I-II per ASTM C 150-92 "Standard Specification for Portland Cement."

3.3.3.2 Mixing water was obtained from the tap in the laboratory.

3.3.3.3 Coarse Aggregate was taken from the bin in the laboratory. This particular coarse aggregate is a glacial gravel having a nominal maximum size of 7/8 inch based on previous sieve analysis in this laboratory. The aggregate has a rounded particle shape and smooth texture permitting reduction in water quantity by about 45 lbs./cu. yd. for proportioning [6]. The aggregate gradation closely approximates the ASTM gradation limits based on sieve analysis performed according to ASTM C 136-84a "Standard Test Method for Sieve Analysis for Fine and Coarse Aggregate." The stockpile moisture

content for design calculations was determined to be 0.6 percent according to ASTM D 2216-92 "Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock." The material was presoaked for 12 - 24 hours and batched in a wet condition to avoid problems of slump variation due to moisture absorption. A gradation summary is provided in Appendix B.

3.3.3.4 Fine Aggregate used in the mixes was a glacial sand. The fine aggregate used for the control mix was acquired from laboratory stocks. Its fineness modulus was determined to be 2.74 and the gradation was verified to be at about the middle of the ASTM C 33-90 specification range based on sieve analysis performed according to ASTM C 136-84a. Material for the other mixes was separated by sieving and rebled to make the other gradations at the limits of the ASTM gradation. The fineness modulus at the maximum gradation limit (fine side) was determined to be 2.15. The fineness modulus at the minimum gradation limit (coarse side) was calculated as 3.43. Use of the maximum and minimum gradation limits resulted in fineness moduli outside of the ASTM C 33-90 specification of 2.3 and 3.1 respectively. The fine aggregate was oven dried for a minimum 12 hours per ASTM D 2216-92 prior to mixing to minimize errors associated with measurements for moisture corrections in the mix design. Summaries of the fine aggregate gradations and fineness moduli are provided in Appendix B.

3.3.4 Description of Mixes:

Four concrete mixes were developed to assess the affects of variations in fine aggregate gradation. The four mixes included the control mix and three test mixes. The control mix had a fineness modulus of 2.74 and a gradation at about mid range of the ASTM C 33-90 specification as described in Sections 3.3.2 and 3.3.3.4. One of the test mixes, designated Mix 1, had a fine sand with a fineness modulus of 2.15 and gradation at

the maximum ASTM limit. The other two mixes, designated Mix 2-Initial and Mix 2-Rebatch, had coarse sand with the same fineness modulus of 3.43 and gradation at the minimum ASTM limit.

The concrete mixes were designed and proportioned to produce a standard 4-inch slump and a design strength of at least 5000 psi [3][6][9]. A w/c of 0.50 was chosen to ensure this design strength (Local experience suggests typical average strength of about 6500 psi for 0.50 w/c.). This over-design was intentional because of the penalties associated with low strengths in the field. A mix design summary is provided in Appendix C. A summary of the proportions for each mix is shown in Table 3-1.

3.3.5 Laboratory Procedures:

3.3.5.1 Mixing was accomplished according to ASTM C 192-90a "Making and Curing Concrete Test Specimens in the Laboratory."

3.3.5.2 Testing procedures:

The standard initial concrete tests were performed upon completion of mixing as prescribed by ASTM C 192-90a. The tests performed include the following:

ASTM C 143-90a "Standard Test Method for Slump of Hydraulic Cement Concrete."

ASTM C 138-81 "Standard Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete" (Note: Performed for unit weight and yield only.).

ASTM C 231-91b "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method."

Initially slump measurements were taken followed by measurements for unit weight and yield. The air content test was performed last. The pressure method for

measuring air content was selected for testing purposes as it is easier to perform and is considered to be common field practice. The tests were conducted within the time limitations set forth in ASTM C 172-90 "Standard Practice for Sampling Freshly Mixed Concrete."

3.3.5.3 Preparation of Cylinder Specimens for Compression Testing: Upon completion of the initial testing of the freshly mixed concrete, test cylinders were prepared in accordance with ASTM C 192-90a. Ten 4 inch dia. by 8 inch long cylinders were cast for each mix. The number of samples was chosen to ensure a representative measure of the compressive strength of each mix. Compression testing was performed at 28 days according to ASTM C 39-86 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."

3.3.5.4 Summary:

The control mix was 4 inch slump and 0.5 water - cement ratio. Mix 1-Initial with finer sand gradation described in Section 3.3.4 was made after the control mix. The slump was expected to be low due to the increased fineness of the sand. Initial tests confirmed a low slump of 1-1/4 inches. Water was subsequently added to the mix to bring the slump up to the required specification [7][9][2]. At this point the mix was redesignated Mix 1-Added Water. After water was added to bring the slump up to 4 inches, the other tests (air content, unit weight and yield) were performed to determine variations resulting from the finer sand gradation and change in water requirement as reflected by the changed water - cement ratio.

The final two test mixes, designated Mix 2-Initial and Mix 2-Rebatch, had the coarser sand gradation as described in Section 3.3.4. The proportions of Mix 2-Initial were similar to the control mix. However, the mix was expected to have a slump much

higher than the control mix due to the coarser sand gradation. Test results indicated a higher slump at 5-3/4 inches. The other tests were also performed to assess the variations. The fresh concrete mix fell apart to one side during measurement of slump as if the concrete was shearing. This observed behavior was probably from the mix being harsh due to the coarser fine aggregate [1].

In Mix 2-Rebatch, the water content was reduced to bring the slump down to the 4-inch requirement. Corresponding corrections were made to the other proportions to maintain the water - cement ratio at 0.50. The slump was measured at 4-1/4 inches, within the tolerance of the standard 4-inch requirement. Again it was observed that the fresh concrete fell off to one side probably indicating harshness from the reduced cement content and coarser sand [1].

Table 3-1 Summary of Mix Proportions in Pounds per Cubic Yard at SSD

Material	Control Mix	Mix 1-Initial	Mix 1-Added Water	Mix 2-Initial	Mix 2-Rebatch
Water	267	267	295	267	254
Cement	535	535	535	535	507
Coarse Aggregate	1925	1925	1925	1925	1925
Fine Aggregate	1300	1300	1300	1300	1358

CHAPTER 4 - RESULTS

4.1 INTRODUCTION: This chapter presents summaries of the interviews and results of the laboratory investigation described in Chapter 3. A listing of the interview questions is included in Appendix A. A summary of the mix designs used in the experimental work is included in Appendix C.

4.2 INTERVIEW SUMMARIES:

4.2.1 State Agency Summary: Interview with Washington State Department of Transportation representative:

The interview took place on 25 June 1993 at the Washington State Department of Transportation (WSDOT) District 1 office in Seattle, Washington. This office is responsible for project engineering functions including inspection and testing for the WSDOT construction program in District 1. The work is accomplished by construction contracts. WSDOT is required by law to perform inspection and acceptance testing with its own personnel or in some cases by directly contracting with a certified testing agency for testing it can not perform in-house due to lack of expertise or heavy workload. The WSDOT representative interviewed was Mr. I. Goller, Project Engineer. Responses from the interview are summarized as follows:

1. *What specification values are employed by the agency for batching, mixing, transporting and placing concrete for a project, i.e. minimum cement content, maximum water content, aggregate weights, minimum mixing time at the plant, drum revolutions of the truck mixer, maximum time between batching and discharge, etc.*

WSDOT's Standard Specifications provide this information [14]. The specification values are contained in sections 5-05, Cement Concrete Pavement, and section 6-02, Concrete Structures, as amended April 19, 1993 and May 17, 1993 respectively.

Batch plant verification is performed for active jobs per the specifications to check such items as scale certifications, accuracy of metering devices, batching process, and coarse aggregate content for contractor mix designs. Batching tolerances are also included in specifications. If batching requirements are found not in compliance, the load can be rejected, and the plant can be put on notice for potential decertification.

WSDOT's specifications include "State-Provided Mix Designs" and permit contractor mix design proposals as well [14]. The approval process for mix designs is set forth in the specification. For the "Contractor-Provided Mix Designs", the specification employs ACI procedures, encourages the use of fly ash, requires a comparable level of testing as for state mixes, and makes the contractor responsible for meeting strength requirements [14]. An example of a State-Provided Mix Design is detailed as follows [14]:

"Class of Concrete: 5000: Thin and heavily reinforced members; Bridge decks, cast-in-place beams, girders and columns;

Specified Compressive Strength at 28 days minimum psi: 5000;

Air content: 6 percent entrained air;

Cement, pounds per cubic yard, minimum pounds: 725;

Water/cement by weight, maximum: 0.40;

Coarse Aggregates, pounds per cubic yard (SSD Basis):

Grading No. 5: 1400, AASHTO No. 8: 400

Fine Aggregate, pounds per cubic yard (SSD Basis), Class 1: 1040;

Aggregate weights are based on a specific gravity of 2.67."

2. *What are the agency's typical specification requirements for initial tests including slump, air content, and yield for ready-mixed concrete delivered to the project site?*

Typical specification requirements including specific values for the initial tests are established in the WSDOT Standard Specification [14]. The specifications require acceptance testing of concrete for slump and air content. Strength specimens are required each time slump and air tests are required. Yield testing is performed for State mix designs to verify the cement factor. The State may also perform yield testing on contractor mix designs, but this testing is for information purposes only as the cement factor is not specified for contractor mix designs.

Requirements are based on State Mix Designs [14]. The state assumes responsibility for strength with these State mix designs so long as the contractor has followed the specified mixing, transporting, placing, and curing procedures. Contractor mix designs must demonstrate required quality and must also meet the specification values for consistency (slump), air content for air-entrained mixes, and 28-day strength requirements.

Typical specification values are summarized as follows[14]:

Consistency (slump):

Maximum 3 inches for bridge and roadway slabs; 4 inches for all other structures; except 7 inches for non vibrated concrete.

Tolerance limit is no more than 1 inch above the maximum slump.

Air content:

4.5 percent minimum to 7.5 percent maximum for air-entrained concrete where required for above ground applications.

Tolerance limit is no more than 1 percent above the maximum, or no more than 1/2 percent below the minimum air content.

3. *How are the tests performed:*

Requirements are based on the WSDOT Test Methods [14]. Sampling and test requirements are set forth in the specifications. The first half cubic yard from a truck is accepted without acceptance testing as it is considered too variable, but also a negligible amount. Tests are required for every truck until there are two successive acceptable tests. Then a test is required every one in five loads on a random basis. If a load is out of specification, then the specifications require testing of subsequent loads by the original procedure (every load until there are two successive acceptable tests).

a. *Who performs the tests: agency, separate testing agency, or contractor?*

WSDOT must perform the tests using in-house personnel. WSDOT may also contract directly with a testing agency if the capability does not exist or if the workload is too heavy for in-house at the time of the requirement. The contractor may perform his own testing prior to testing by WSDOT personnel.

b. *What procedures are employed: standard specifications, methods, equipment, or agency modifications?*

This agency has developed its own specifications for concrete testing because the national test methods do not reflect local field conditions [14]. For instance the national methods do not address sampling out of a revolving drum mixer in a

manner for acceptance purposes. Sampling and testing specifications are listed as follows [14]:

"WSDOT Test Method No. 801 Method of Test for Compressive Strength of Molded Concrete Specimens

WSDOT Test Method No. 803 Method of Sampling Fresh Concrete

WSDOT Test Method No. 804 Method of Test for Slump of Portland Cement Concrete

WSDOT Test Method No. 805 Method of Test for Determination of Entrained Air in Portland Cement Concrete

WSDOT Test Method No. 806 Method of Test for Weight per Cubic Foot and Cement Factor"

4. *What is the typical scenario for testing as the concrete is delivered to the project site:*

a. *When are the tests taken after arrival of the concrete truck?*

Tests are performed when the concrete is ready to be discharged at the point of placement. The applicable procedure is WSDOT Test Method No. 803 Method of Sampling Fresh Concrete. The preferred method is for the inspector to obtain a sample at the point of placement. However, at the contractor's request, tests may be performed at the truck, but results must account for adjustments due to various factors such as pumping. The State will check the contractor adjustment values. Samples are taken at the truck about 50 percent of the time.

b. *What are the time limits for conducting the tests?*

Existing specifications do not have time requirements. Revisions to the test

methods due out in the near future will have time limits similar to the requirements of ASTM and ACI standards: 15 minutes after the sample is taken to complete the testing; 5 minutes to complete slump, 5 minutes to complete air content, and 5 minutes to complete three strength specimens.

- c. *Who is represented at the site for the test, i.e. agency's representatives, contractor's representatives, supplier's representatives (other than the driver)?*

Representatives and functions are summarized as follows:

State Tester takes the sample in a wheel barrel, measures the temperature, performs the slump and air content tests, and completes the cylinder specimens within about 15 minutes from taking the sample.

State Field Inspector is in charge at the site and makes the ultimate decisions. He checks placement methods, observes and monitors the placement. He informs the contractor if the tests are acceptable or not.

Contractor Designated Representative at the site is responsible for controlling the operation. He must invoke the tolerance requirements if the tests do not meet the specifications as the State Field Inspector will not.

Contractor Quality Control (QC) Representative may be a contractor employee or the supplier's representative other than the driver. Supplier's QC representative is often at the site, especially early in the project and for critical placements and major structures to ensure immediate feedback. Contractor QC representative observes the field testing and is required to report deviations per the specifications.

Supplier's Driver discharges the concrete.

5. *How are the initial test results used by the agency:*

a. *What are the criteria for acceptance or rejection of the load?*

The load is considered to be out of specification if it is out of the specified range for slump and air content. The State field inspector advises the contractor if the test results are acceptable or if the test results are out of specification and will accept or reject the load. The contractor may invoke the tolerance specification for slump and air content if he feels the load can be placed properly, but a reduction will be taken by the State according to the formula in the specifications. Though the State does not test each truck, the contractor may reject any load on his own decision.

Another strict criteria is the time limitation of 1 1/2 hours from batch to discharge [14]. The load is considered to be out of specification if over the time limit. However, the time may be extended at the State's discretion to 1 3/4 hours if the concrete temperature is less than 75° F and may be extended to 2 hours if the conditions are still acceptable. This condition provides flexibility and working windows within the specification. The limitation will not automatically be extended as the primary concern is the potential for early hydration, placement and setting problems as may be indicated by concrete temperature.

In general, WSDOT's philosophy is to take as much action up front during the placement process. The specifications emphasize that the contractor hires the supplier and the contractor has the requirement to deal with the supplier directly concerning acceptance or rejection of the load.

b. *What type of information is provided as feedback to the supplier?*

The contractor provides feedback directly to the supplier. The State will only work directly with the supplier if the contractor has identified the supplier as his agent. In this case decisions of the supplier will be considered as if they were the contractor's decisions.

c. *Under what conditions, if any, may concrete be accepted that does not meet the test requirements?*

The concrete is rejected if it is not in compliance with the specified test values. The only exception is when the contractor wants to place the concrete that is out of specification, but within the slump or air content tolerances. The concrete may be accepted at a reduction in contract price. [14]

Verbal Questions:

(1) *Is feedback provided directly to the supplier or just the driver?*

Feedback is provided directly to the supplier.

(2) *Is yield and unit weight used as lbs./cu. yd. pay conversion?*

Yield test is performed for State design mixes, but is not used as a pay conversion. Superstructures are based on lump sum. Substructures are based on cubic yards. The delivery ticket certifies the load by quantity in cubic yards and batch weights.

(3) *Is yield and unit weight used as a check for concrete quality, i.e. air content and ability to consolidate?*

The State uses the results to advise the contractor how to adjust the mix proportions for State mix designs including aggregate, cement factor, and gradation. Yield is used to calculate and verify the cement factor in State mixes.

The contractor uses the yield results to check volume.

6. *Lab experiments of this research project looked at fine aggregate gradation and water requirement as factors affecting the test results. For example, in moving from the center of the ASTM gradation specification to the fine side, the slump decreased by 2 3/4 inches. In this case the water requirement had to be increased by 21 lbs./cu. yd. to bring the slump back up to 4 inches.*

a. *To what extent does the agency consider the affect of gradation variation within the specification range on specified slump?*

WSDOT understands that variations can occur in the gradation and the impacts these variations may have on slump. Adjustments are addressed early in the process. The agency will accept what is coming out of the plant within specifications for gradation and limitations on water - cement ratio.

b. *What limitations are placed on the addition of water at the job site to bring slump up to the specified range?*

The contractor may add water to bring slump up to the maximum water - cement ratio, but added water must be indicated on the delivery ticket. Also, the form used by the State inspector is annotated to indicate that water was added in the field, i.e.

driver adding water in the truck. The addition of water is limited by the maximum water - cement ratio. [14]

c. *What are the agency's procedures for retesting a truck load?*

Inspectors are obligated to run one test. There is no objection to one additional test at the discretion of the inspector. It depends on the circumstances.

Verbal questions:

(1) *If the agency considers gradation variations, how often is the fineness modulus of the fine aggregate verified after acceptance of gradation limits?*

Fineness modulus is checked periodically for pit qualification by the district and headquarters labs. Gradation is not formally checked on a project basis unless there is a problem requiring an examination of all possible factors such as fineness modulus. The requirements for fineness modulus are included in the WSDOT specifications. A tolerance of ± 0.2 is allowed for the fineness modulus by specification [14].

(2) *If water is added, is it checked against the maximum water content?*

Added water is checked against the maximum water content or maximum water - cement ratio.

(3) *Does the agency account for water in the drum after clean out from the previous batch?*

Wash water is not permitted to be left in the truck. It is rolled out and placed in detention ponds. It can be reused for mix water later. The reason it is not permitted is that one can not determine the quantity in the drum.

(4) *Are variabilities of other factors considered by the agency, i.e. yield on aggregate content.*

On a general production basis, these factors are addressed at the headquarters and district labs. These factors are addressed on specific projects as problems arise.

7. *How are the tests related to expected performance:*

a. *Short term performance: uniformity, consistency, and workability for effective consolidation and placement without segregation?*

The agency uses the tests and visual inspections of the fresh concrete to provide an indication of expected short term performance.

b. *Long term performance: strength and durability?*

The agency uses the tests and visual inspections of the fresh concrete to provide an indication of expected long term performance. Also, for State and Contractor mixes, cylinder strength tests are performed to verify long term performance.

Three cylinders are cast at the time the other tests are taken prior to placement into the formwork. Two of the cylinders are tested at 28 days. The third cylinder is tested only when the second cylinder is more than 10 percent different from the first cylinder. The closest two are then averaged for the test result. [14]

c. *To what extent are the tests used as a reflection of expected performance:*

(1) *Are they used strictly for acceptance / rejection or,*

The tests are used for acceptance or rejection determinations for both State and Contractor mixes. The agency has confidence in its test methods and trained inspectors. The agency has a good working relationship with the contractor and concrete producer communities who have indicated their confidence in the system as well.

(2) *Is there a graduated pay scale, i.e. concrete is out of the slump range, but reimbursed at less than the bid price as a penalty; also, a bonus payment is provided for concrete that is consistently within the specification range for slump, air content, yield, etc.?*

There is a graduated pay scale for slump and air content results that do not meet the specified value, but are within a certain tolerance of the value. The agency considers the concrete as failing the test. However, the contractor may invoke the tolerance limits at a reduction in price according to the formula in the specifications. There is no bonus clause in the specifications. [14]

Verbal questions:

(1) *If there is a graduated pay scale, what role does expected performance play?*

The agency has looked at expected performance in determining the graduated pay scale. Tolerance limits are set at values that will still result in quality long term performance. Reductions are based on a procedure employed by the Colorado DOT

and reasonable pay factors. The graduated pay scale addresses minor technical specification violations that will not impair long term performance.

8. *Does the agency consider the tests adequate enough indicators of expected performance to accept or reject the load of concrete? If not, what are the limitations of the tests for your applications?*

The agency considers the tests as adequate enough indicators of expected performance to make a determination to accept or reject the concrete. The "go-no-go" basis is workable with the contractors who are more involved in taking responsibility for acceptance / rejection determinations on their own.

4.2.2 Federal Agency Summary: Interview with U. S. Navy representatives:

The interview took place on 24 June 1993 at the Navy Construction Office in Everett, WA. This office is responsible for administering the construction program for the new Navy base. Work includes the construction of numerous base facilities and waterfront facilities. The work is being accomplished by construction contracts. The Navy employs a contractor quality control (CQC) program where the contractor is responsible for the day to day inspection and testing. The specifications require the contractor to obtain the services of an approved lab to perform the inspection testing. Representatives included Lieutenant Steven Dupes (Deputy Resident Officer in Charge of Construction) and Mr. Tom Lenda (Project Engineer).

A brief explanation of the Navy's contractor quality control (CQC) program is necessary at this point as the program differs significantly from most other agencies. The Quality Control program requirements are set forth in the Navy Guide Specification [15]. Contractors provide Quality Control by employing a "formal inspection system" to compare

work performed to the contract requirements [16]. Navy Contracting Officers accomplish Quality Assurance by verifying the work "at any time" to ensure that the contract requirements are being met. Construction Quality Control is a three phase program that corresponds to the stages of work: preparatory, initial, and follow-up phases. In the preparatory phase, the contractor reviews the "quality standards" and "defines acceptable work" while obtaining the resources (workers, material, and equipment) for the work element. The contractor also determines if previous work is acceptable at this point. In the initial phase, the contractor makes comparisons (through inspection and testing) of the work to the contract standards. In the follow-up phase, the contractor verifies (through inspection and testing) on a "recurring basis" that the work continues to meet contract requirements. Quality Assurance is very "flexible" in that verifications can be made on "a random basis, a planned basis, before work reaches a critical stage, only after work reaches a critical stage, in response to other indications, or on a continuous basis." Limitations on the Navy's actions are: Navy inspectors "may not change or waive", but "may interpret contract requirements", or "evaluate contractor performance"; the Navy will notify the contractor if the work is "unacceptable" and the reasons for its determination. [15][16]

Responses from the interview are summarized as follows:

1. *What specification values are employed by the agency for batching, mixing, transporting and placing concrete for a project, i.e. minimum cement content, maximum water content, aggregate weights, minimum mixing time at the plant, drum revolutions of the truck mixer, maximum time between batching and discharge, etc.*

The Navy Guide Specification provides this information [15]. The document provides the specification with recommended values for each of these requirements, or it will refer to standards such as ACI or ASTM. The Guide Specification is tailored by the

designer to the particular construction project. As an example, the Guide Specification recommends a 60 - 90 minute limit from batching to discharge. The contract specifications will have the specific value or range as required. The specification values are employed as acceptance or rejection criteria.

2. *What are the agency's typical specification requirements for initial tests including slump, air content, and yield for ready-mixed concrete delivered to the project site?*

Typical specification requirements are set forth in the Navy Guide Specification [15]. Section 03300 contains the specifications for cast-in-place concrete including reference standards (ACI, ASTM), details of required tests, and recommended values. Specific values are established for each contract by the designer using the Guide Specification recommendations. The slump range is based on the type of structure, but is normally set at 2 inches - 4 inches, and sometimes 3 inches - 5 inches. Air content is specified for concrete affected by weather at 5 percent \pm 1 percent tolerance. Yield testing is not required except for structural light weight concrete. Cylinders are also taken for compressive strength testing.

3. *How are the tests performed:*

a. *Who performs the tests: agency, separate testing agency, or contractor?*

The contractor obtains the services of an approved testing laboratory. This Navy office receives the test reports in about ten days (after testing) from the lab marked as conforming or nonconforming.

- b. *What procedures are employed: standard specifications, methods, equipment, or agency modifications?*

Testing procedures are based on standard references from the Navy Guide Specification [15]. The Guide Specification includes the standard ASTM specifications for sampling and testing concrete.

4. *What is the typical scenario for testing as the concrete is delivered to the project site:*

- a. *When are the tests taken after arrival of the concrete truck?*

The tests are performed just prior to placement. The tests are completed within about 15 minutes.

- b. *What are the time limits for conducting the tests?*

The limits are in accordance with ASTM C 172 specifications: Slump and air content tests are to be started within 5 minutes after obtaining the sample and should be completed in an expeditious manner. Strength specimens are to be cast within 15 minutes after obtaining the sample.

- c. *Who is represented at the site for the test, i.e. agency's representatives, contractor's representatives, supplier's representatives (other than the driver)?*

Representatives at the site include the testing lab technician performing the tests, the contractor's quality control (CQC) representative, and the driver for the supplier. Occasionally, this Navy office will have a representative at the site to spot check the

testing. The testing lab technician takes a sample from the truck in a wheel barrel, sets up and performs slump test first, (and determines how much water to add if the slump is low). Next, he measures air content normally by the pressure method (ASTM C 231). (Air entraining admixture can be added to bring the air up to the specified percentage.) Yield test is not performed except for structural light weight concrete. The technician also measures temperature.

5. *How are the initial test results used by the agency:*

a. *What are the criteria for acceptance or rejection of the load?*

The contract specification requirements for the tests are used to accept or reject the concrete. The contractor (CQC representative) is responsible for making the determination based on the test results. The inspectors of this Navy office will spot check the contractor, especially for critical placements.

b. *What type of information is provided as feedback to the supplier?*

The contractor advises the supplier if the load has been rejected. Often, the contractor has radio communication with the supplier so there is immediate notification of problems. Reasons for variations and problems are addressed between the contractor and supplier as well.

c. *Under what conditions, if any, may concrete be accepted that does not meet the test requirements?*

The test results must meet the specification requirements otherwise the concrete will be rejected. However, inspectors tolerate $\pm 1/4$ inches around the specified range for slump and may allow one retest, although this is not done often. Water may be added at the site to bring the slump up to specification and admixture may be added to bring the air content up to specification as required. In general, the contractor is expected to meet the test requirements and make the determination to accept or reject the concrete. If the inspectors of this Navy office observe nonconforming tests, they will check with the CQC representative to determine the contractor's intentions concerning the disposition of the load. If the contractor accepts the nonconforming load, then this Navy office may take action directing the contractor to comply with the specifications and withhold payment until he is in compliance. Normally the inspectors of this Navy office do not observe the field tests, but receive test reports from the testing agency later that are marked conforming, or nonconforming per the specifications. The Navy representatives address nonconforming tests with the contractor to determine his intentions. If the contractor indicates that he has accepted the concrete, then the Navy may take similar actions as indicated above.

d. *Verbal Questions:*

(1) *Is feedback provided directly to the supplier or just the driver?*

Feedback is provided directly to the supplier by the contractor.

(2) *Is yield / unit weight used as lbs./cu. yd. pay conversion?*

Yield is not required for normal concrete. Pay quantities may be determined from the theoretical yield of the mix design and the quantities on the ticket. Pay is by cubic yard.

(3) *Is yield / unit weight used as a check for concrete quality - air content and ability to consolidate?*

Yield is not required for normal concrete.

6. *Lab experiments of this research project looked at fine aggregate gradation and water requirement as factors affecting the test results. For example, in moving from the center of the ASTM gradation specification to the fine side, the slump decreased by 2 3/4 inches. In this case the water requirement had to be increased by 21 lbs./cu. yd. to bring the slump back up to 4 inches.*

a. *To what extent does the agency consider the affect of gradation variation within the specification range on specified slump?*

This Navy office will check the contractor mix design submittal to determine if it meets the compressive strength, and water - cement ratio requirements. Engineers will also verify the gradation against ASTM requirements. After acceptance of the mix design this Navy office does not generally check into variations, as this is the contractor's responsibility. This Navy office requires the contractor to meet the test requirements for slump, etc. The mix design is optimized at the plant. The batching process is computer controlled to ensure gradation is within the specification and per the approved mix design. The contractor and supplier consider gradation variations if difficulties arise in the field. Normally the contractor does not experience a problem.

b. *What limitations are placed on the addition of water at the job site to bring slump up to the specified range?*

Water may be added in the field to bring the slump up to specifications, but is limited to the ACI requirements (maximum water - cement ratio must not be exceeded) [7]. The testing lab representative determines on site how much additional water is required.

c. *What are the agency's procedures for retesting a truck load?*

In general, this Navy office expects the contractor to meet the specification requirements on the first test, or the concrete may be rejected. However, depending on the circumstances, the inspector may permit one retest within 15 minutes at his discretion.

d. *Verbal Questions:*

(1) *If the agency considers gradation variations, how often is the fineness modulus of the fine aggregate verified after acceptance of gradation limits?*

After the mix design is accepted the Navy representative does not check these factors closely as this is the contractor's responsibility to address with the supplier.

(2) *If water is added, is it checked against the maximum water content?*

The contractor is required to ensure that the maximum water - cement ratio is not exceeded.

(3) *Does the agency account for water in the drum after clean out from the previous batch?*

The engineer being interviewed was not sure how this was handled by the contractor.

(4) *Are variabilities of other factors considered by the agency, i.e. yield on aggregate content?*

The contractor via his CQC representative is responsible for addressing these problems with the supplier.

7. *How are the tests related to expected performance:*

a. *Short term performance: uniformity, consistency, and workability for effective consolidation and placement without segregation?*

If the test results meet the specification requirements, short term performance is expected to be satisfactory.

b. *Long term performance: strength and durability?*

Quality long term performance is anticipated, if the test results are in conformance with the specification requirements.

c. *To what extent are the tests used as a reflection of expected performance:*

(1) *Are they used strictly for acceptance / rejection or,*

Test results are strictly used for acceptance or rejection of the load of concrete.

(2) *Is there a graduated pay scale, i.e. concrete is out of the slump range, but reimbursed at less than the bid price as a penalty; also, a bonus payment is provided for concrete that is consistently within the specification range for slump, air content, yield, etc.?*

There is no graduated pay scale. However, if nonconforming test results are received showing slump or air content out of specification, engineers will use the strength tests and visually observe the concrete for cracks to determine if a reduction should be taken or repairs be required in accordance with the Federal Acquisition Regulation.

8. *Does the agency consider the tests adequate enough indicators of expected performance to accept or reject the load of concrete? If not, what are the limitations of the tests for your applications?*

The tests are considered to be good indicators of expected performance. The tests are very practical and are used to accept or reject the load of concrete.

4.2.3 Private Company Summary: Interview with Concrete Technology Corp.

representative:

The interview took place on 29 June 1993 at Concrete Technology Corporation (CTC) in Tacoma, WA. CTC manufactures precast and prestressed concrete structures for a variety of customers including private companies, and public agencies such as the U. S. Navy and Washington State Department of Transportation (WSDOT). CTC employs an in-house quality control organization for the day to day inspection and testing requirements. The CTC representative interviewed was Mr. D. Heizenrader, CTC Concrete Materials Manager. Responses from the interview are summarized as follows:

1. *What specification values are employed by the company for batching, mixing, and placing concrete, i.e. minimum cement content, maximum water content, aggregate weights, minimum mixing time at the plant, maximum time between batching and*

discharge, etc.

Specifications for these requirements are usually provided by the customer especially the public agencies during the bidding process. The plant is certified by the Prestressed Concrete Institute (PCI). CTC performs its plant operations in compliance with the PCI Manual for Quality Control for Plants and Production of Precast and Prestressed Concrete Products [17]. The plant is inspected twice a year by an independent agency hired by PCI. Plant operations are also based on standard ASTM and ACI procedures. The batch plant operation is run by computer.

2. What are the company's typical specification requirements for initial tests including slump, air content, and yield for structural concrete?

Specific test requirements will depend on the customer or particular agency contract. CTC also has an in-house program that includes the standard test requirements. Strength specimens are cast for each product line. Six specimens are taken at each location and used as follows: one pair will provide strength data at form stripping; a second pair will provide strength data at shipping; and a third pair will provide strength data at 28 days. Slump tests are performed on all mixes at the time strength specimens are cast. In addition, air content tests are performed on air entrained mixes at the time strength specimens are cast. Unit weight and yield determinations are made weekly on all mixes when strength specimens are cast. The frequency of testing, required values and tolerance limits are based on PCI/ACI/ASTM or customer specifications if provided. Typical specification values are summarized as follows:

Consistency (slump):

Maximum 4 inches for water reduced mixes;

No tolerance limits specified in-house. Normally, concrete must not exceed maximum slump. Determination of tolerance limit is made case by case.

Air Content:

5 percent for air entrained; 1 1/2 percent to 2 percent for non air entrained;

Tolerance limits are $\pm 1\ 1/2$ percent for air entrained mixes;

Yield: Tolerance of $\pm 3/10$ cu. ft./cu. yd. of specification requirement.

3. How are the tests performed:

- a. *Who performs the tests: in-house personnel, or separate testing agency?*

Tests are performed by in-house personnel.

- b. *What procedures are employed: standard specifications, methods, equipment, or company modifications?*

ASTM procedures are used to perform the tests. The pressure method (ASTM C 231-91b) is used for the air content test except for mixes with lightweight aggregate which employ the gravimetric method (ASTM C 138-81). Strength specimens are vibrated externally rather than by rodding to more closely approximate plant conditions. The specimen size is 4 inch dia. by 8 inch long. This size is used because it is easy to work with and takes up less space. Test data are initially recorded in a log book and then later transferred to a computer data base for statistical analysis.

4. What is the typical scenario for testing the concrete:

- a. *When are the tests taken after mixing?*

A truck with nonagitating buckets delivers the fresh concrete from the batch plant to placement location. Samples are taken from the buckets prior to placement. Tests are taken for each line once a day. The sequence of testing depends upon the grind of cement and admixtures. For instance, in WSDOT mixes with high range water reducers (HRWR), strength specimens are cast first, then slump tests allowing the mix to stabilize for slump loss, then air content, unit weight and yield tests.

b. *What are the time limits for conducting the tests?*

Tests are performed within about 15 minutes after taking the samples.

c. *Who is represented at the site for the test, i.e. company's representatives, testing agency's representatives, customer's representatives?*

The company tester performs the tests. WSDOT will have a representative at all tests for their contracts. Navy representatives make visits to the plant on a random basis to inspect their contract work. Other customers may or may not visit the site for tests.

5. *How are the initial test results used by the company:*

a. *What are the criteria for acceptance or rejection of the concrete batch?*

The criteria depends on the customer's specifications. For instance, WSDOT will take deductions if slump and air content are out of specification. The company periodically makes visual inspections to check batches. If the concrete does not appear good, tests will immediately be performed to check the quality. The

company tester may accept or reject any batch based on the results.

b. *What type of information is provided as feedback to the plant operator?*

The plant operator is provided with the test results so he can make any necessary adjustments to the mix.

c. *Under what conditions if any may concrete be accepted that does not meet the test requirements?*

The conditions depend on the customer's specifications. Also, the company may wait for the strength test results before making a decision.

Verbal Questions:

(1) *Is yield and unit weight used as a check for concrete quality, i.e. air content and ability to consolidate?*

Yield results are used in-house to check if the batch is consistent with estimated amounts, check uniformity of materials, and check air content, slump and strength.

6. *Lab experiments of this research project looked at fine aggregate gradation and water requirement as factors affecting the test results. For example, in moving from the center of the ASTM gradation specification to the fine side, the slump decreased by 2 3/4 inches. In this case the water requirement had to be increased by 21 lbs./cu. yd. to bring the slump back up to 4 inches.*

- a. *To what extent does the company consider the affect of gradation variation within the specification range on specified slump?*

The mix design will have a gradation within specifications. The company requires a fine aggregate fineness modulus of 3.0 - 3.2 from its supplier. The company does consider gradation problems, but usually gradation is fairly consistent from the supplier.

- b. *What limitations are placed on the addition of water to bring slump up to the specified range?*

Additional water may be added at the plant up to the limitation of the maximum water - cement ratio. Addition of water to the batch in the truck is not permitted because the trucks are nonagitating.

- c. *What are the company's procedures for retesting a batch?*

Retesting is performed on a case by case basis. If past the ASTM time limitation, the batch will not be retested.

Verbal Questions:

- (1) *If the company considers gradation variations, how often is the fineness modulus of the fine aggregate verified after acceptance of gradation limits?*

Gradation and fineness modulus of company stockpiles will be checked at least once a week. Also, the stockpiles are checked for segregation and contamination of

materials. Acceptance tests are performed on the material as the barge arrives at the plant. WSDOT also runs samples on the material for their contracts.

(2) *If water is added, is it checked against the maximum water content?*

It is checked against the maximum water - cement ratio.

(3) *Are variabilities of other factors considered by the company, i.e. yield on aggregate content?*

The mix may be impacted by the grind of cement causing strength and workability variations.

7. *How are the tests related to expected performance:*

a. *Short term performance: uniformity, consistency, and workability for effective consolidation and placement without segregation?*

The tests provide an indication of expected short term performance. Yield test results are important as well as feedback from the placing crew.

b. *Long term performance: strength and durability?*

Test results and water - cement ratio are important measures of the expected quality of the product.

c. *To what extent are the tests used as a reflection of expected performance:*

(1) *Are they used strictly for acceptance / rejection or,*

The results are not used strictly for acceptance or rejection. A batch may be rejected if it does not meet the specifications. However, if the initial tests on the

fresh concrete are close to specification, the company will wait for the strength results to make a decision.

- (2) *Are alternative procedures employed by the company, i.e. concrete is out of the slump range, but later strength tests on hardened concrete meet specifications so customer accepts product?*

If the strength tests are within the specification, acceptance will be worked out between the parties.

8. *Does the company consider the tests adequate enough indicators of expected performance to accept or reject the batch of concrete? If not, what are the limitations of the tests for your applications?*

The tests are considered to be good indicators. Slump for mixes with an HRWR may not be applicable.

4.3 LABORATORY RESULTS SUMMARY: Four separate mixes were prepared in the laboratory portion of this study; a control mix, a mix with fine sand, and two mixes with coarse sand. The fine sand mix had additional water added after initial slump testing to bring the slump up to 4 inches. The initial coarse sand mix had too high a slump, and would have been rejected in many cases. A second coarse sand mix was prepared with reduced water (and cement) to meet the 4 inch slump requirement and target mix strength. Strength specimens were cast for the control mix, the fine sand mix after adding water, and both coarse sand mixes. The results of the four mixes (along with initial slump results from the fine sand mix prior to adding water) are presented in Table 4-1.

Table 4-1 Laboratory Results Summary

	Control Mix	Mix 1-Initial	Mix 1-Added Water	Mix 2-Initial	Mix 2-Rebatch
Water (Lbs./Cu. Yd.)	267	267	295	267	254
Cement Factor (Sacks/Cu. Yd.)	5.69	5.69	5.69	5.69	5.39
w/c	0.50	0.50	0.55	0.50	0.50
Sand Fineness Modulus	2.74	2.15	2.15	3.43	3.43
Slump (In.)	4	1-1/4	4-3/4	5-3/4	4-1/4
Air (%)	1.5	(1)	2.3	1.4	1.8
Unit Weight (Lbs./Cu. Yd.)	150.3	(1)	150.2	151.8	151.4
Ave. 28-Day Compr. Strength (PSI)	6248	(1)	5430	6090	5972
Std. Deviation (PSI) (2)	231	(1)	106	285	241
28-Day Design Strength (PSI) (3)	5944	(1)	5126	5786	5668

- Notes: (1) Tests not conducted as water was added to the mix to correct slump after initial slump test.
(2) Standard Deviations were combined to obtain a composite value for all mixes. The composite value calculated as 227 psi per ACI 318 Commentary, Section 5.3.1, Eq. (R5B) [18].
(3) Design Strength calculated as Mean Strength - 1.34 x Composite Standard Deviation per ACI 318, Section 5.3.2.1., Eq. (5-1) [18].

CHAPTER 5 - ANALYSIS AND CONCLUSIONS

5.1 INTRODUCTION: Job site quality along with acceptance and rejection criteria and procedures for state, federal, and private agencies are compared and contrasted in this Chapter. The results of laboratory testing examining the influence of fineness modulus on slump, yield, and 28-day compressive strength are also presented in this Chapter.

5.2 AGENCY PROCEDURES: The agencies consulted for this research included the Washington State Department of Transportation (WSDOT), the U. S. Navy Construction Office in Everett, WA, and the Concrete Technology Corporation of Tacoma, WA. A brief summary of their procedures is presented in the following paragraphs.

5.2.1 Job Site Procedures:

WSDOT has established their own formal procedures for job site inspection and testing [14]. Specifications limit the time from batching to discharge to 1 1/2 hours, but may be extended to as much as 2 hours under favorable ambient conditions. The sample for acceptance testing and cylinder specimens is provided by the contractor from a point that will be representative of the condition of the concrete at the point of placement. The sample is acquired from the initial portion of the load after about 1/2 cu. yd. of concrete has been discharged from the truck as described by WSDOT Test Method No. 803. The sample is obtained at two or more regular intervals throughout the batch. The elapsed time for obtaining the sample should be no more than 15 minutes. The sample is to be transported to the test site in as short a time as possible (no specified time limit). The State inspector performs slump and air content tests within 5 minutes after remixing the sample. The air content test is performed on air entrained mixes by the pressure method (WSDOT Test Method No. 805). Strength specimens are cast within 15 minutes after remixing the

sample. Temperature of the concrete is also taken per testing requirements. Unit weight is performed to verify the cement factor (State mixes) and for information purposes (contractor mixes). Testing is required for every truck until there are two successive acceptable tests. Testing is then performed on one truck in every five on a random basis.

Procedures employed by the U. S. Navy Construction Office in Everett are included in the Navy Guide Specification [15]. The document contains the acceptance testing procedures. Standard ACI and ASTM procedures are referenced in the Guide and are to be included in Navy construction contracts. The contractor is responsible for sampling and acceptance testing according to the Contractor Quality Control program of the contract. The Navy inspectors spot check the testing as part of the Government's Quality Assurance program [16]. The time from batching to discharge is limited to 60 - 90 minutes. The contractor's representative (certified technician) performs the tests. Samples are usually taken from the truck at the time of placement. Samples are obtained according to ASTM C 172-90. Slump and air content tests are performed within about 15 minutes of sampling followed by casting of strength specimens. The air content test is performed on air entrained mixes by the pressure method (ASTM C 231-91b) or volumetric method (ASTM C 173-78). The volumetric method is required for lightweight aggregate. The technician also measures the concrete temperature. Unit weight test is performed only for structural lightweight concrete. Slump and air content testing is required at the beginning of placement operations, whenever strength specimens are cast, and "for each batch (minimum) or every 10 cubic yards (maximum)" per the Navy Guide Specification [15].

Procedures employed by the Concrete Technology Corporation (CTC) are based on the customer's specifications as well as in-house procedures. Their in-house program is based on the PCI quality control manual [17], ASTM and ACI standards. The tests are performed by in-house personnel. The concrete is delivered from the on-site batch

plant to the placement location in trucks with nonagitating buckets. Samples are taken from the bucket prior to placement. Slump, air content, unit weight and yield tests are performed at the time strength specimens are cast. The air content test is performed on air entrained mixes by the pressure method (ASTM C 231-91b), except for mixes with lightweight aggregate which require the gravimetric method (ASTM C 138-81). The sequence of testing may vary, i.e. for high range water reducing (HRWR) mixes, strength specimens are cast first to allow the mix to stabilize for slump loss. Tests are completed within about 15 minutes of taking the sample. Testing is performed for each product line once a day. Customer representatives may observe the testing depending on their inspection procedures.

5.2.2 Quality Control Criteria:

WSDOT has established quality control requirements for State-Provided Mix Designs [14]. The contractor is required to provide concrete that meets the requirements for consistency and air content (air entrained mixes). The State maintains responsibility for strength so long as the contractor has followed all of the specified procedures. For Contractor-Provided Mix Designs, the contractor is required to meet specified strength in addition to concrete consistency and air content [14]. Water may be added at the job site for low slump, but only up to the maximum design water - cement ratio. Typical quality control criteria for ready-mixed concrete delivered to the project site include [14]:

Consistency (slump): maximum 4 inches for structural applications;

Air content: 4.5 percent minimum to 7.5 percent maximum for air entrained concrete where required.

General quality control requirements employed by the Navy Construction Office are set forth the Navy Guide Specification [15] which are based on ACI and ASTM standards. Specific criteria are established for each contract by the designer based on the

Guide Specification recommendations. Water may be added at the job site to bring low slump up to specifications, but limited to ACI requirements (maximum design water - cement ratio must not be exceeded) [7]. Air entraining admixture may be added at the job site to bring low air content to within the specification range. Typical quality control criteria for ready-mixed concrete delivered to the project site include [15]:

Slump range: 2 inches to 4 inches, but may vary based on type of structure;

Air content: 5 percent to 7 percent for concrete affected by weather.

Quality control criteria used by CTC is provided by the customer during the bidding process. If the customer does not specify the criteria, CTC uses established in-house requirements based on PCI, ACI and ASTM standards. Additional water may be added at the plant for low slump, but limited by the maximum design water - cement ratio. The addition of water to the batch in the truck is not permitted because the trucks are nonagitating. Typical requirements for structural work include:

Consistency (slump): 1 inch to 4 inches;

Air content: 5 percent for air entrained, 1 1/2 percent to 2 percent for non air entrained when performed.

Yield: Tolerance of $\pm 3/10$ cu. ft. per cu. yd. of the specification value.

5.2.3 Acceptance and Rejection Procedures:

Under WSDOT's procedures, a load of concrete is considered to be out of specification if it is out of the specified range for consistency (slump) and air content. The State field inspector advises the contractor if the test results are acceptable or if the tests results are out of specification and will accept or reject the load. The contractor may invoke the tolerance limits established in the specification, but at a reduction in contract price [14]. Tolerance limits are specified as 1 inch above the maximum specified slump, and 1 percent

above the maximum and 1/2 percent below the minimum air content values. The concrete is rejected if it is outside the tolerance limits. The State inspector is obligated to perform one test, but may perform one retest at his discretion. Though the State does not test each truck, the contractor may reject any load on his own decision.

Procedures of the Navy Construction Office require the concrete to be rejected if it does not meet the specifications for slump and air content. Navy inspectors may tolerate about $\pm 1/4$ inch around the specified slump range and about ± 1 percent for the specified air content range. The contractor should meet the specification on the first test, but depending on the circumstances, one retest may be permitted within 15 minutes at the discretion of the inspector. Test results are used strictly for acceptance or rejection of the concrete load. The contractor quality control (CQC) representative is expected to make the determination to accept or reject the concrete based on the test results. If the contractor accepts nonconforming concrete, this Navy office may take action to direct the contractor to comply with the specifications and withhold payment until he is in compliance.

CTC's procedures depend on the customer's specifications. The company tester may accept or reject a batch based on his inspection and test results. There are no tolerance limits for slump specified in-house. Normally, concrete must not exceed the maximum slump. Determination of the tolerance limit for slump may be made on a case by case basis. The tolerance limit for air content is $\pm 1 1/2$ percent for air entrained mixes. Retesting is performed on a case by case basis, but the batch will not be tested again if past the ASTM time limits. Determination to accept or reject a batch is not based strictly on test results. If the initial tests (slump and air content) are close to the specification limits, the company will wait for the strength results to make a decision. If the strength tests are within specification, acceptance of the product will be worked out with the customer.

5.2.4 Summary of Procedures: Job site, acceptance and rejection procedures of the agencies are summarized in Tables 5-1 and 5-2. Typical agency quality control criteria are compared with the laboratory results in Table 5-3.

Table 5-1 Summary of Job Site Procedures

	WSDOT	U. S. Navy	Concrete Technology Corp. (CTC) (1)
Batch to Discharge (Min.)	90 (2)	60 to 90	Customer Specifications
Sampling: - Portion of Load	About 1/2 Cu. Yd.	Two or more intervals from middle portion. (3)	Customer Specifications
- Time Limit (Min.)	15	15	Customer Specifications
Testing: Slump and Air Content: - Time Limit (Min.)	15	15	15
- Frequency	Every truck until there are two successive acceptable tests. Then one in every five on random basis.	Minimum each batch. Maximum every 10 Cu. yd.	Once a day for each line.
Unit Weight and Yield	Cement factor (State Mixes. Information for Contractor Mixes.	For Structural Lightweight Concrete.	Verify batch quantities and uniformity of materials.
Addition of Water at Job Site	Yes. Limited by maximum design w/c.	Yes. Limited by maximum design w/c.	No
Verification of Fineness Modulus (after mix design approval)	When problems arise.	When problems arise.	Weekly

Notes: (1) Concrete Technology's requirements based on customer and in-house procedures.
(2) WSDOT may extend to two hours under favorable ambient conditions [14].
(3) ASTM C 172-90 sampling procedures per Navy Guide Specification [15].

Table 5-2 Summary of Acceptance and Rejection Procedures

	WSDOT	U. S. Navy	CTC
Tests used strictly for acceptance/rejection	Yes	Yes	No
Person authorized to make determination	State Field Inspector	CQC Representative	Company Tester
Retesting	One retest	One retest	One retest

Table 5-3 Comparison of Typical Agency Quality Control Criteria and Laboratory Results

	WSDOT	U. S. Navy	CTC	Control Mix	Mix 1- Initial	Mix 1- Added Water	Mix 2- Initial	Mix 2- Rebatch
w/c	0.40 (1) 0.44 (2)	0.45 (4) 0.50 (4)	(5)	0.50	0.50	0.55	0.50	0.50
Fineness Modulus	(3)	2.3 to 3.1 (ASTM)	3.0 to 3.2 (5)	2.74	2.15	2.15	3.43	3.43
Slump (In.)	4 {+1}	1 to 4 {±1/4}(4)	1 to 4 (5)	4	1-1/4	4-3/4	5-3/4	4-1/4
Air Content (%)	4.5 to 7.5 {-1/2 below +1 above}	5 to 7 {±1} (4)	5 {±1 1/2} (5)	1.5 (6)	Test not conducted	2.3 (6)	1.4 (6)	1.8 (6)
28-Day Design Strength (PSI)	5000 (1) 4000 (2)	4000 (4)	(5)	5944	Test not conducted	5126	5786	5668

- Notes: (1) WSDOT Class 5000 ("Reinforced members; Bridge decks, cast-in-place beams," etc.) [14].
(2) WSDOT Class 4000 ("General use, traffic barriers, approach slabs, bridge footings," etc.) [14].
(3) Determined from contractor sample (within WSDOT Class 2 limits). Tolerance is ± 0.20 . [14]
(4) "Concrete exposed to weather" per Navy Guide Specification [15] and sample Navy contracts. Values may vary based on type of structure and conditions, i.e. 0.45 w/c for "thin sections and 0.50 for other elements exposed to freezing and thawing conditions" [15].
(5) Concrete Technology's requirements based on customer and in-house specifications.
(6) Air contents shown are indication of entrapped air as mixes were not air entrained.
(7) Tolerances for slump and air content are shown in {brackets}.

5.3 LABORATORY TESTING: Experimental analysis was performed to examine the affects of changing the fineness modulus of the fine aggregate on slump. An assessment was also made of the impact on compressive strength due to fineness modulus after slump was met. Analysis of the test results is summarized in the following paragraphs.

5.3.1. Effect of Fineness Modulus on Slump: The effects of fineness modulus on slump were analyzed first under constant water content and then constant slump. The analysis is summarized in the following sections.

5.3.1.1 Constant Water Content: Slump results were compared against the fineness modulus of three mixes over the ASTM gradation range at constant water and cement contents per cubic yard. Experimental results indicate that slump will increase as the fine aggregate gradation becomes coarser. The relationship is shown in Figure 5-1. Mix 1 had a very fine sand at the maximum ASTM C 33-90 gradation limits. The fineness modulus (2.15) of the mix was below the ASTM C 33-90 minimum (2.3). The slump (1-1/4 inches) of Mix 1-Initial (before increasing the water content) was well below the target slump of 4 inches resulting in a very dry consistency. The control mix met the target slump with a coarser gradation and higher fineness modulus (2.74) close to the center of the ASTM C 33-90 specification range. Mix 2 had an extremely coarse sand at the minimum gradation limit. The fineness modulus (3.43) was above the ASTM C 33-90 maximum (3.1). Mix 2-Initial experienced a high slump of 5-3/4 inches, but the sample fell apart to one side (shear slump) being harsh from the coarser gradation. This mix did not appear to be sufficiently workable for consolidation based on the previous experience in casting some of the strength specimens. The experimental results demonstrate that there is a considerable difference in slump over the ASTM C 33-90

gradation range, although it may have been exaggerated somewhat as the fineness moduli of two of the mixes were slightly out of specification.

5.3.1.2 Water Demand for Constant Slump: The water requirements for a 4-inch slump were examined for three mixes with different fineness moduli as described in Section 5.3.1.1. The mixes covered the full ASTM C 33-90 gradation spectrum. The laboratory results presented in Figure 5-2 suggest that the water demand will be reduced as the fine aggregate gradation of a mix becomes coarser. The fine sand (upper ASTM gradation limit) of Mix 1 required about 289 lbs. of water per cu. yd including added water to achieve the target slump of 4 inches. Additional water (about 21 lbs. per cu. yd.) was required to raise the slump of the mix from its initial value of 1-1/4 inches. The control mix with a coarser sand (middle of ASTM gradation range) achieved the target slump with 267 lbs./cu. yd. Mix 2 with a coarser sand (lower ASTM gradation limit) had to be rebatched at a reduced water content of 251 lbs./cu. yd. and cement content of 503 lbs./cu. yd. to achieve the target slump, but still maintain a 0.50 water - cement ratio. The results indicate that the water demand to maintain a constant slump varies greatly (about 38 lbs./cu. yd.) over the ASTM C 33-90 gradation range.

5.3.2 Effect of Fineness Modulus on Yield: In this analysis, unit weight and yield results were compared with expected values to determine if the test could detect differences resulting from mix gradation. This analysis also examined whether changes in water and cement contents of the mixes could be identified by the unit weight and yield test.

5.3.2.1 Constant Ingredients: The measured unit weight was compared with the expected unit weight (corrected for measured air content) of the control mix and Mix 2-Initial. These two mixes had the same quantity of ingredients by weight, but different fine

SLUMP VS. FINENESS MODULUS
AT CONSTANT WATER AND CEMENT CONTENTS PER CU. YD.

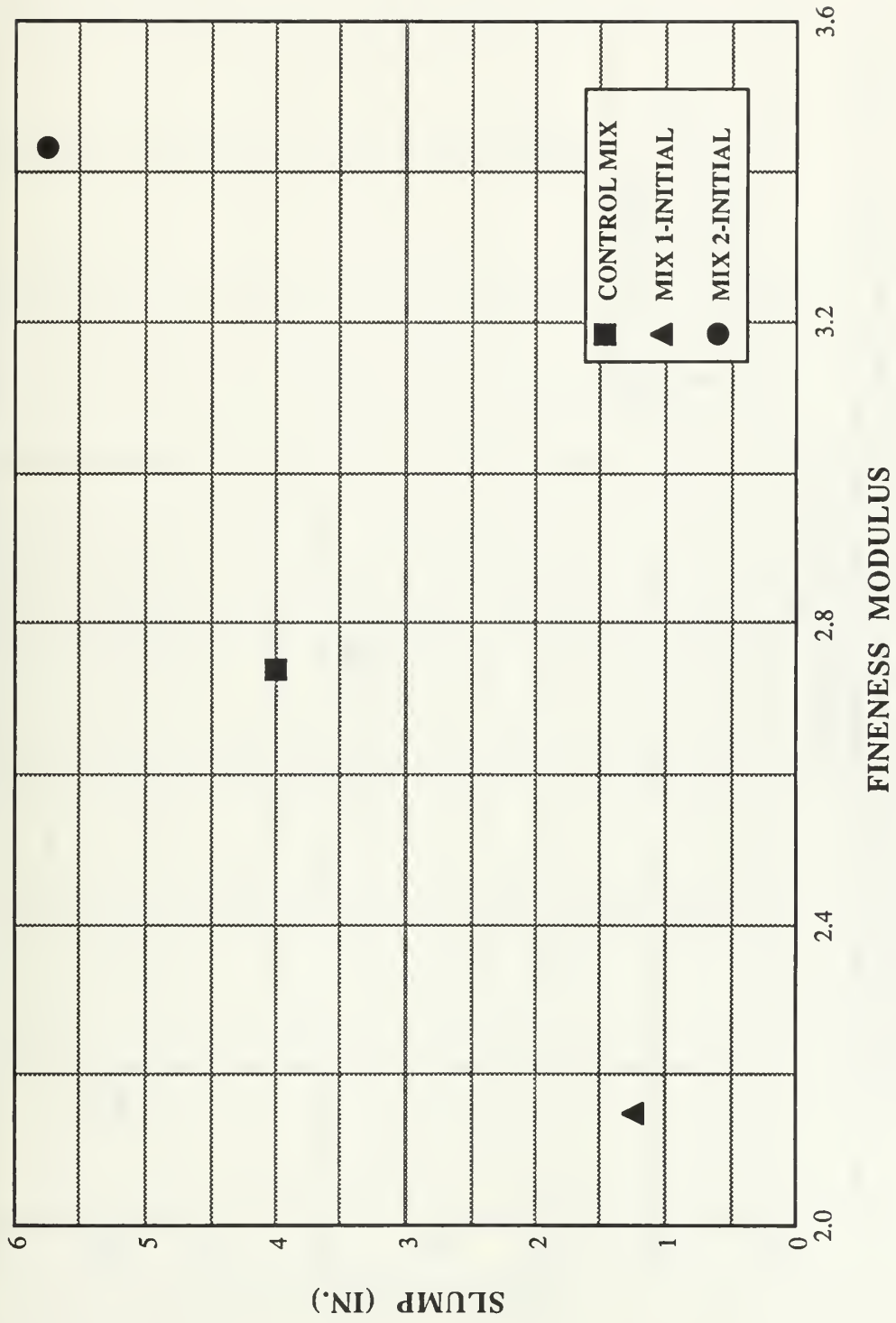
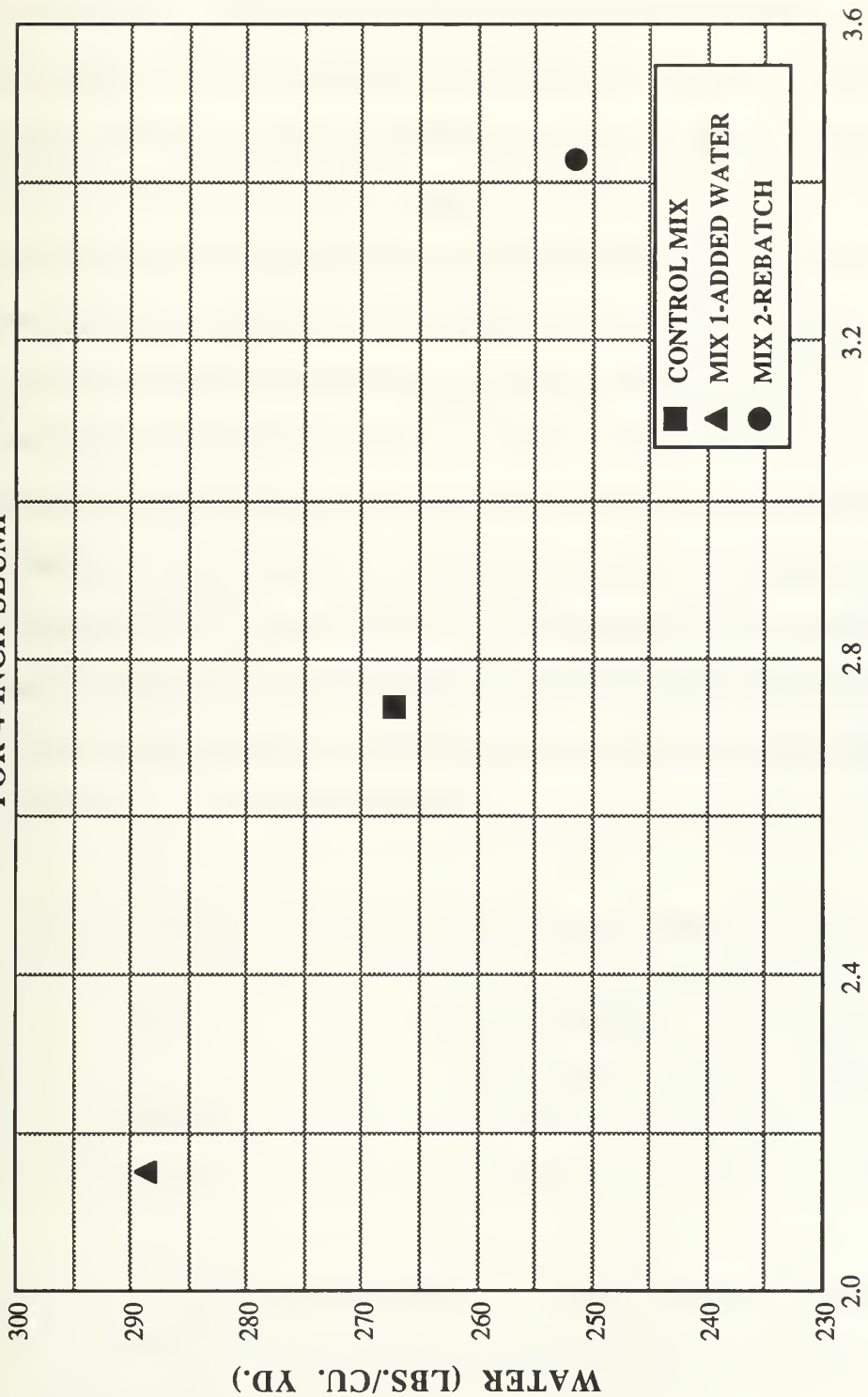


Figure 5-1 Slump vs. Fineness Modulus at Constant Water and Cement Contents per Cu. Yd.

WATER DEMAND VS. FINENESS MODULUS FOR 4-INCH SLUMP



Notes: (1) The actual slump of the 2.15 fineness modulus mix (Mix 1-Added Water) was 4-3/4 inches.
 The data plotted in this graph was adjusted to exactly 4-inch slump by reducing water content by 6 lbs./cu. yd.
 (2) The actual slump of the 3.43 fineness modulus mix (Mix 2-Rebatch) was 4-1/4 inches.
 This graph was adjusted to exactly 4-inch slump by reducing water content by 3 lbs./cu. yd.

Figure 5-2 Water Demand vs. Fineness Modulus for 4-Inch Slump

aggregate gradations. The control mix should have a lower unit weight because its air content is higher. The data presented in Table 5-4 indicates a difference in the measured unit weights as one would anticipate. However, the spread between the measured unit weights is slightly more than the difference between the expected unit weights. The larger difference in the measured unit weights may be from testing variabilities such as possible inconsistencies in consolidating the samples, removing excess concrete, and weight measurements, or from other factors such as differences in the mix ingredients, i.e. the specific gravities of the aggregates. It should be noted from Table 5-4 that there is also a noticeable, but consistent difference between the expected and measured values for both mixes. Differences in these values suggest a consistent testing variability or other differences, i.e. measured versus actual specific gravities of the aggregates. The unit weight and yield test results of these mixes indicate some inherent variabilities in testing. These variabilities should be kept in mind when evaluating unit weight results. Also, this limited amount of data may not be sufficient for a conclusive statement concerning the precision of the unit weight and yield test.

Table 5-4 Measured and Expected Unit Weights of Mixes with Constant Ingredients

Mix	Measured Unit Weight (Lbs./Cu. Ft.)	Expected Unit Weight (Lbs./Cu. Ft.)
Control Mix	150.3	147.8
Mix 2-Initial	151.8	147.9

5.3.2.2 Varying Water and/or Cement: These conditions were examined separately to assess the effects of fineness modulus on yield. A summary of the analysis is provided in the following sections.

5.3.2.2.1 Varying Water Content: A comparison of the measured unit weight and expected unit weight (corrected for measured air content) was made between the control mix and Mix 1-Added Water. The mixes had the same quantities of ingredients except for the additional water in Mix 1-Added Water to raise the slump as described in Section 5.3.1.2. Mix 1-Added Water had a finer sand than the control mix. The expected unit weights were based on the control mix quantities. These were corrected for the measured air contents of each mix. The expected unit weights were calculated in this manner to determine if the unit weight and yield test results would detect the higher water content. The expected unit weight for the control mix was higher due to a lower measured air content than Mix 1-Added Water. The addition of water to a mix should also cause a reduction in unit weight as the denser aggregate are displaced by the water. There was only a slight difference in the measured unit weights that was less than the difference between the expected unit weights as shown in Table 5-5. One might expect the difference in measured unit weights to be greater reflecting the additional water as well as the higher air content of Mix 1-Added Water. The differences between the measured and the expected unit weights indicate a consistent variability in testing and/or other factors as described in Section 5.3.2.1. The data suggest that the unit weight and yield test may not be adequate to permit detection of varying water content (i.e. w/c from 0.50 to 0.54 for constant cement) in batches of a mix delivered to a job site and/or the addition of water at the job site. Caution is expressed in drawing this conclusion as the amount of data may not be sufficient.

Table 5-5 Measured and Expected Unit Weights of Mixes with Varying Water Content

Mix	Measured Unit Weight (Lbs./Cu. Ft.)	Expected Unit Weight (Lbs./Cu. Ft.)
Control Mix	150.3	147.8
Mix 1-Added Water	150.2	146.6

5.3.2.2.2 Varying Cement Content: The measured unit weight was compared with the expected unit weight (corrected for measured air content) of the control mix and Mix 2-Rebatch as shown in Table 5-6. As indicated in Section 5.3.1.2, Mix 2-Rebatch was rebatched at reduced water and cement contents. This caused an increase in the total batch weight of all materials (0.46 lbs./cu. ft.) from control mix quantities as the fine aggregate weight went up more than offsetting the reductions in water and cement to meet the volume requirement. Mix 2-Rebatch had a coarser sand than the control mix. The expected unit weights were based on the control mix quantities. These were corrected for the measured air contents of each mix. The expected unit weights were calculated in this manner to determine if the unit weight and yield test results would detect the lower cement content. The expected unit weight for the control mix was higher due to a lower measured air content than Mix 2-Rebatch. The differences between the measured and expected unit weights indicate a consistent variability in testing and/or the factors similar to those described in Section 5.3.2.1. In view of data shown in Table 5-6, it is difficult to determine whether the unit weight and yield test can detect variations in cement content of batches of a mix delivered to the job site.

Table 5-6 Measured and Expected Unit Weights of Mixes with Varying Cement Content

Mix	Measured Unit Weight (Lbs./Cu. Ft.)	Expected Unit Weight (Lbs./Cu. Ft.)
Control Mix	150.3	147.8
Mix 2-Rebatch	151.4	147.4

5.3.3 Effect of Fineness Modulus on Compressive Strength: The average strengths for each mix were determined and compared against the fineness modulus, first under constant water - cement ratio, and then under constant slump. Analysis is provided in the following paragraphs.

5.3.3.1 Determination of Average Strength: Ten 4 inch dia. by 8 inch long specimens were cast and tested for each mix. Strength results for each mix were examined as a group to determine outlying data. The criteria used to determine outlying results was the standard range of ± 500 psi about the mean of the group. One specimen from Mix 2-Initial was considered outlying based on this criteria. In addition, the strength result for one specimen from Mix 1-Added Water was not recorded as the specimen was impact loaded during testing. These two specimens were removed from the data and the average strength of each mix was then determined based on the remaining data in each corresponding group. The average strengths for each mix are shown in Table 4-1 of Chapter 4.

5.3.3.2 Constant w/c: A comparison was made of strength versus fineness modulus for three mixes at constant water - cement ratio. The mixes covered the lower half of the ASTM C 33-90 gradation range. The relationship of the experimental results is presented in Figure 5-3. The results indicate that strength tends to decrease as the fine aggregate gradation becomes coarser. The control mix (mid range sand gradation) had an average

strength of 6248 psi. Mix 2 had a coarse sand at the minimum ASTM gradation limit. Mix 2-Initial attained an average strength of 6090 psi. Mix 2-Rebatch (reduced water and cement) average strength was 5972 psi. Statistical analysis presented in Table 5-7 indicates that there is no significant difference between Mix 2-Initial and Mix 2-Rebatch at 95 percent confidence level. Also, the data in the table indicate that there is no statistical difference in strengths between the control mix and Mix 2-Initial at 90 percent or 95 percent confidence limits. There is, however, a significant difference (at 95 percent confidence) between the control mix and Mix 2-Rebatch. At constant w/c, slump, and coarse aggregate content, increasing fineness modulus from 2.74 to 3.43 can significantly reduce strength.

5.3.3.3 Constant Slump: The strengths were examined against the fineness modulus of three mixes at a 4-inch slump. The relationship shown in Figure 5-4 suggests that there is an optimal sand fineness modulus for constant slump and coarse aggregate content. Additional data would be necessary to confirm a definite relationship. The fine sand of Mix 1-Added Water had the lowest average strength (5430 psi). This result may have been a combination of factors: fine gradation, and increased w/c (after adding water to the mix). The control mix (middle of ASTM gradation range) attained the highest average strength (6248 psi) of all experimental results. Mix 2-Rebatch attained an average strength (5972 psi) in between the other two mixes. The analysis presented in Table 5-7 indicates that there is a statistical difference between all of these mixes at 95 percent confidence level. This analysis appears to support the suggestion that the strength of a mix maximizes at the middle of the ASTM gradation range for the given coarse aggregate content. The strength appears to fall off as the gradation moves towards the limits (finer and coarser) of the ASTM gradation.

COMPRESSIVE STRENGTH VS.
FINENESS MODULUS AT CONSTANT W/C

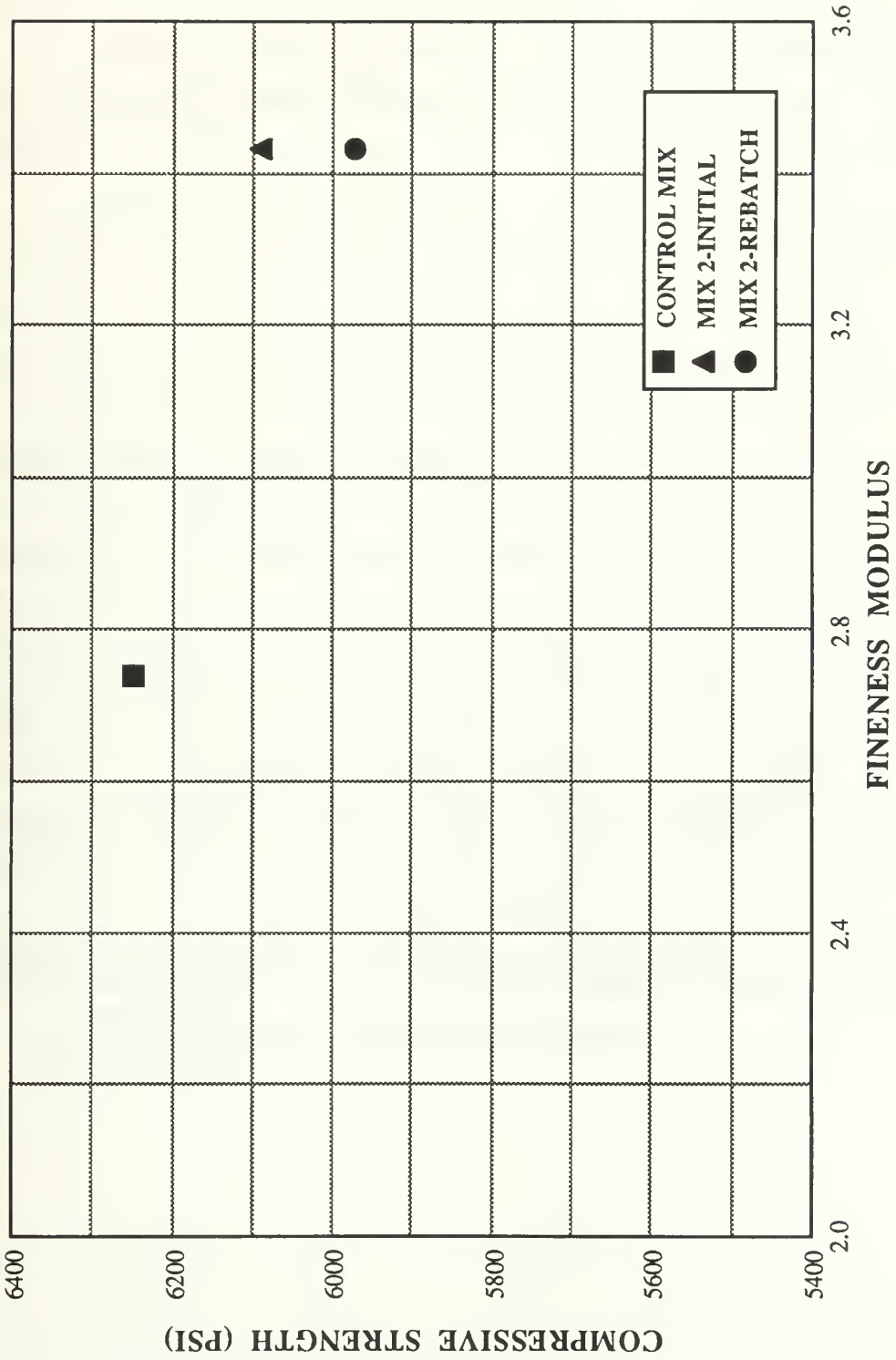


Figure 5-3 Compressive Strength vs. Fineness Modulus at Constant w/c

Table 5-7 Comparison of Compressive Strength Results

Mixes Compared	90% Confidence $t_{0.05}$	95% Confidence $t_{0.025}$	99% Confidence $t_{0.005}$	t_{calc}	Significant Difference $ t_{calc} > t_{0.05} $	Significant Difference $ t_{calc} > t_{0.025} $	Significant Difference $ t_{calc} > t_{0.005} $
CM vs. 1-Added Water	-	2.111	2.898	9.727	-	YES	YES
CM vs. 2-Initial	1.740	2.110	2.898	1.336	NO	NO	NO
CM vs. 2-Rebatch	-	2.101	2.878	2.623	-	YES	NO
1-Added Water vs. 2-Initial	-	2.120	2.921	-6.502	-	YES	YES
1-Added Water vs. 2-Rebatch	-	2.110	2.898	-6.218	-	YES	YES
2-Initial vs. 2-Rebatch	-	2.110	2.898	0.980	-	NO	NO

Notes: (1) Analysis was performed on average strengths by applying "two-sample t test for small samples" [19].

(2) $t_{0.05}$, $t_{0.025}$ and $t_{0.005}$ based on "two-tailed" distribution [19].

(3) CM - control mix.

COMPRESSIVE STRENGTH VS.
FINENESS MODULUS FOR 4-INCH SLUMP

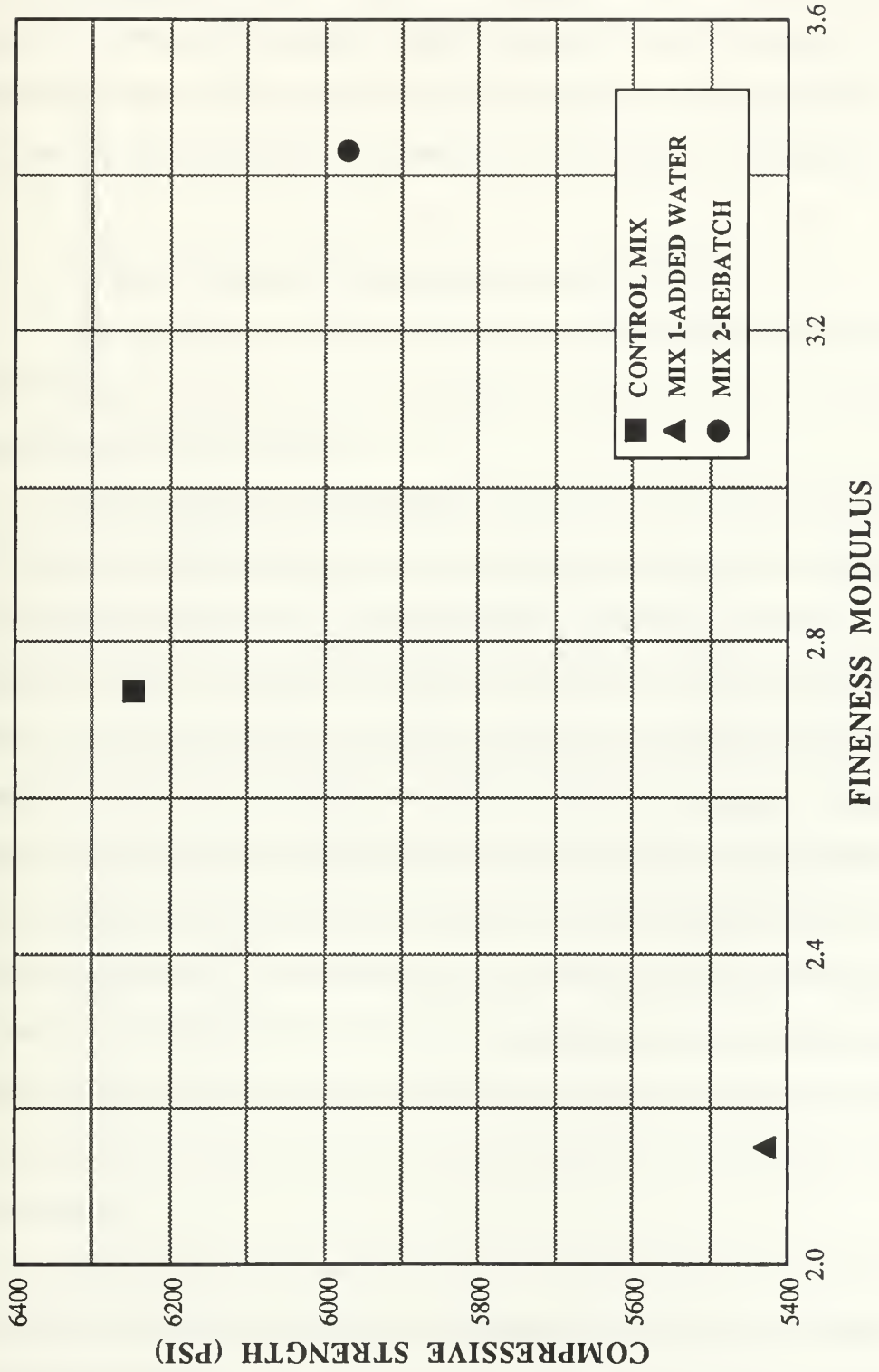


Figure 5-4 Compressive Strength vs. Fineness Modulus for 4-Inch Slump

5.4 CONCLUSIONS: In this section an assessment is provided concerning the adequacy of current job site procedures based on analysis of the interviews and experimental portions of this research. Recommendations for improving job site procedures and areas requiring further work are also summarized in this section.

5.4.1 Adequacy of Current Procedures for Job Quality Control:

An analysis of the agency procedures and the laboratory testing of this research established important aspects about the adequacy of current procedures. An assessment is provided in the following paragraphs.

The two public agencies (WSDOT and U. S. Navy) and private company (CTC) consulted for this research consider current job site procedures to be adequate. The initial tests (slump and air content) performed on ready-mixed concrete delivered to the job site provide sufficient information about expected performance to make a determination to accept or reject a load of concrete. The results of the interviews with the public agencies indicate the slump and air content tests are employed strictly as acceptance or rejection criteria. Tolerances have been established to account for variations in mixing and handling as well as variabilities associated with the testing, but at levels that will still ensure quality long term performance. CTC uses the tests as an indication of expected performance, but may wait for the strength results to make a determination depending on the customer contract. In general, the unit weight and yield test is not used for acceptance or rejection criteria, but rather as a check of the cement factor, proportions of ingredients, and batch to batch uniformity.

Results of the interviews suggest that the slump test provides a good indication of uniformity and workability for short term performance requirements; the ability to place and consolidate the fresh concrete. The interviews also suggest that the slump test provides a good indication of expected long term performance because strength and durability should

be met with effective placement and compaction if at the proper water - cement ratio. The air content test is employed for air entrained mixes as an important indication of the long term durability of the hardened concrete against freezing and thawing. The agencies also use the tests as indications of variations in the mix delivered to the job site. In particular, it is realized that variations in aggregate gradation can have a significant impact on the mix over the specification range. The public agencies do not check the gradation after approval of the mix design unless problems arise in the field. The tests are used to identify problems early in the process and make the necessary adjustments. It should be noted that CTC considers the potential for gradation problems and checks the gradation and fineness modulus of its stockpiles on a weekly basis. The public agencies permit the addition of water at the job site for low slump based on results of the slump test. The addition of water is limited to the maximum design water - cement ratio to minimize the affect on strength and durability.

The laboratory testing identified several interesting aspects about the tests. The slump test can play a very effective role in identifying mix variations such as fine aggregate gradation. The experimental results demonstrated that there is a significant difference in slump (about 4-1/2 inches) over the ASTM gradation range. The difference can easily be identified by the slump test. Water demand was also shown to vary significantly (about 38 lbs./cu. yd.) over the ASTM gradation range again brought to light by slump testing. The unit weight and yield test appears to have some inherent variabilities in testing that should be kept in mind when evaluating the test results. Also, the unit weight and yield test seems inconclusive about other mix variations such as water and cement contents. This may be the reason the test is not currently being employed as acceptance or rejection criteria. Results of compression testing revealed that the slump test could also provide insight into the effects on compressive strength resulting from variations in fine aggregate gradation. This variation can have detrimental affects on the strength especially if water is

added to improve the slump for short term performance. Overall the tests seemed fairly sensitive to variations in gradation and could be used to provide indications of expected performance.

Both the interviews and laboratory testing tend to suggest the current procedures and testing of ready-mixed concrete at the job site are adequate enough indicators of quality control and expected performance to make a determination to accept or reject the concrete. In particular, the slump test seems very useful for detecting variations in aggregate gradation providing important information about the expected performance of the fresh and hardened concrete. The slump test may not be as effective for mixes with water reducers or high range water reducers as indicated during the interviews. The agency specifications permit a higher slump for mixes with these admixtures. For example, WSDOT's specifications indicate that the "maximum slump limit can be increased an additional two inches" and the Navy specifies that the maximum "slump may be increased to 7 inches" for mixes with high range water reducers [14][15]. The air content test is especially important in determining the expected resistance of the concrete to freezing and thawing. The unit weight and yield test does not appear to be as useful as the other tests.

5.4.2 Recommendations for Modifications to Job Site Procedures: The research did not reveal the requirement for any significant modifications to job site procedures and testing. However, it seems that the fine aggregate gradation should be checked more often during a project as variations even within the standard specification range will cause variations in the testing and can adversely affect both the short term and long term performance of the concrete.

5.4.3 Areas Requiring Further Work:

Both the interviews and laboratory testing conducted for this research

demonstrate the requirement for further investigation in the areas of job site procedures and factors affecting the tests. Further observation of job site procedures and additional laboratory testing is needed to further assess the applicability of the initial tests.

Testing at the job site should be observed to evaluate how inspectors are interpreting the specification requirements, especially the test procedures. An evaluation would be helpful in assessing the most important aspects of the procedures to provide insight into the possible variabilities associated with field testing. A project should be studied from start to finish to observe how consistent the testing procedures are performed throughout the life of a project. Slump, air content, unit weight and yield test data should be correlated to strength results for the project to analyze actual relationships between these factors in the field.

Additional laboratory testing should be performed to assess other factors in addition to fine aggregate gradation: variations in mix proportions, type of cement, fineness of cement, temperature, aggregate specific gravity, and admixtures. In particular, testing with air entraining admixture and/or high range water reducer would be especially useful to assess slump and air content testing as these admixtures are currently being used in the field. It should be noted that during the interviews, the comments suggested that the application of the slump test for mixes with high range water reducers may be questionable. More testing data is needed to evaluate the relationships between the test results and expected performance especially the unit weight and yield test which is not currently being used as acceptance criteria.

Further observation and evaluation of job site procedures as well as additional laboratory testing should help to isolate some of the testing variabilities and provide more test data to clarify the relationships of the factors affecting the tests. Additional work in these areas should provide a better understanding of the tests and their use as indications of expected performance in the field.

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APPENDIX A
Interview Questions

U. S. Navy Construction Office in Everett, Washington and
the Washington State Department of Transportation, District 1 Office in Seattle

1. What specification values are employed by the agency for batching, mixing, transporting and placing concrete for a project, i.e. minimum cement content, maximum water content, aggregate weights, minimum mixing time at the plant, drum revolutions of the truck mixer, maximum time between batching and discharge, etc.

2. What are the agency's typical specification requirements for initial tests including slump, air content, and yield for ready-mixed concrete delivered to the project site?

3. How are the tests performed:
 - a. Who performs the tests: agency, separate testing agency, or contractor?
 - b. What procedures are employed: standard specifications, methods, equipment, or agency modifications?

4. What is the typical scenario for testing as the concrete is delivered to the project site:
 - a. When are the tests taken after arrival of the concrete truck?
 - b. What are the time limits for conducting the tests?
 - c. Who is represented at the site for the test, i.e. agency's representatives, contractor's representatives, supplier's representatives (other than the driver)?

5. How are the initial test results used by the agency:
 - a. What are the criteria for acceptance or rejection of the load?
 - b. What type of information is provided as feedback to the supplier?
 - c. Under what conditions if any may concrete be accepted that does not meet the test requirements?

6. Lab experiments of this research project looked at fine aggregate gradation and water requirement as factors affecting the test results. For example, in moving from the center of the ASTM gradation specification to the fine side, the slump decreased by 2 3/4 inches. In this case the water requirement had to be increased by 21 lbs./cu. yd. to bring the slump back up to 4 inches.
 - a. To what extent does the agency consider the affect of gradation variation within the specification range on specified slump?
 - b. What limitations are placed on the addition of water at the job site to bring slump up to the specified range?
 - c. What are the agency's procedures for retesting a truck load?

7. How are the tests related to expected performance:
 - a. Short term performance: uniformity, consistency, and workability for effective consolidation and placement without segregation?
 - b. Long term performance: strength and durability?
 - c. To what extent are the tests used as a reflection of expected performance:
 - (1) Are they used strictly for acceptance / rejection or,
 - (2) Is there a graduated pay scale, i.e. concrete is out of the slump range, but reimbursed at less than the bid price as a penalty; also, a bonus payment is provided for concrete that is consistently within the specification range for

slump, air content, yield, etc.?

8. Does the agency consider the tests adequate enough indicators of expected performance to accept or reject the load of concrete? If not, what are the limitations of the tests for your applications?

Concrete Technology Corp. of Tacoma, Washington

1. What specification values are employed by the company for batching, mixing, and placing concrete, i.e. minimum cement content, maximum water content, aggregate weights, minimum mixing time at the plant, maximum time between batching and discharge, etc.
2. What are the company's typical specification requirements for initial tests including slump, air content, and yield for structural concrete?
3. How are the tests performed:
 - a. Who performs the tests: in-house personnel, or separate testing agency?
 - b. What procedures are employed: standard specifications, methods, equipment, or company modifications?
4. What is the typical scenario for testing the concrete:
 - a. When are the tests taken after mixing?
 - b. What are the time limits for conducting the tests?
 - c. Who is represented at the test, i.e. company's representatives, testing agency's representatives? customer's representatives?
5. How are the initial test results used by the company:
 - a. What are the criteria for acceptance or rejection of the concrete batch?
 - b. What type of information is provided as feedback to the plant operator?
 - c. Under what conditions, if any, may concrete be accepted that does not meet the test requirements?

6. Lab experiments of this research project looked at fine aggregate gradation and water requirement as factors affecting the test results. For example, in moving from the center of the ASTM gradation specification to the fine side, the slump decreased by 2 3/4 inches. In this case the water requirement had to be increased by 21 lbs./cu. yd. to bring the slump back up to 4 inches.

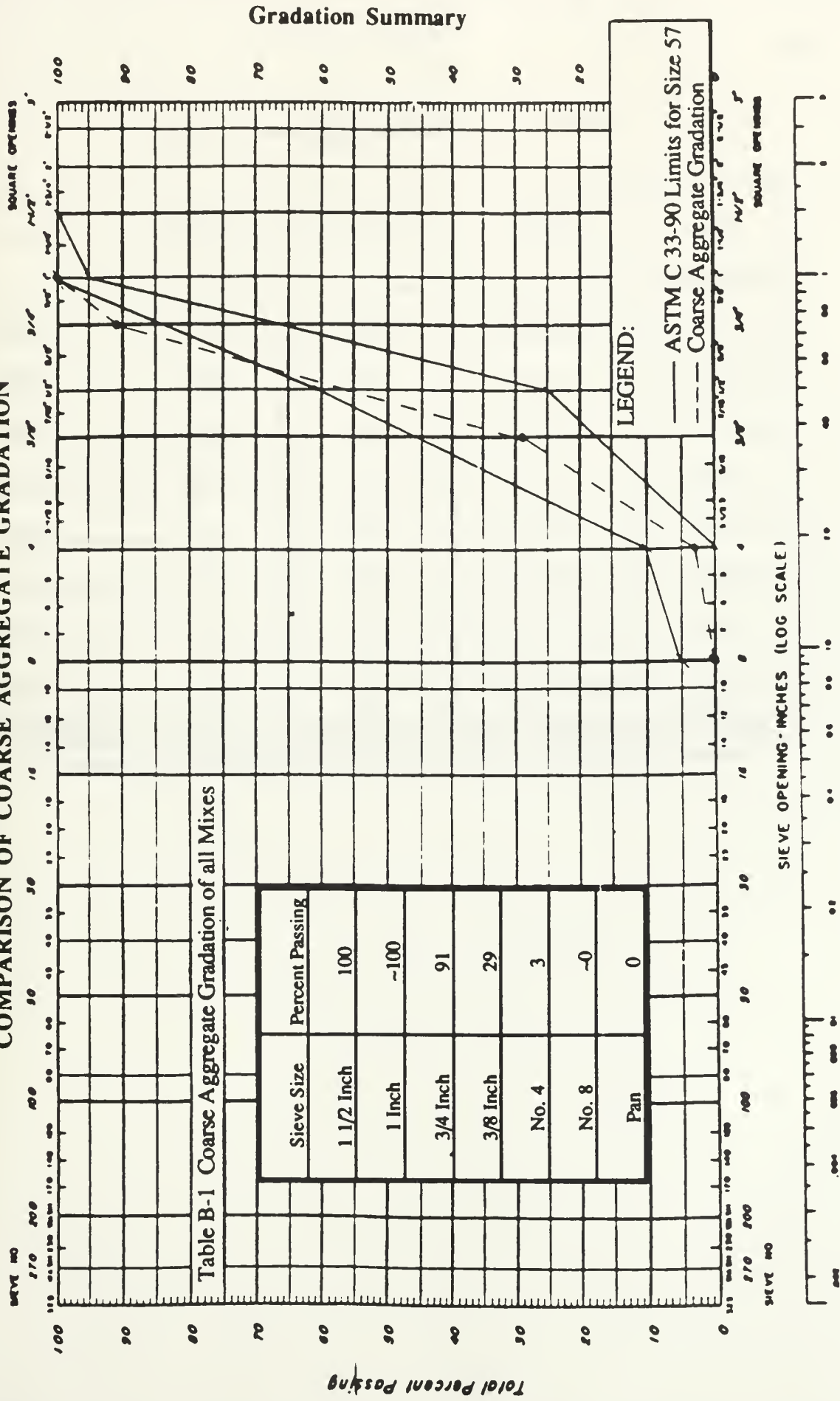
- a. To what extent does the company consider the affect of gradation variation within the specification range on specified slump?
- b. What limitations are placed on the addition of water to bring slump up to the specified range?
- c. What are the company's procedures for retesting a batch?

7. How are the tests related to expected performance:

- a. Short term performance: uniformity, consistency, and workability for effective consolidation and placement without segregation?
- b. Long term performance: strength and durability?
- c. To what extent are the tests used as a reflection of expected performance:
 - (1) Are they used strictly for acceptance / rejection or,
 - (2) Are alternative procedures employed by the company, i.e. concrete is out of slump range, but later strength tests on hardened concrete meet specifications so customer accepts product.

8. Does the company consider the tests adequate enough indicators of expected performance to accept or reject the concrete? If not, what are the limitations of the tests for your applications?

AGGREGATE GRADING CHART
COMPARISON OF COARSE AGGREGATE GRADATION



U. S. STANDARD SIEVES - ASTM DESIGNATION E 11-39

Figure B-1 Comparison of Coarse Aggregate Gradation

Table B-2 Fine Aggregate Gradation for each Mix

Sieve Size	Control Mix	Mix 1 (1)	Mix 2 (2)	ASTM Specification
3/8 Inch	100	100	100	100
No. 4	~100	100	95	95 - 100
No. 8	90	100	80	80 - 100
No. 16	70	85	50	50 - 85
No. 30	44	60	25	25 - 60
No. 50	18	30	10	10 - 30
No. 100	4	10	2	2 - 10
Pan	0	0	0	-
Fineness Modulus	2.74	2.15	3.43	2.3 - 3.1

Notes: (1) Gradation set at maximum ASTM C 33-90 limit for Mix 1-Initial and Mix 1-Added Water.

(2) Gradation set at minimum ASTM C 33-90 limit for Mix 2-Initial and Mix 2-Rebatch.

APPENDIX C

Sample Mix Design Calculations

The mix designs were proportioned according to the absolute volume method [3][6]. Design parameters used in the proportioning were based on standard specifications and previous laboratory testing.

Design parameters are summarized as follows:

- Slump:	4 inches.
- Compressive strength:	5000 PSI
- Air content:	~1.75%, non air entrained
- Water - cement ratio:	0.50
- Cement specific gravity (SG)	3.15
- Admixtures:	None
- Aggregate properties:	
--Coarse aggregate (1):	
Shape:	Rounded
Bulk specific gravity (BSG) (Saturated Surface Dry (SSD))	2.68 (2)
Absorption:	1.0% (2)
Stockpiled moisture content:	0.6% (3)
Dry rodded weight:	108 lbs./cu. ft.
Nominal maximum size aggregate:	7/8 inch
-- Fine aggregate (4):	
BSG(SSD):	2.60 (5)

Fineness Modulus (FM):	2.71 (5)
Absorption:	1.8% (5)
Stored moisture content:	3.32% (6)

Notes:

- (1) Coarse aggregate used in mixes was from stockpile in laboratory bin.
- (2) Values for coarse aggregate were obtained from tests performed in previous laboratory testing.
- (3) Moisture content was determined per ASTM D 2216-92.
- (4) Fine aggregate used for control mix was from barrel located in storage area near the laboratory.
- (5) Values for fine aggregate were obtained from previous laboratory testing on sand from bin located in laboratory.
- (6) Moisture content determined per ASTM D 2216-92 on sand of note (4).

Sample mix design calculations for the control mix:

Design parameters as described in previous paragraph.

Batch quantities at saturated surface dry (SSD) condition in lbs./cu. yd. of concrete:

Water content:

Table 7-6 of PCA manual [6]: water content = $(340+325)/2 - 45 = 287.5$ lbs./cu. yd. Note: 45 lbs. subtracted for rounded aggregates [6].

Based on previous trial mix that resulted in slump of 6 inches, water content reduced by 20 lbs./cu. yd. to bring slump back to 4 inch requirement [6].

Revised water content = $287.5 - 20 = 267.5$ lbs./cu. yd.

Cement content:

Cement content = water content / (water - cement ratio) = $267.5/0.50 =$
535.0 lbs./cu. yd.

Coarse Aggregate:

Coarse aggregate content = dry rodded weight of coarse aggregate * volume of coarse aggregate / unit volume of concrete.

Table 7-5 of PCA manual [6]: volume of coarse aggregate / unit volume of concrete = 0.66.

Coarse aggregate content = $108 \text{ lbs./cu. ft.} (27 \text{ cu. ft./cu. yd.}) * 0.66 =$
1924.6 lbs./cu. yd.

Air content:

Table 7-6 of PCA manual [6]: entrapped air ~ 1.75%.

Air content = **1.75%**.

Fine Aggregate:

Fine aggregate volume = 27 cu. ft./cu. yd. of concrete - absolute volume of known ingredients.

Absolute volume of known ingredients = known weight/(SG*unit weight of water)

Absolute volume of known ingredients:

Water = $267.5 \text{ lbs.}/(1.0*62.4 \text{ lbs./cu. ft.}) = 4.29 \text{ cu. ft./cu. yd. of}$
 concrete.

Cement = $535.0/(3.15*62.4) = 2.72 \text{ cu. ft.}$

Coarse Aggregate = $1924.6/(2.68*62.4) = 11.51 \text{ cu. ft.}$

Air = $27 \text{ cu. ft.} * 1.75\% = 0.47 \text{ cu. ft.}$

Fine aggregate volume = $27 - 4.29 - 2.72 - 11.51 - 0.47 = 8.01 \text{ cu. ft.}$

Fine aggregate content = volume * BSG(SSD)*unit weight of water =

8.01 cu. ft./cu. yd.*2.60*62.4 lbs./cu. ft. = **1299.5 lbs./cu. yd.**

Batch quantities at SSD in lbs./cu. ft. of concrete:

Water content = (267.5 lbs./cu. yd.)/27 cu. ft./cu. yd. =

9.90 lbs./cu. ft.

Cement content = (535.0 lbs./cu. yd.)/27 cu. ft./cu. yd. =

19.81 lbs./cu. ft.

Coarse aggregate content = (1924.6 lbs./cu. yd.)/27 cu. ft./cu. yd. =

71.28 lbs./cu. ft..

Fine aggregate content = (1299.5 lbs./cu. yd.)/27 cu. ft./cu. yd. =

48.13 lbs./cu. ft.

Corrections for aggregate moisture conditions:

Additional mix water required = coarse aggregate weight*(absorption - stockpile moisture content) + fine aggregate weight *(absorption - moisture content). Note: Moisture content of fine aggregate was 0.0% as it was in the oven dry condition prior to mixing.

Additional mix water required = 71.28 lbs./cu. ft.*(1.0%-0.6%) + 48.13 lbs./cu. ft.*(1.8%-0.0%) = 0.29 +0.86 = **1.15 lbs./cu. ft.**

Corresponding reduction in coarse aggregate content =

71.28 - 0.29 = 70.99 ~ **71.00 lbs./cu. ft..**

Corresponding reduction in fine aggregate content =

48.13 - 0.86 = **47.27 lbs./cu. ft..**

Increased water content = 9.90 + 1.15 = **11.05 lbs./cu. ft.**

Correction for free and absorbed water on coarse aggregate:

Weight of free and absorbed water on coarse aggregate from presoaking for about 22 1/2 hours prior to mixing was measured at 1.18 lbs.

Decreased water content = 11.05 - 1.18 = **9.87 lbs./cu. ft.**

Final control mix batch quantities in lbs./cu. ft. of concrete:

Water content: 9.87 lbs./cu. ft.

Cement content: 19.81

Coarse aggregate content: 71.00

Fine aggregate content: 47.27

Mix design calculations for the other mixes were performed in a similar manner.

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