Quality control testing for concrete during construction for a nuclear project

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Abstract. This paper presents the results of an oversight evaluation of qualification and production testing of concrete materials and concrete for a nuclear project in United States. The testing requirements for qualification of concrete materials, including cement, fly ash, fine and coarse aggregates, admixtures, were in accordance with American Concrete Institute (ACI) ACI 349, ASME/ANSI and ASTM standards. Concrete was produced from a ready mixed plant and delivered to the site in truck mixer/agitator trucks. Qualification tests for selecting concrete mix proportions for the 4000 psi design compressive strength concrete were performed, using the proposed concrete materials, in accordance with the specifications. Qualification tests for aggregates included alkali-silica reactivity, Los Angeles abrasion, gradation, minus 200 material, moisture content, and deleterious materials, and were performed in accordance with ASTM C33 requirements. Quality control tests for concrete during production included slump (ASTM C143), air content (ASTM C231), unit weight (ASTM C157), and compressive strength (ASTM C39). Minimum ACI 349/ASME/ANSI N45.2.5 testing frequencies for concrete constituents and concrete are also described. Results of the QC tests including an evaluation of the 7-day and 28-day compressive strength tests are presented.

1 Concrete Materials and Qualification Testing

1.1 Concrete Aggregates

Project Specification stipulated that all aggregates conform to ASTM C33, Standard Specification for Concrete Aggregates including the following requirements:

1.1.1 Coarse Aggregate:

Number 57 or 1-inch nominal maximum size

LA abrasion (ASTM C131) weight loss: 45% at 500 revolutions

Alkali-Silica Reactivity expansion (ASTM C1260/C1567): 0.1% at 16 days

Material passing No. 200 sieve (ASTM C117): 2% maximum

1.1.2 Fine aggregate

Alkali-Silica Reactivity expansion (ASTM C1260/C1567): 0.1% at 16 days

Limit for Clay Lumps and Friable Particles: 8%

Percent Passing # 50 Sieve: 25-40% (was relaxed provided the fineness modulus was within 0.20 of the average fineness modulus).

From the beginning of the project, it was recognized that the available local fine and coarse aggregate materials grading, including fines, were generally deficient in meeting ASTM C33 specification requirements for gradation and percent finer than 200 sieve limits for fine aggregate. For fine aggregate, the allowable amount passing the No. 50 sieve was relaxed to 40 (vs. 30 by ASTM C33) percent, with a provision that the fineness modulus (FM) of the fine aggregate would be maintained within 0.20 of the average FM (ten consecutive tests).

The aggregates sources were approved for use after the materials were tested for petrographic analysis and alkali-reactivity tests. Fly ash and silica fume were added into concrete mixture to mitigate alkali-reactivity and to enhance the durability of the concrete.

1.2 Cement

The cement conformed to an ASTM C150 Type I/II.

1.3 Fly Ash

Fly ash conformed to ASTM C618 Class C. Fly ash in amounts of approximately 20% by weight of cement replacement was used to mitigate sulfate attack and to improve durability of the concrete.

1.4 Silica Fume

Silica fume conformed to ASTM C1240. Silica fume, in amounts of approximately ten percent by weight of cement replacement, was used to improve durability of concrete.

1.5 Admixtures

Air-entraining admixture conformed to ASTM C260. The air content requirements for concrete were 5-7.5%.

A water reducing admixture, conforming to ASTM C494 Type D and conforming to ASTM C94 Type F, were added at the batch plant to each concrete batch for workability. The slump requirements were 5-8 inches.

1.6 Concrete Design Mix

The concrete design mix proportions for Class (minimum design compressive strength 4000 psi at 28 days) were established in accordance with ACI 318 such that the

average compressive strength of the design mix was 5200 psi or more at 28 days.

2 Concrete Plant

Concrete was delivered from a ready-mix concrete plant, located approximately 2 miles from the project. The concrete plant was operated under a Quality Control Plan that meets State DOT certification.

Transit/mixer delivery trucks, used to transport ready-mix concrete, also met the State DOT certification.

2.1 Production Testing

Testing of concrete materials, including cementitious materials and aggregates during production was performed in accordance with the current industry standards as presented in Table 1:

Table 1. Concrete Material Test Frequency

	Specification	Industry Standards [2]		
MATERIAL/TEST	Requirements	ACI 349	ACI 359/NQA-1	ANSI N45.2.5
Cement				
1. Chemical Composition	Each shipment	Mfr's CMTR with Each Shipment	Each 1,200 tons	Each 1,200 tons
2. Loss on Ignition	Not required		Not required	
3. Insoluble Residue	Not required		Not required	
4. Normal Consistency	Not required		Not required	
5. Air Content of Mortar	Not required		Not required	
6. Finess	Each shipment		Each 1,200 tons	
7. Autoclave Expansion	Each shipment		Each 1,200 tons	
8. Compressive Strength	Each shipment		Each 1,200 tons	
9. Vicat Initial Set Time	Each shipment		Each 1,200 tons	
Silica Fume				
SiO_2	Not required	Mfr's CMTR with Initial Shipment	Not mentioned	Not mentioned
Moisture Content	Not required			
Loss on Ignition	Each shipment			
Oversize	Each shipment			
Strength Activity Index	Each shipment			
Specific Surface	Not required			
Flyash				
$SiO_2 + Al_2O_3 + Fe_2O_3$	**[1]**	Mfr's CMTR with Initial Shipment	Each 2,000 tons	Each 200 tons
SO_3	Not required		Not required	
Moisture Content	Not required		Not required	
Loss on Ignition	**[1]**		Each 400 tons	
Fineness	**[1]**		Each 400 tons	
Strength Activity Index	**[1]**		Not required	
Autoclave Expansion	**[1]**		Each 2,000 tons	
Air-Entraining Agent				
Infrared Analysis	Each shipment	Each shipment	Each shipment	Each shipment
pH		Mfr's C of C		Not required
Residue by Oven Drying		Mfr's C of C		Not required
Water-Reducing Agents				
Infrared Analysis	Each shipment	Each shipment	Each shipment	Each shipment
Specific Gravity	Each shipment	Mfr's C of C	Each shipment	Not required
Residue by Oven Drying	Each shipment	Mfr's C of C	Each shipment	Not required
Chloride Content	Not required	Mfr's C of C	Not required	Not required
Fine Aggregate				
Gradation	Every 3 days	Daily	Each 2,000 yds	Daily
Finer than #200 Sieve	Every 3 days	Daily	Each 2,000 yds	Daily
SG & Absorption	Annually	Not required	Semiannual	Not required
Organic Impurities	Monthly	Initially	Each 2,000 yds	Weekly
Alkali Reactivity	Annually	Initially	Not required	Semiannual
Petrographic Analysis	**[3]**	Not mentioned	Semiannual	Not required
Coarse Aggregate				
Gradation	Every 3 days	Daily	Each 2,000 yds	Daily
Finer than #200 Sieve	Every 3 days	Daily	Each 2,000 yds	Daily
SG & Absorption	Annually	Not required	Semiannual	Not required

MATERIAL/TEST	Specification	Industry Standards [2]		
	Requirements	ACI 349	ACI 359/NQA-1	ANSI N45.2.5
LA Abrasion	Annually	Initially	Semiannual	Semiannual
Alkali Reactivity	Annually	Initially	Not required	Semiannual
Petrographic Analysis	**[3]**	Not mentioned	Semiannual	Not required

[1] *Manufacturer's CMTR with each shipment and designated tests with initial and every other shipment.*

[2] *ACI 359 applies to reactor containment and ACI 349 applies to all other power structures. ANSI N45.2 was adopted by NRC Regulatory Guide 1.94. ANSI N45.2.5 has been superseded by NQA-1 which currently references ACI 359 concrete material testing frequencies.*

[3] *Test is only required when aggregate sources change or there is a significant change in annually-required test results. 4) No cost since fine and coarse aggregate are tested together.*

2.2 Sieve Analysis Test Methods

ASTM C136 and AASHTO T27 are standard test methods for sieve analysis of fine and coarse aggregates. Both ASTM C136 and AASHTO T27 test methods, which are similar in scope, are used to determine compliance with the grading requirements and to provide necessary control on the production of aggregates and concrete mixtures containing the aggregates. It includes the minimum sample sizes for testing, and the maximum weight of the material retained on a sieve for testing fine and coarse aggregates. ASTM C136 and AASHTO T27 limit the quantity of material on a given sieve so that all particles have opportunity to reach sieve openings a number of times during the sieving operation, as reproduced below in Table 2:

Table 2. ASTM C136 and AASHTO Test Sample Size and Allowable Material Retained on Sieves for Fine and Coarse Aggregates

Reference	Sieve Opening inches (mm)	Allowable Material Retained	Test Sample Size for Fine and Coarse Aggregate	Remarks
8-inch Sieve	1 (25)	1800 g	10,000 g	ASTM recommends mechanical shaker for >20 kg sample and for fine aggregate samples
	3/4 (19)	1400 g	5, 000 g	
	1/2 (12.5)	890 g	2, 000 g	
	3/8 (9.5)	670 g	1, 000 g	
	No.4 (4.75)	330 g		ASTM recommends adding intermediate sieves to prevent overload
12-inch Sieve	1 (25)	4200 g	10, 000 g	ASTM recommends 12-inch sieve for coarse aggregate
	¾ (19)	3200 g	5,000 g	
	½ (12.5	2100 g	2,000 g	
	3/8 (9.5)	1600 g	1,000g	
	No. 4 (4.75)	800 g		

For the fine aggregate, ASTM requires a 300g minimum sample weight, while AASHTO T27 has no minimum limit. The precision statement for the ASTM C136 standard is based on the AASHTO test data which used 500g test samples. USBR Concrete Manual (Reference 2) recommends the fine aggregate sample size according to FM of the material. For fine aggregate FM >2.5, the recommended test sample size is 400 to 1000 g (Appendix H).

2.2.1 Aggregate Tests

The fine and coarse aggregate gradation tests were performed in accordance with ASTM C136 and AASHTO T27. During production several non-conformances were reported, where the weight of material retained on individual sieve exceeded the ASTM C136 requirements: 200 grams for fine aggregate sieves #16, #30 and #50, 800 grams for coarse aggregate sieve #4, and 2100 grams for coarse aggregate ½ inch sieve. A summary of the aggregates test data is presented in Table 3 and 4. The sieve analysis for the aggregates was based on the following:

1. 12-inch sieves were used for testing coarse aggregate. Coarse aggregate samples were split into 2 or 3 portions, and an intermediate sieve 3/8 inch was used between ½-inch and No.4 sieves.
2. 8-inch sieve and 12-inch sieves were used for testing fine aggregate.
3. A mechanical sieve shaker was used for testing both the fine and coarse aggregates.

2.2.2 Fine Aggregates Tests

Sample Size: The sample size for fine aggregate testing ranged from 431g to 1071g. Two samples exceeded the 1000g weight limit.

Sieve Analysis and Gradation results: The sieve analysis and gradation was performed using 8-inch sieve, and a mechanical shaker. Due to smaller sieve and large sample size, the amount retained on #16, #30, and 50 sieves exceeded the ASTM C136 limit (200g), in 10 out of 30 tests as indicated below:

Table 3. Fine Aggregate Test Summary

Tests Sample Size	Tests	Non-Conforming
431 - 600 g	11	0
601 – 800 g	8	2
801 - 1000 g	8	5
1001 – 1072 g	3	3
Total	**30**	**10**

The base fineness modulus (FM) for fine aggregate was 2.65. Based on a 0.20+/- FM variation in FM, the acceptable FM range during production was 2.45 and 2.85

2.2.3 Coarse Aggregates Tests

Sample Size: The sample size for coarse aggregate testing ranged from 10 kg to 12.4 kg. The sample size was in compliance with the ASTM C136 minimum weight (10 kg) requirement.

Sieve Analysis and Gradation: The sieve analysis and gradation was performed using 12-inch sieve and a mechanical shaker. As shown in Table 4, non-conforming (excessive weight retained on ½-inch and No.4 sieves) tests were found:

Table 4. Coarse Aggregate Test Summary

Sieve Number	Tests	Non-Conforming	Remarks
1/2-inch	54	20	The max. amount retained varied from 2140g to 2418g (2% to 15% above the 2100g limit)
No. 4 Sieve	54	38	The max. amount retained varied from 813g to 1822g (4% to 10% above the 800g limit)
3/8-inch **[1]**	54	0	The max. amount retained varied from 604g to 1420g (within the 1600g limit)

[1] To mitigate the non-conforming conditions, 3/8-inch in accordance ASTM C136 Section 8.3.1 recommendations was inserted. For all (54) tests, the weight retained was in compliance with the 1600g limit per ASTM C136 (see Table 2).

Table 5 presents the results of the periodic tests on fine and coarse aggregates during production. It includes the number tests for fine and coarse aggregates and the non-conforming tests including deviations from maximum weight retained and respective sieve sizes.

Table 5. Fine and Coarse Aggregates Tests Summary

Period	Fine Aggregate Tests			Coarse Aggregate Tests			Remarks
	Lab 1	Lab 2		Lab 1	Lab 2		
	Total	Total	Non-conforming	Total	Total	Non-conforming	
2011	12	30	10 [a]	16	54	10 [b] 38 [c]	Gradation tests were acceptable

[a] Retained weight exceeded 200g (#16, #30, #50)
[b] Retained weight exceeded 2100g(1/2 inch sieve)
[c] Retained weight exceeded 800 g (No. 4 sieve)

2.2.4 Concrete Field Tests

Tests for concrete upon delivery, included: slump, air content, unit weight, casting cylinders for compressive strength, and subsequent testing.

Slump and air contents tests were performed at the truck discharge, every 50 cubic yards.

The slump and air content ranges were within the specified requirements. The workability of the concrete was adjusted in the field with dosage of a high range water reducing (HRWR) admixture, additional mixing and testing. Concrete failing to meet the slump and air content requirements was rejected. There were several instances when low air concrete batches were rejected.

The average 7 day and 28-day compressive strength, for the construction periods, are shown below:

	7-day	*28-day*
For the entire Concrete	*5005 psi*	*6731 psi*

The minimum 28-day design compressive strength was 4000 psi. The average 28-day compressive strength for the tests was 68% higher than the required design strength (4000 psi).

Quality Control

During construction, several quality issues and deviation from specification requirements were identified, which required engineering resolution. Some of the issues including proposed resolutions are presented in Table 6:

Table 6. Quality Control Deviations during Production and Proposed Resolutions

Specification Requirement	Deviation	Resolution
Compressive Strength shall be between 3000-4000 psi range	5 tests out of 16 tests strength exceeded 4000 psi	Requires Engineer's evaluation
Batching Tolerance shall conform to ASTM C94	26 batches out of 100 exceed the allowable tolerance for cement (1%)	Acceptance of the deviation should be based on the 28 day compressive strength. A full time inspector at batch plant is required to verify compliance.
Batch ticket shall include quantities of all concrete materials	Incomplete Batch Ticket	A full time inspector at batch plant is required to verify compliance.
Concrete shall be discharged within 90 minutes of batching	One batch is discharged 105 minutes after batching	A full time inspector at batch plant is required
Minus 200 material(1.5%) in coarse aggregate	Several tests exceed the limit (range: 1.7-1.9%)	Wash aggregates for compliance. Also relax the limit to 2% if the fines are free of clay or shale.
Fineness modulus(FM) of sand during production shall be with +/- 0.2 of the base FM	Sand gradation is such the base FM design tolerance is exceeded	For low production volumes, FM should be the average value based on 10 consecutive tests
Air content of concrete shall be within 1.5% of the specified value	Individual batches with inadequate or lower air than specified	Use average air content based on 10 consecutive tests for acceptance
Concrete slump shall not exceed by 1 inch of the specified value	The actual slump exceeds the specified values by up to 2 inches	Allow concrete mixing for additional 50 revolutions to lower the slump
The total number of truck revolutions upon concrete delivery shall not exceed 300	Total revolutions are exceeded but slump and air content of the batch are within tolerances	Accept the batch as-is
ASTM C33 Limit on Friable particles in fine aggregate	Friable particles in fine aggregate exceed 7%	Allow increase in friable particles provided the alkali-silica reactivity (ASTM C1567) expansion is < 0.1%
ASTM C33 Gradation Limits	The amount passing the individual sieve is 2-5 % higher than specified	Allow the deviation, provided the FM (average 10 tests)is within 0.20 of the base FM.

3 Conclusions

Based on a review of the aggregate tests and concrete placement data at nuclear project, the following conclusions were made:

The fine aggregates sieve test anomalies, described above, were acceptable since the gradation tests and fineness modulus were in compliance with the specification. The fineness modulus of the overloaded (sieve) tests was 2.68 and was similar to the average FM (2.64) for the entire testing period.

The coarse aggregates sieve overloaded tests, described above, were acceptable, based on the use of the 3/8-inch intermediate sieve. The overall coarse aggregate gradations were comparable with the entire test data.

The concrete field tests reports confirmed that concrete delivery, including slump, air content, and truck revolutions were also in compliance with the requirements of the Project Specification.

The 28-day compressive strength of concrete met and exceeded the acceptance criteria of the Specification, The average 28 day compressive for all the placements was 6731 psi and no individual strength test was less than 4,000 psi.