Report to

DANIEL INTERNATIONAL CORPORATION
Strawn, Kansas

WOLF CREEK GENERATING STATION
REACTOR BASEMAT CONCRETE
SECOND TESTING PROGRAM

by

J. J. Shideler

Submitted by

CONSTRUCTION TECHNOLOGY LABORATORIES
A Division of the Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077

February 27, 1979

construction technology laboratories

a Division of the PORTLAND CEMENT ASSOCIATION

5420 Old Orchard Road, Skokie, Illinois 60077 • Area Code 312/966-6200

POOR ORIGINAL

February 27, 1979

Mr. Glenn L. Koester
Vice President - Operations
Kansas Gas and Electric Company
Wichita, Kansas

Re: Wolf Creek Generating Station
Reactor Basemat Concrete
Second Testing Program

Mr. Koester:

We have completed the testing program outlined in Mr. W. R. Waugh's letter of January 12, 1979, to you and authorized by your letter of January 19, 1979, to Mr. Hitt.

The attached reports together with this covering letter comprise our report.

The Petrographic Services Report (Appendix A) gives results of:

1. Microscopic examination of the cylinder remnants to determine:
   - general quality of the concrete,
   - paste-aggregate bond,
   - evidence of deleterious reactions.

2. Compressive strength of 2-in. cubes cut from the bottom remnants of previously tested 6x12-in. cylinders, and comparison of cube and cylinder strengths.

3. Air content determinations by the method described in ASTM C-457.

4. Deviations from planeness of the bottoms of the tested cylinders.

The Chemical Services Report (Appendix B) gives results of cement content determinations on the designated cylinder remnants, and compressive strengths of ASTM C-109 cubes for four cements designated as CUT-15, -18, -20, and -21.

Principal conclusions are given on the first page of each of these reports.

POOR ORIGINAL

Of major interest is the relevance of the strength of 2-in. cubes cut from tested cylinders in estimating the strength of the cylinder and the in-place basemat concrete.

The attached bibliography "Effect of Size and Shape of Specimen on the Compressive Strength of Concrete" (Appendix C) gives principal references on this subject, and some of the papers list as many as 128 additional references. Much thought and research has been given to this subject, but I do not find any reference to the relationship between cubes sawed from tested cylinders and the strength of the cylinder.

I have reviewed the conclusions of several of the authorities on the subject in the attached summary "Ratio of Strength of 2-in. Cubes to 6x12-in. Cylinders" (Appendix D). The general conclusion is that the strength of cubes should be reduced by a factor of about 0.80 to equal the strength of 6x12-in. cylinders. In all cases, the data are based on molded cubes and cylinders.

The attached memorandum "Possible Causes of Retrogression of Strength of Concrete" (Appendix E) lists and discusses several possible causes of retrogression of strength. None of these apply to the composition of the subject concrete or to its environmental exposure. In my opinion retrogression of strength of the subject concrete can be totally discounted.

It is my belief that the erratic reported compressive strengths of the 90-day cylinders, both with respect to sequential and companion cylinders, was due to some combination of improper testing procedures. The most probable circumstances include the large number of cylinders tested in a given day; improper capping of cylinders, possibly due to temperature control of capping compound or contamination by oil from the capping jig or plate, sometimes "frozen" head of the testing machine, and lack of proper alignment of cylinders in the testing machine.

Sincerely,

J. J. Shideler

J. J. Shideler, Director
Administrative and Technical Services

JJS/md
CT-0407

Copy to-
W. E. Kunze
E. Hognestad
L. M. Meyer
D. H. Campbell

1050 219

APPENDIX A

PETROGRAPHIC SERVICES REPORT

Petrographic Services Report

Project No.: CT-0407 Date: February 27, 1979

Re: Daniel International Corporation

Remnants of 48 6x12-in. concrete cylinders, previously compression tested at age 90 days, and four samples of cement were delivered December 13, 1978, to the Construction Technology Laboratories from Daniel International Corporation for additional testing and examination relating to a reported problem of low 90-day cylinder strengths. The concrete represents materials used in a nuclear reactor basemat at the Wolf Creek Generating Station. K. G. & E./Daniel have certified that concrete cylinder remnants delivered to PCA are representative of concrete in the subject basemat. The present report covers compression tests on 2-in. cubes cut from some of the received cylinders, petrographic examinations, and determination of air contents of selected cylinders. This investigation was directed primarily to those cylinders that had reported strengths of less than the specified 5000 psi at age 90 days.

Findings and Conclusions

1. Compressive strength tests of 2x2-in. cubes cut from previously tested 6x12-in. concrete cylinders indicate an average corrected strength of 6690 psi, with a range of 5340 to 7930 psi. These reported values are 80 percent of actual measured compressive strengths of the cubes.

2. Measured air contents ranged from 4.0 to 5.9 percent, averaging 4.9 percent.

3. The paste is hard and firmly binds the aggregates.

4. No evidence of inadequate mixing was observed.

5. No evidence of paste-aggregate reactions was observed on freshly broken or lapped surfaces, or in thin sections.

6. These data strongly suggest that the concrete is of high quality, the materials being properly proportioned, batched, and mixed.

Test Methods

After initial photography of all received cylinder remnants, those from which one or more 2-in. cubes could be cut were listed. Each cylinder was examined and the exposed fracture

surface, from the previous compression test, was described. A square was laid along the side of the cylinder and across the bottom, and using a depth gauge-vernier caliper, the unevenness of each remnant cylinder bottom was measured and recorded.

Cylinders from which cubes were to be cut were selected in consultation with W. G. Eales of K. G. & E and W. R. Waugh, consultant (see Mr. Waugh's letter of January 12, 1979 to G. L. Koester and Mr. Koester's letter of January 19 to W. E. Hitt). The cylinders selected, in most part, represented those giving low strengths at age 90 days. Thirteen of these had strengths below 5000 psi, and six below 4500 psi.

From each of the 18 cylinders designated to supply a 2x2-in. cube, a longitudinal side piece was cut and the cut surface on the body of the cylinder was used as a "reference surface" for the remaining cuts to produce the cube. An arrow indicating the longitudinal direction of each cylinder and the cylinder number were placed on each cube during its preparation. Each piece cut from the cylinder was also labeled with the cylinder number. After the cubes were cut, measurements between center points of opposite top edges and bottom edges were made in order to calculate surface areas. The minimum surface areas were used in the calculation of compressive strengths, after correction of surface areas for those cubes showing slight damage (missing edges or corners) due to sawing. Cube height was also measured. All of the remnants from which cubes were cut were bottom remnants.

The cubes were checked for obvious cracks, using a stereomicroscope and alcohol, then placed in water for at least a 48-hour soak for determination of unit weights. The tops and bottoms of the cubes were lapped to insure smooth surfaces.

Compression testing of the cubes was accomplished in a Southwark-Emery Testing Machine, Serial Number 57271 of 75,000 pounds capacity. The machine was recalibrated immediately following the tests and found to be in compliance with ASTM E74, Standard Methods of Verification of Testing Machines (see attached Calibration of Testing Machine).

After testing, each cube was weighed and placed in an oven at 105°C for 24 hours in order to calculate absorption for use in chemical tests.

Lapped longitudinal sidepieces from 11 remnant cylinders designated by Mr. Waugh (see again Mr. Waugh's letter of January 12, 1979 to G. L. Koester) were used for determination of air contents (ASTM C-457, Standard Recommended Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete) and petrographic examinations (most of which is covered in ASTM C-856, Standard Recommended Practice for Petrographic Examination of Hardened Concrete). Thin sections were prepared by drilling a one-inch

diameter plug from a selected area of each lapped sidepiece; the plug was then sliced and placed on a glass microscope slide with epoxy resin and reduced to a thickness of 25 microns for determination of aggregate and paste mineralogy, and paste microstructure with a transmitted polarized-light microscope. Numerous freshly broken surfaces and the lapped sidepieces were also studied with an ordinary stereomicroscope.

Results and Discussion

Aggregates

Coarse aggregate is crushed limestone of various types (fossiliferous, microcrystalline, sandy, pyritic, with minor amounts of dolomite and clay). Fine aggregate is a natural sand composed of grains of quartz, feldspar (microcline and plagioclase), metaquartzite, and chert. Aggregate dust occurs in trace amounts, indicating properly washed materials.

Aggregate distribution is uniform and no occurrences of segregation were observed (Photograph 1). Aggregates appear properly shaped and distributed, and of moderate hardness. Coarse-to-fine aggregate ratio is approximately 55/45 to 50/50.

No evidence of paste-aggregate reactions was observed on freshly broken or lapped surfaces, or in thin sections.

Paste

The paste contains normal hydration products (primarily calcium silicate hydrate and calcium hydroxide, abbreviated as CH) and is evenly distributed in all samples observed. The paste is hard and firmly binds the aggregates, as indicated by numerous sheared aggregates both on freshly broken surfaces and on those present on the cylinders (as received).

Thin-section data on the concrete pastes are presented in Table 1. Percentages of unhydrated portland cement clinker particles (UPC's) range from 12 to 26 percent of the paste (see example in Photograph 2), the data presented included a reassessment of thin sections from cylinders received in March 1978. UPC's are comprised of normal clinker phases (alite, belite, aluminate, and ferrite) with the ferrite phase being dominant, as expected because it is relatively slow to hydrate. Residual alite (impure C_3S) shows prominent rims, a common feature in most concretes.

Calcium hydroxide (CH) occurs mostly as small irregular, microcrystalline masses in the paste and as narrow aggregate fringes. Blade-form CH is common.

Abundances of UPC's and relative scarcity of CH suggest a moderately low water-cement ratio (w/c) for all the cylinders

examined by thin section. A w/c of 0.45 to 0.50 appears to be a reasonable interpretation.

The amount of unhydrated cement clinker observed is not detrimental to the compressive strength of the concrete. As a matter of fact very high strength concrete generally would have considerably more unhydrated cement clinker than observed in these samples.

Concentrations of UPC's around coarse aggregates were not observed in significant amounts; thus mixing is judged to be adequate.

Fractured Surfaces on Received Cylinders and Mold-Bottom Impressions

The type of fracture surface on the received cylinder remnants was described (Table 2) before preparation of the respective cubes. As Table 2 indicates, most of the cylinder remnants have a strong tendency to display diagonal fracture surfaces as a result of compression testing. A typical diagonal fracture is illustrated in Photograph 3. The diagonal fracture, a departure from the ideal conical fracture, may suggest a problem with the testing machine or procedure. Most broken surfaces on the cylinders expose cross-fractured aggregates.

Measurements of maximum relief on the bottoms of the received cylinders (Table 3) shows considerable variance. The cylinder bottoms are generally uneven with a central, relatively "high" point. Some of the bottom surfaces were warped. The cause of mold warping is not apparent, but its effect was to produce an uneven bottom surface on the concrete cylinder. The effect of the unevenness may have been eliminated by the sulfur capping compound. A plot of 90-day cylinder strengths vs. maximum relief shows no observable correlation (see Fig. 1).

Cube Compression Tests

Cube compressive strengths (corrected) range from 5340 to 7960 psi, averaging 6690 psi, with a standard deviation of 675 psi (Table 4). These reported values are 80 percent of actual compressive strength of the cubes. A plot of corrected cube strengths and 90-day cylinder strengths as a function of cylinder number shows similar patterns of strength variation (see attached plot).

Areas used in calculation were corrected if small portions (edges or corners) of the cubes were missing due to damage in sample preparation. After the cubes were sawed, inspection revealed that cubes from Cylinders 6558 and 6767 were cracked and these were not compression tested.

Air Content

Data from linear traverse (ASTM C-457) indicate a range of air contents from 4.0 to 5.9 percent, averaging 4.9 percent, with a standard deviation of 0.58 percent. These, and other air void data, are given in Table 5, which also shows unit weights and absorptions of cubes for which the cement contents were determined. The range in air contents, although known to have an effect on cylinder strengths, is not of a magnitude to cause the strength fluctuations reported by Daniel. There was no correlation between determined air content and reported compressive strength of cylinders. The volume percent air in voids greater than, or equal to, 114 microns is slightly higher than normal air-entrained concrete, but is judged to have no significance with respect to compressive strength.

D. H. Campbell

D. H. Campbell, Supervisor
Petrographic Services
Technical Services Section

DHC/md
CT-0407

Copy to-
J. J. Shideler
L. M. Meyer

1050 225

POOR ORIGINAL

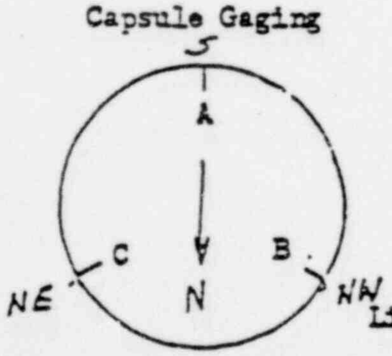
CALIBRATION OF TESTING MACHINE

Machine Data:
Serial No. 57271
Capacity 75 000 LB
Range 75,000 LB

Proving Ring Data:
Ring No. 212
Capacity 50,000 LBS

Indicated Load, lbs	Proving Ring Reading, div	Deflect, div	Temp. Read, °F	Temperature Adjustment	True Load, lbs	Error lbs	Error %
0	4.1		21.8 C				
5000	72.7		22.1 C		5149		-2.9
0	4.0		22.0				
10000							
0	4.65		21.6				
5000	72.7		21.8		5075		-1.5
10 000	13[illegible]		22.2		10008		-0.01
15000	209.4		22.3		150[illegible]4		-0.40
20000	277.1		22.4		20109		-[illegible]
25000	345.0		22.4		25050		-0.3
30000	413.8		22.5		30030		-0.01
40000	550.6		22.6		40053		-0.1
50000	689.0		22.7		50084		-0.2
0	4.8		22.7				
NEEDLE CHECK							
0	4.8						
30000	413.3		22.6		30055		+0.2
30000	413.8				29974		+0.1
0	4.7		22.6				
0	4.7		22.3				
5000	73.1		22.8		5055		-1.1
0	4.7		22.9				

Capsule Gaging



Limits of gaging

Gage	Gage Locat.	Initial Reading	Final Reading	Deflect. at Ult. Load
A	SOUTH	0.026	→	0.028
B	NW	0.029	→	0.031
C	NE	0.026	→	0.028
Avg.	→	0.027	→	0.029

0.002 OK

Operator Jimmie Petrich Calibrator Albert W. J. Hernes Date Jan 30, 1979

David R. [illegible]

1050 226

TABLE 1 - MICROSCOPIC EXAMINATION

(Thin Sections)

POOR ORIGINAL

Cylinder No.	Percent UPC's*	Percent CH**	Miscellaneous
6540	12-15	10-14	Fringe and blade CH** common
6546	16-20	12-15	Blade CH scarce; large inter-paste CH
6551	22-26	10-12	Common, blade CH; trace E**
6558	18-22	10-12	Common, blade CH
6599	22-26	12-16	Common, blade CH
6606	22-26	10-12	Common, blade CH
6659	16-20	10-12	Common, blade CH
6671	22-26	10-14	Voids contain traces of E and CH; common, blade CH
6696	22-26	12-16	Common, blade CH
6767	16-20	10-12	Common, blade CH and carbonation
6785	18-22	12-15	Common, blade CH
- - -	- - -	- - -	- - -
*6444	16-20	12-15	Common, blade CH
*6503	16-20	10-12	Common, blade CH
*6784	12-15	12-15	Common, blade CH
*6850	12-15	12-15	Common, blade CH

*Percentages of the paste estimated by comparison with percentage diagram; last four cylinders re-examined. (Previously examined per our report of 4/19/78.)

**E refers to ettringite
CH refers to calcium hydroxide

CT-0407

TABLE 2 - FRACTURE SURFACES OBSERVED ON CYLINDER REMNANTS

(As Received)

Cylinder No.	Type of Fracture	Cylinder No.	Type of Fracture
6527*	D/L/T	6659*	D
6533	C	6660	D
6534*	D	6671*	T/L
6540*	L/T	6683*	D
6546	D/L	6689*	D
6551*	D/T	6690*	D
6552	D	6695	T/L
6557	D	6696	T/D
6558* (cube not tested)	C	6713	L/T
6563	D	6714*	D
6575	D/T	6720	D
6576	D	6725	D
6582	D	6726	D
6587	L/D(?)	6731*	L
6588	D/T	6737	T
6594	D	6744	D
6599*	L/T	6761*	D
6605*	D/T	6767* (cube not tested)	D
6606	D	6772	D
6611	D	6773	D
6629	D	6779	D/T
6636	D	6785*	D/T
6642	L	6790	L
6648*	D	6845	D

*Cylinder from which cube was cut.

D = diagonal
C = conical
T = transverse
L = longitudinal

CT-0407

TABLE 3 - MAXIMUM RELIEF ON CYLINDER ENDS

Cylinder No.	From Highest Point to Lowest Maximum Relief (inches)	90-Day Cylinder Strength, (psi)
6527	0.122	4700
6533	0.061	4810
6534	0.050	4660
6540	0.046	4320
6546	0.044	3270
6551	0.097	4290
6552	0.049	5110
6557	--- No bottom surface	4180
6558	0.042	5380
6563	0.067	4620
6575	0.029	5600
6576	0.036	5090
6582	0.072	5130
6587	0.050	4670
6588	0.048	4970
6594	0.074	5310
6599	0.046	4010
6605	0.061	4350
6606	0.071	4340
6611	0.039	5180
6629	0.095	6270
6636	0.135	5620
6642	0.069	5460
6648	0.065	5150
6659	0.053	5390
6660	0.035	5530
6671	0.135	4370
6683	0.027	4990
6689	0.113	4830
6690	0.115	5940
6695	0.035	4650
6696	0.043	4280
6713	0.051	4630
6714	0.052	4370
6720	0.031	4950
6725	0.076	4800
6726	0.030	4950
6731	0.034	5620
6737	0.090	4520
6744	0.056	5080
6761	0.067	4710

Continued on next page...

TABLE 3 - MAXIMUM RELIEF ON CYLINDER ENDS
(Continued)

Cylinder No.	From Highest Point to Lowest Maximum Relief (inches)	90-Day Cylinder Strength, (psi)
6767	0.112	5850
6772	0.052	4990
6773	0.041	4780
6779	0.057	4970
6785	0.067	4830
6790	0.047	4700
6845	0.067	6010

TABLE 4 - CUBE COMPRESSION TESTS

Southwark-Emery Machine (Ser. No. 57271)
January 30, 1979

Cylinder No.	Corrected Minimum Area (sq.in.)	Height (in.)	Load (lbs)	Comp. Strength (psi)	Corrected Strength (80%) (psi)	90-Day Cylinder Strength (Daniel data)	Comments
No Visible Defects							
6527	4.00	2.03	28,800	7,200	5,760	4,700	
6534	4.18	1.98	34,700	8,301	6,640	4,660	
6540	4.39	2.07	34,200	7,790	6,632	4,320	
6540 II	4.06	2.20	28,300	6,970	5,576	4,320	
6551	4.16	1.99	31,800	7,644	6,115	4,290	
6599	3.98	2.02	31,400	7,889	6,311	4,110	
6605	3.80	2.04	29,900	7,868	6,294	4,350	
6659	4.20	2.03	37,300	8,880	7,104	5,390	
6671	3.94	1.99	33,400	8,477	6,781	4,370	
6683	3.37	2.09	22,500	5,677	5,341	4,990	Small area
6689	3.98	2.00	36,700	9,221	7,376	4,830	
6689 II	3.66	2.00	33,800	9,234	7,387	4,830	Small area
6690	4.18	1.99	41,600	9,952	7,961	5,940	
6714	4.24	2.03	35,600	8,396	6,716	4,370	
6761	4.08	1.91	32,800	8,039	6,431	4,710	
6785	4.35	2.01	36,800	8,460	6,768	4,830	
6785 II	4.14	2.01	35,300	8,527	6,822	4,830	

II indicates second cube from given cylinder.

1050 231

CT-0407

TABLE 4 - CUBE COMPRESSION TESTS (Continued)

Southwark-Emery Machine (Ser. No. 57271)
January 30, 1979

Cylinder No.	Corrected Minimum Area (sq.in.)	Height (in.)	Load (lbs)	Comp. Strength (psi)	Corrected Strength (80%) (psi)	90-Day Cylinder Strength (Daniel data)	Comments
Some Broken Corners and Edges (areas are corrected for these)							
6527 II	3.99	1.98	31,400	7,870	6,296	4,700	2 Bottom Corners (-0.25 in.^{2})
6534 II	4.03	1.95	29,100	7,220	5,776	4,660	Possible Crack
6648 II	3.61	2.01	34,900	9,668	7,734	5,150	Bottom Edge (-0.25 in.^{2})
6648	3.86	2.01	34,300	8,886	7,108	5,150	Lower Edge (-0.3 in.^{2})
6683 II	3.08	1.89	27,600	8,961	7,168	4,990	Bottom Corner (-0.25 in.^{2})
6690 II	3.92	1.97	35,800	9,132	7,306	5,940	Bottom Edge (-0.25 in.^{2})
6714 II	3.99	2.08	30,200	7,569	6,055	4,370	Lower Edge (-0.25 in.^{2})
6731	4.01	2.03	37,300	9,302	7,442	5,620	Upper Corner (0.25 in.^{2})
6761 II	3.98	2.00	35,300	8,869	7,095	4,710	Lower Edge (-0.2 in.^{2})
				Ave.	6,690	4,790	
				S.D.	675	519	

Cracked (not tested)

6558, 6767

CT-0407

1050 232

TABLE 5 - UNIT WEIGHTS, ABSORPTIONS, AND AIR-VOID DATA

Cylinder No.	Cube Unit Weight lbs/ft^3	Cube Absorption Percent of dry wt.	Percent Air	Number Voids/ inch	Specific Surface (in.^{2}/in.^{3})	Spacing Factor*	Volume % Voids ≥ 114 microns
6527	147.4	6.3					
6527 II	145.6	6.2					
6534	145.3	6.1					
6534 II	146.7	6.5					
6540	146.9	5.6	4.5	7.0	624	0.0065	52.8
6540 II	147.2	6.4					
6546	146.6	5.6	5.0	7.0	563	0.007	52.0
6551	145.3	6.9	4.5	6.6	589	0.0075	52.7
6558	146.3	6.3	4.4	7.2	652	0.0065	52.7
6599	148.5	5.4	5.7	8.5	597	0.006	53.6
6605	146.6	6.2					
6605 II	145.6	6.5					
6606	146.6	5.0	4.6	4.9	424	0.010	65.8
6648	147.4	4.7					
6648 II	147.5	4.9					
6659	145.9	5.9	5.9	8.8	600	0.0055	49.0
6659 II	146.9	5.9					
6671	146.7	5.6	4.0	6.7	682	0.007	54.1
6671 II	146.3	5.5					
6683	144.4	5.2					
6683 II	145.1	5.4					
6689	150.0	5.5					
6689 II	147.9	6.8					
6690	148.3	5.2					
6690 II	147.0	6.2					
6696	144.8	6.0	5.1	6.4	506	0.008	55.6
6714	147.3	5.2					

1050 233

Continued on next page . .

TABLE 5 - UNIT WEIGHTS, ABSORPTIONS, AND AIR-VOID DATA (Continued)

Cylinder No.	Cube Unit Weight lbs/ft^3	Cube Absorption Percent of dry wt.	Percent Air	Number Voids/ inch	Specific Surface (in.^{2}/in.^{3})	Spacing Factor*	Volume % Voids ≥ 114 microns
6714 II	145.6	6.2					
6731	147.6	5.8					
6761	145.9	5.2					
6761 II	148.1	6.2					
6767	145.6	5.4	5.3	9.1	684	0.0055	50.3
6767 II	146.0	5.4					
6785	145.6	5.0	5.0	8.2	657	0.006	48.3
6785 II	145.6	5.3					

*20 percent paste assumed

II indicates second cube

1050 234

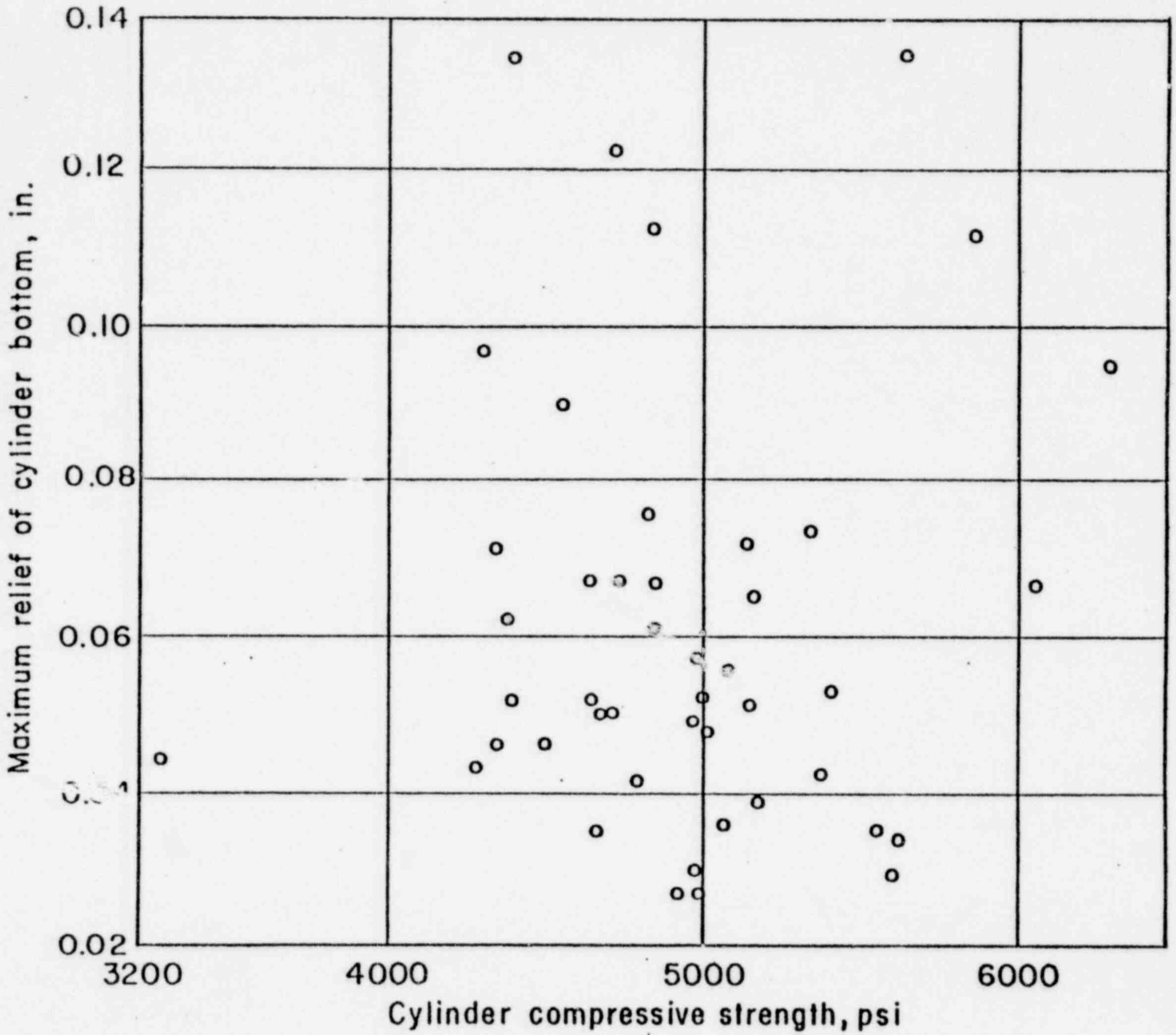


FIG. I RELATIONSHIP BETWEEN CYLINDER STRENGTH AND MAXIMUM RELIEF OF CYLINDER BOTTOM

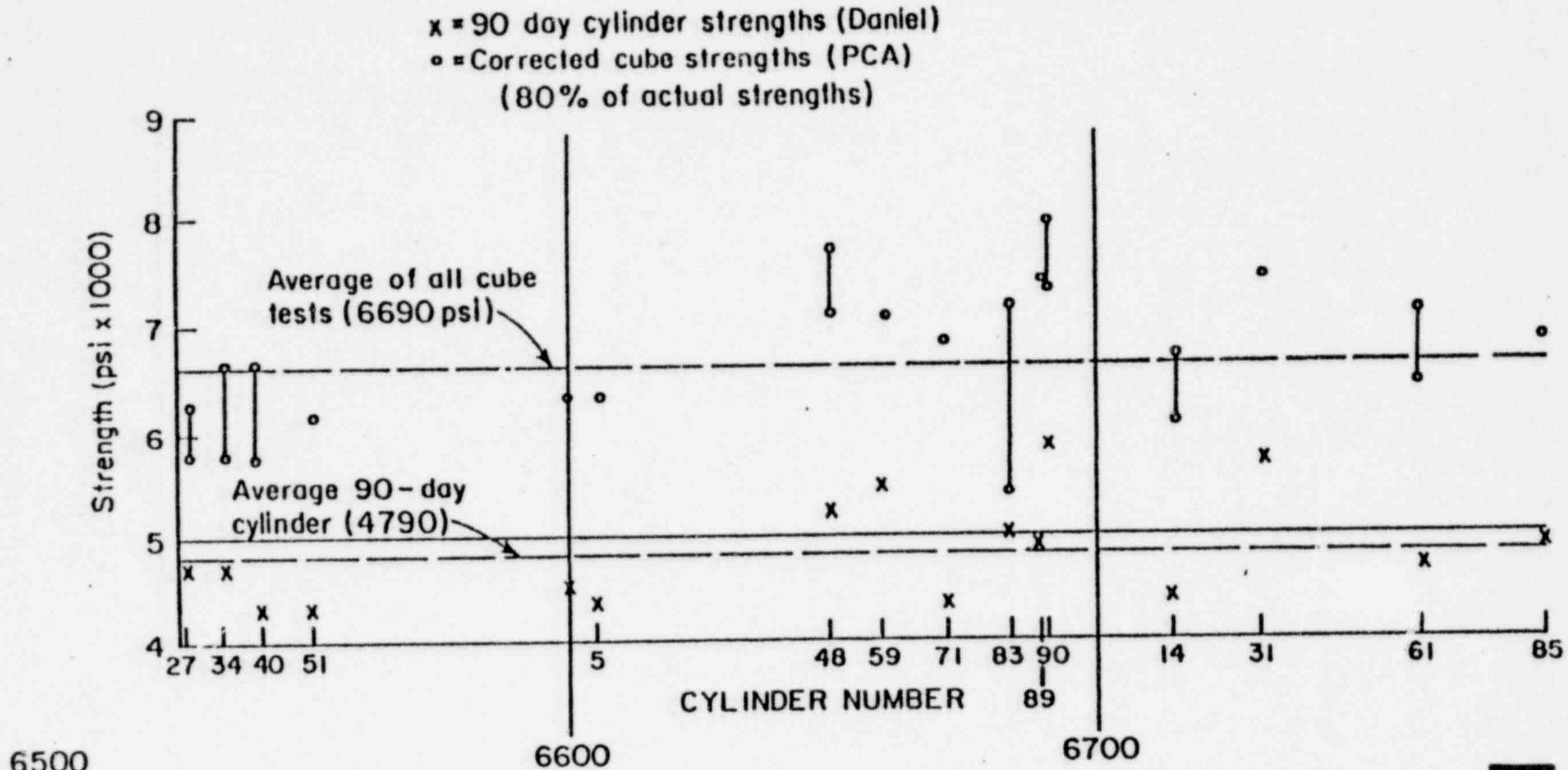


FIG. 2 COMPARISON OF COMPRESSIVE STRENGTHS OF CUBES AND CYLINDERS

1050 236

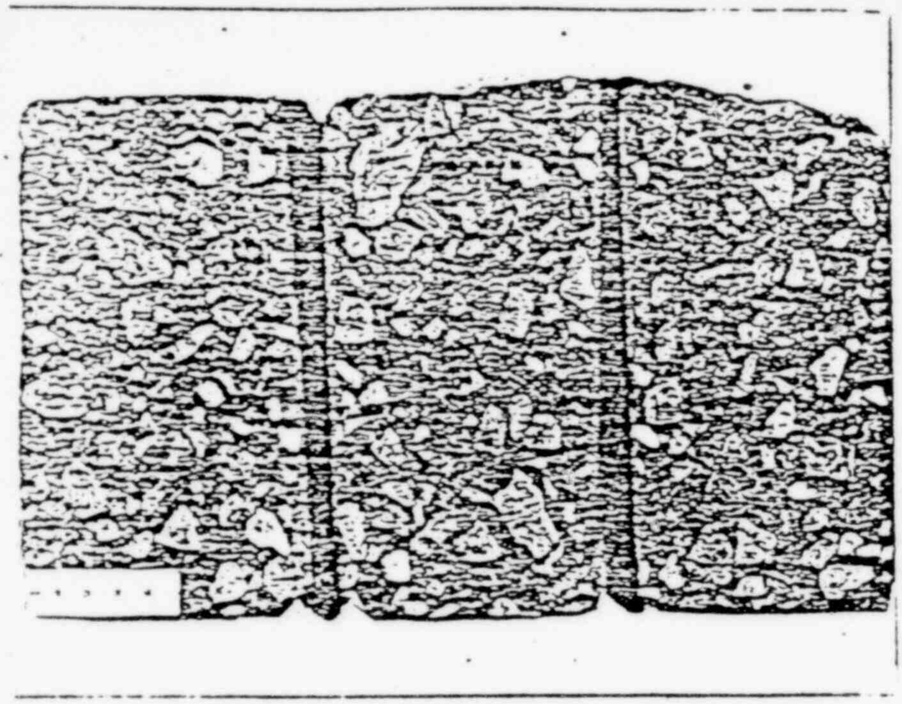


Photo 1 — Lapped and polished cylinder sidepieces showing uniformly distributed aggregates.

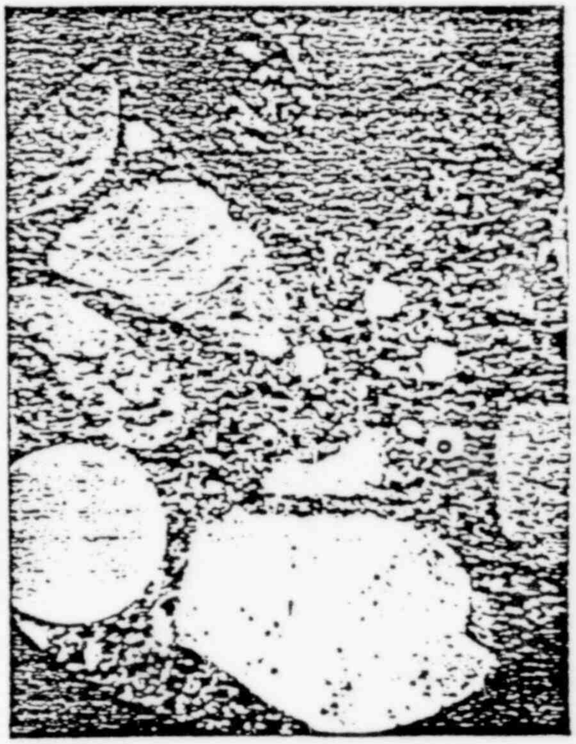


Photo 2 — Thin section photomicrograph of drilled plug from cylinder 6540 showing fine aggregates, dark UPC's, and small spherical air voids. Plane polarized transmitted light, field diameter = 1.3 mm.

POOR ORIGINAL

Photo 3 — Cylinder remnants showing typical diagonal fractures resulting from compression tests.

1050 237

APPENDIX B

CHEMICAL SERVICES REPORT

Chemical Services Report

POOR ORIGINAL

Project No.: CT-0407 Date: February 26, 1979

Re: Wolf Creek Generating Station
(Daniel International Corporation)

Our Chemical Services report details the results of tests for the cement contents and approximate water-cement ratios of 11 samples of hardened concrete. Also included are the results of mortar cube compressive strength tests obtained with four samples of Ash Grove Type II portland cement. The samples of cement and concrete were delivered personally to us on December 13, 1978, by Mr. W. G. Eales of K. G. & E. Daniel/K. G. & E. have certified that concrete cylinder remnants, aggregates and cements are representative of the concrete and concrete materials used in the basemat. This work is intended to supplement that already performed relative to the strength of concrete placed in the Reactor Basemat.

Conclusions

1. The cement contents of all the samples of hardened concrete we analyzed were at least comparable to that specified in the concrete mix design (564 lbs/yd^3). The actual range of determined values was 550 to 620 lbs/yd^3.

2. No correlation was observed between the reported cylinder strengths and the determined cement content.

3. In general, the approximate water-cement ratios (w/c) of the hardened concrete samples were below the level of 0.49 obtained from the concrete mix design. One sample (Specimen No. 6551) showed a slightly higher value (w/c = 0.52), but this was not considered significant.

4. In general, the cement contents and approximate water-cement ratios obtained with the latest samples of hardened concrete compare favorably with those obtained from the previous set of samples (PCA report by J. J. Shideler to Daniel International dated April 19, 1978). These observations suggest concrete batching procedures produced a relatively uniform grade of concrete.

5. The compressive strength of ASTM C-109 mortars made with the four samples of Ash Grove Type II portland

1050 239

cement exceed the minimum strength requirements specified in ASTM C-150 (Standard Specification for Portland Cement) through the age of seven days.

Results and Discussion

A. Determination of Cement Contents and Approximate Water-Cement Ratios of Hardened Concrete

The cement contents and approximate water-cement ratios of 11 concrete cylinder remnants, identified as Nos. 6540, 6551, 6558, 6599, 6659, 6671, 6767, 6785, 6546, 6606, and 6696, were determined. These specimens were recommended for such testing by Mr. W. R. Waugh, Consulting Engineer (consultant to K. G. & E.). All the cylinder remnants, except Nos. 6659 represented concrete involved in the apparent low strength problem. Specimen Nos. 6659 and 6785 exhibited 90-day cylinder compressive strengths above the corresponding 28-day values. Specimen Nos. 6558 and 6767 were especially of concern, because their 90-day average strengths apparently were less than the 28-day average strengths. Analyses were performed on three cylinder remnants (Nos. 6546, 6606, and 6696) using samples carefully selected from each. The remaining cylinder remnants were analyzed using the 2-inch cubes prepared from each by Dr. D. H. Campbell for his compressive strength determinations.

The cement contents of the concrete specimens were determined using the Sulfur Trioxide (SO_3) Method. The SO_3 level used to calculate the cement contents is an average value (2.09%) obtained from chemical analyses performed on previously supplied samples of Ash Grove Type II portland cement (see again PCA report by J. J. Shideler dated April 19, 1978). These samples represent the cement actually used in the Reactor Basemat concrete. The results of the tests are presented in the attached cement content analysis report by Ms. D. L. Glochowsky and Mr. A. A. Alonzo.

The results show the cement contents of all the concrete cylinder remnants were comparable to, or slightly higher than, the quantity of cement specified in the reported mix design (564 lbs/yd^3). Two of the cylinder remnants (Nos. 6546 and 6696) exhibited slightly high cement contents, 610 and 620 lbs/yd^3, respectively, but they were not retested. The cement content of one cylinder remnant (No. 6599) appeared at first to be slightly low (initial test results given in parenthesis), so it was retested after preparation of a new and larger size sample. The retest showed the cement content was close to the proper amount. The anticipated accuracy of the cement content test, in this case, is $\pm$ 30 lbs/yd^3.

The approximate water-cement ratios of all but one of the 11 cylinder remnants were less than the level indicated in the

1050 240

concrete mix design (w/c = ∿0.49). Specimen No. 6551 exhibited a slightly higher value (w/c = 0.52), but this was not considered significant with respect to "over-watering" (excessive re-tempering) of the concrete mix. The other w/c values ranged from 0.38 (Specimen No. 6606) to 0.47 (Specimen No. 6558).

Determination of the approximate water-cement ratios is considerably less precise than the determination of cement contents, because of other variables (concrete unit weight, absorption, and cement content and absorption of aggregates).

A comparison of the cement content and approximate water-cement ratio values with reported cylinder compressive strengths revealed that no direct relationship could be established. There were no significant differences observed between the higher strength and the lower strength cylinder remnants with respect to cement content and water-cement ratio.

B. Determination of Compressive Strength (ASTM C-109)

Four samples of Ash Grove Type II portland cement, identified as C-UT-15, C-UT-18, C-UT-20, and C-UT-21, are currently under test to determine mortar compressive strength according to ASTM C-109 (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars). The purpose is to ascertain whether or not these samples comply with the strength requirements specified for a Type II portland cement in ASTM C-150 (Physical Requirements).

The test results, which are reported as average values representing three individual tests in each case, are given in the table below. For purposes of comparison, the appropriate ASTM C-150 strength requirements also are shown in the table. An extra 2-inch cube from each cement sample is available for testing at some later date should that prove desirable.

Cement Sample	Compressive strength, psi (ASTM C-109)		
	3 Days	7 Days	28 Days
C-UT-15	2460	3565	5365
C-UT-18	2485	3390	5340
C-UT-20	2035	2885	5015
C-UT-21	2290	3315	5400
(ASTM C150-78)	1500	2500	4000

These data show all four cement samples have surpassed the minimum strength requirements specified in ASTM C150-78 (Physical Requirements) for a Type II portland cement through the age of 28 days. It is our understanding that the cement to be used in this project needed only to comply with the less stringent ASTM C150-74 strength requirements for a moderate heat of hydration

1050 241

Type II portland cement (based upon chemical limitation). The sample identified as C-UT-20 is somewhat lower in strength than the others.

L. Michael Meyer

L. M. Meyer, Manager
Technical Services Section

LMM/md
CT-0407

Copy to-
J. J. Shideler
L. M. Meyer
A. A. Alonzo/D. L. Glochowsky

1050 242

CEMENT CONTENT

POOR ORIGINAL

Project No.: CT-0407

Completion Date: 2/13/79

Sulfur Trioxide (SO_3) Method

Concrete Cylinder No.:	6540	6546	6551
Cement content, lbs/yd³:	575	610	560
% SO_3 (oven dry weight basis):	0.32	0.34	0.32
Unit Weight, lbs/ft³:			
S.S.D.	147.1	146.6	145.3
Oven Dry (@ 105°C)	138.7	138.8	136.0
Free water content, %: (S.S.D. weight basis)	5.7	5.3	6.4
Combined water content, %: (Oven dry weight basis)	1.8	1.9	2.1
Total water, lbs/yd³: (Free water + combined water)	295	280	330
Approximate W/C: (Corrected for aggregate absorption)	0.44	0.39	0.52
Total dry aggregate, lbs/yd³:	3100	3070	3035

Comments:

(1) Concrete and aggregate SO_3 contents determined gravimetrically in duplicate (modification of ASTM C114). Aggregate SO_3 content was negligible.

(2) Cement SO_3 content 2.09% (average of Type II Portland Cement samples C-UT-16 and 17).

(3) Overall aggregate absorption 1.25% (average absorption of a 50/50 C.A. to F. A. mix with respective absorption values of 1.8% and 0.7%).

1050 243

POOR ORIGINAL

CEMENT CONTENT

Project No.: CT-0407

Completion Date: 2/13/79

Sulfur Trioxide (SO_3) Method

Concrete Cylinder No.:	6558	6599	6606
Cement content, lbs/yd³:	570	550 (510)	580
% SO_3 (oven dry weight basis):	0.32	0.31 (0.28)	0.32
Unit Weight, lbs/ft³:			
S.S.D.	146.3	145.6 (148.5)	146.6
Oven Dry (@ 105°C)	137.5	137.6 (142.0)	139.7
Free water content, %: (S.S.D. weight basis)	6.0	5.5 (4.4)	4.7
Combined water content, %: (Oven dry weight basis)	2.0	1.8 (1.8)	2.0
Total water, lbs/yd³: (Free water + combined water)	310	285 (245)	260
Approximate W/C: (Corrected for aggregate absorption)	0.47	0.45 (0.39)	0.38
Total dry aggregate, lbs/yd³:	3070	3095 (3255)	3120

Comments:

(See Page 1)

POOR ORIGINAL

CEMENT CONTENT

Project No.: CT-0407 Completion Date: 2/13/79

Sulfur Trioxide (SO_3) Method

Concrete Cylinder No.:	6659	6671	6696
Cement content, lbs/yd^3:	555	555	620
% SO_3 (oven dry weight basis):	0.31	0.31	0.35
Unit Weight, lbs/ft^3:			
S.S.D. -	146.4	146.5	144.8
Oven Dry (@ 105°C) -	138.2	138.7	136.7
Free water content, %: (S.S.D. weight basis)	5.6	5.3	5.6
Combined water content, %: (Oven dry weight basis)	1.7	1.7	1.8
Total water, lbs/yd^3: (Free water + combined water)	285	275	285
Approximate W/C: (Corrected for aggregate absorption)	0.44	0.42	0.40
Total dry aggregate, lbs/yd^3:	3115	3125	3005

Comments:

(See Page 1)

POOR ORIGINAL

CEMENT CONTENT

Project No.: CT-0407 Completion Date: 2/13/79

Sulfur Trioxide (SO_3) Method

Concrete Cylinder No.:	6767	6785
Cement content, lbs/yd³:	570	560
% SO_3 (oven dry weight basis):	0.32	0.31
Unit Weight, lbs/ft³:		
S.S.D. -	145.8	147.2
Oven Dry (@ 105°C) -	138.4	139.5
Free water content, %: (S.S.D. weight basis)	5.1	5.2
Combined water content, %: (Oven dry weight basis)	1.7	1.7
Total water, lbs/yd³: (Free water + combined water)	265	270
Approximate W/C: (Corrected for aggregate absorption)	0.39	0.41
Total dry aggregate, lbs/yd³:	3100	3145

Comments:

(See Page 1)

D L Glochowsky
D. L. Glochowsky
Assistant Research Chemist

A. A. Alonzo
A. A. Alonzo
Associate Research Chemist

APPENDIX C

BIBLIOGRAPHY No. 231

"EFFECT OF SIZE AND SHAPE OF SPECIMEN ON THE COMPRESSIVE STRENGTH OF CONCRETE"

construction technology laboratories
a Division of the PORTLAND CEMENT ASSOCIATION
5420 Old Orchard Road, Skokie, Illinois 60077 • Area Code 312/966-6200

POOR ORIGINAL

EFFECT OF SIZE AND
SHAPE OF SPECIMEN ON
THE COMPRESSIVE
STRENGTH OF CONCRETE

19[illegible]-1976

LIMITED BIBLIOGRAPHY NO. 231

By

Joseph J. Shideler
Director of Administrative and Technical Services
and
Marilynn LaSalle
Librarian

February 19, 1979

CONSTRUCTION TECHNOLOGY LABORATORIES
R&D Library

1050 248

1976 AM-42-2 Pamphlet Serial File

Anon.

Concrete Core Testing for Strength

Gt. Brit., Concrete Society Technical Report No. 11, 44pp (1976)

#51.071

Keywords: recommended procedures; compression tests; concrete cores; samples; test procedures; cores; Concrete Society T.R. No. 11

This report provides recommended procedures for obtaining and the compressive testing of concrete cores and for the interpretation of the results. Evidence from practice and research is provided for the formulae and conversion factors recommended.

128 References

RP-1-6-1 AM-42-2

5/20/77 - 886 - mt

1975 AM-42-2 Pamphlet Pamphlet File (Faggett, Edward)

Faggett, Edward

Determination of the Relative Compressive Strength of Concrete Cores of Various Sizes and the 6" x 12" Standard Test Cylinder

Texas, Univ. of Texas. Thesis. 116 pp (1975)

Keywords: compressive strength; cylinders; specimens

By attempting to control all other variables such as capping of specimens, curing conditions, mixing time, specimens' moisture condition during load testing etc., this research was intended to provide information on the core size to strength relationship. Strength correction factors were determined.

AM-40a AM-42-2

2/13/76 - 358 - mt

1974 AM-42-2 Pamphlet Pamphlet File (Lopez, Robert V.)

Lopez, Robert V.
Apparent Compressive Strength of Concrete Cylinders as Related to Specimen Size.
Texas, Univ. of Texas at Arlington. Thesis. 101pp (1974)

Keywords: compressive strength; specimens; cylinders

By testing 30 cylinders of 3 different sizes for a given design strength, and statistically validating the apparent concrete strength for each size-design strength, correction factors are established for concrete strengths of 3" x 6" and 4" x 8" cylinders. These correction factors may then be applied to compressive test results of these cylinder sizes to establish a correlation with the standard 6" x 12" cylinder.

AM-42-2 AM-40a

2/13/76 - 359 - mt

1972 AM-42-2 Pamphlet Serial File

Lewis, R.K.
The Compressive Strength of Concrete Cores.
Australia, CSIRO, Dept. Bldg. Res. Report L-18, 34pp (1972).

Tests have been done on the comparison of concrete cores of various diameters with standard concrete cylinders. The results confirm that the compressive strength of cores from well-cured concrete slabs is less than the strength obtained from the standard cylinders. The variation in compressive strength of concrete cores is also greater than in cast cylinders, but the variation in core strengths was not related to the diameter.

AM-42-2

4/5/74 - 744 - mt

POOR ORIGINAL

1972 AM-42-2 Pamphlet Serial File

Pomeroy, C.D.
The Effect of Curing Conditions and Cube Size on the Crushing Strength of Concrete.
Gt. Brit., C&CA Technical Report 42.470, 16pp (July 1972).

2" 6"

Cubes from 50 to 150 mm were used. For wet-cured specimens, there is a substantial decrease in crushing strength as the cube size is increased for the strongest mixes used. The drying history is shown to affect the size relationships: premature drying of small cubes before hydration has progressed far, limits the strength development and reduces the strength as surface cracks are formed. The result is that small cubes are up to 20% weaker than large ones.

AM-42-2

11/14/72 - 1353 - mt

1971 AM-42-~~4~~ 2 Periodical

Lewandowski, R.
Relationship Between Cylinder and Cube Compressive Strengths of Cement (In German with English Abstract.)
Betonstein Zeitung 37 (9) 562-566 (Sept. 1971).

What relationship is there between the strengths ascertained of test cylinders of random dimensions and the cube compressive strength of concrete? On test cylinders of the slenderness h/d = 1.0, the cube compressive strength can be determined direct, provided the cylinder diameter is d = 15 cm; on specimens of d = 10 cm are found values which are by approx 5% above the effective strength. Even under unfavorable conditions, the conversion factors determined allow sufficiently correct statements for field applications.

AM-42-~~4~~-2

11/10/71 - 1097 - mt

1050 251

1970 AM-42-2 Periodical

Anon.
Cores of Small Diameter
Bulletin Du Ciment 38 (3) 1-4 (March 1970).

Fig. 1. Comparison of compressive strength of 5 cm diam cylinders, 5.6 cm high with cubes (20 cm sides).

AM-42-2

6/4/70 - 490 - mt

1969 AM-42-2 Periodical

Meininger, R. C.
Effect of the Core Diameter on the Measured Strength of Concrete. (IN SPANISH)
Revista IMCYC 7 (38) 54-69 (May/ 969).

A 16-in.-deep slab and a 16-in.-thick wall were constructed, moist-cured for 3 months, and then cored to obtain 2, 4, and 6 in.-dia. specimens. The 16-in.-long cores were sawed into 2 by 4, 4 by 8 and 6 by 12 in. specimens for compression tests. Half of the cores were soaked in water 40 to 44 h; the others were immersed for 28 days before testing. Also 4-in.-diameter cores were drilled 10 in. into the wall specimen and broken out; the resulting cores were trimmed to 4 by 8 in., soaked 40 to 44 h, and then tested in compression. Neither the difference in core size nor the breaking out of cores affected the measured strength significantly.

AM-42-2

8/28/69 - 2565 mt

1967 AM. 42. 2	Periodical	693.505 B46

Albrecht, W.
The Effect of the Relationship of Sample Thickness to Maximum Particle Diameter and the Effect Size of Sample on the Compressive Strength of Concrete.
Beton: Herstellung Verwendung 17 (5) 175-178 (May 1967) (In German with English summary).

In the evaluation of reports on tests and in the testing on concrete taken from structures, in which test pieces necessarily occur in various sizes and forms, the effect of the size of sample on the strength must be taken into account. In samples taken from structures the relationship of the sample thickness to the largest particle diameter is often extremely small. The effect of this ratio on the compressive strength is to be taken into account. The cube has so far predominated as the sample shape for compressive strength testing but the cylindrical shape with various diameters is gaining in importance. The general use of cylinders for the proof of strength must, therefore, also be kept in mind.

AM-42-2 2430
AM-37-1 6/30/67

1967 AM. 42. 2	Periodical	691.305 Am3

Bhargava, Jitendra K.
Discussion of: "A General Relation for Strengths of Concrete Specimens of Different Shapes and Sizes," by A. M. Neville.
J. Am. Concr. Inst., Proc. 64 (6) [Pt.2] 1561-1565 (June 1967).

Author has used a value of 0.91, taken from ASTM STandard C 42-64, in arriving at a factor of 0.85 for converting the strength of a 6 x 12-in. cylinder to that of a 6-in. cube. This is not correct in the present case because: (1) the ASTM value is for making allowance for the ratio of length to diam. of drilled cores, when the length-diam. ratio is one; (2) these coeffs. are not valid for dry concrete, which may differ considerably...The relation between cylinder and cube strengths also depends on the strength level of the concrete. According to L'Hermite's formula, used by the author, the conversion factor can vary from 0.76 to 0.86 over the range of concrete strengths from 3000 psi. to 8500 psi...

(Abstr. by HC)

AM-42-2
CM-1-1-2
9/14/67-3392

1050 253

1967 AM-42-2	Periodical	691.305 Am3

Campbell, Richard H. and Tobin, Robert E.
Core and Cylinder Strengths of Natural and Lightweight Concrete.
J. Am. Concr. Inst., Proc. 64 (4) 190-195 (Apr. 1967).

The compressive strength of lab. cured and field cured cylinders are compared with 4 and 6 in. diam. cores at ages up to 84 days. Nearly 500 samples of natural and lightweight concrete under simulated job conditions showed that all cores at comparable ages tested lower than cylinders.

Ag-5-3
AM-42-2
4/28/67-1490

1967 AM-42-2	Periodical	

Pineiro, Moises; Jara, Jose; Valenzuela, Sergio and Genta, Jose
Compressive Strength of Concrete: Relationship Between Cylindrical and Cubical Strength. (IN SPANISH).
Revista del Idiem 6 (3) 141-156 (December 1967).

In order to study the relationship between cylindrical and cubical strength for conditions of more practical interest, the following factors were considered: nature of aggregate, maximum size, age and type of cement. Statistical analysis showed that those factors were not significantly important. A relationship is proposed between cylincrical and cubical strength consisting of two intersecting straignth lines: the first one $R_{cyl} = 0.86\ R_{cub}$ up to kg/cm^2 cubical strength, and above 400 kg/cm^2, R_{cyl} = 0.[illegible] + 152. The results of some other investigators are analy[illegible]

AM-42-2
8/26/68-2704 MF

1050 254

1967 AM-42-2	Pamphlet	Serial File

Popovics, Sandor (Prof., Dept. Civ. Eng., Auburn Univ.)
Relations Between Various Strengths of Concrete.
Highway Research Board. Record No. 210 pp. 67-94 (1967).

Analysis of published experimental data shows certain correlations between cylinder, cube, and modified cube strength; between compressive, flexural, direct tensile, and splitting strengths; and between torsion, shear, and other strengths. Formulas related to these correlations are discussed. However, their general application requires caution because they would not necessarily hold for tests carried out under different conditions.

AM-42-2
CM-4-21
6/21/68-1980 mp

1966 AM-42-2	Periodical	691.305 Am3

Neville, Adam M.
A General Relation for Strengths of Concrete Specimens of Different Shapes and Sizes.
J. Am. Concr. Inst., Proc. 63 (10) 1095-1110 (Oct. 1966).

It is shown that the strengths of concrete test specimens (cylinders, cubes, and prisms) can be related to one another by simple expressions. Substantiating test results are presented. The secondary influence of the fineness modulus of aggregate on this relation is discussed.

AM-42-2
CM-1-1-2
10/25/66-3258

1050 255

1965 AM-42-2	Pamphlet Periodical	Serial File 691.06 Am3p

Bloem, D. L.

Concrete Strength Measurement - Cores Versus Cylinders.

A.S.T.M., Proc. 65, pp.668-696 [with disc.] (1965).

Nat'l. Sand & Gravel & Nat'l. Ready Mix. Concr. Assn. JRL Publ.15

Compressive strength tests were made comparing molded cylinders with cores drilled from structural-size elements of the same concrete. Variables included: concretes made with 3 types of aggregates, excellent and poor field curing, flat slabs cored vertically and columns cored horizontally, specimen location, and treatment and age of specimen...Cores drilled at 91 days and tested in accordance with ASTM Methods C 42 had strengths 10 to 40% lower than molded cylinders depending on type of specimen, curing and other factors. Soaking cores 48 hr prior to testing did not improve agreement with cylinders. Cores dried for 7 days gave the best indication of in-situ concrete strength...Strength of cylinders cured for 28 days correlated well with air-dried core specimens drilled at 91 days. Thus, molded cylinders cured to simulate conditions in concrete structures may be used to indicate environmental effects on strength. Standard-cured cylinders are most suitable for acceptance tests. AM-42-2 . . . 3/11/66-825

1965 AM-42-2	Periodical	691.305 C33

Hughes, B.P. and Bahramian, B.

Cube Tests and the uniaxial Compressive Strength of Concrete

Magazine of Concrete Research, 17 (53) pp.177-182 (December 1965)

AM-42-2

5/6/66-1500

The cube is undoubtedly the most convenient specimen to use when large numbers of crushing tests are required for concrete control purposes. The cylinder, or prism, on the other had can give a much better estimate of the uniaxial compressive strength of concrete. The paper shows that variable differences can occur between the cube crushing strength and uniaxial compressive strength, and then indicates how these differences can be greatly minimized by a suitable modification of the testing technique. This simple modification to the cube test enables the uniaxial strength to be determined very readily. The extremely convenient cube specimen can therefore now be used for uniaxial compressive strength determinations as well as for normal control purposes. The continued use of the cube as the standard form of test specimen is therefore recommended.

1050 256

1965 AM-42-2	Periodical	691.06 R45

Rajendran, Sri S.
Effect of the Size of the Specimen on the Compressive Strength of Concrete.
R.I.L.E.M. Bull. 26, pp.81-83 (Mar. 1965).

Cubes of 4" and 6" as well as cylinders 6" diam. X 12" height are commonly adopted for conducting compressive strength test on concrete...The phys. characteristics of fine and coarse aggregate as well as the grading charts are given...Table 4: Showing the standard deviation and coeff. of variation of test results...Conclusion: the size of the specimen affects the compressive strength of concrete, the general trend being that the recorded strength of the cube is lowered by about 4% for every 2 in. increase in size starting from 4" cube onwards.

AM-42-2
CM-1-1-2
FCP-9-1-1
5/17/65-1704

1962 AM-42-2	Periodical	691.06 R45

Hansen, H., Kielland, A., Nielsen, K.E.C. and Thaulow, S.
Compressive Strength of Concrete - Cube or Cylinder?
RILEM Bulletin (17) 25-30 (Dec. 1962).

When RILEM in 1956, and the Comite Europeen du Beton, in 1957, resolved to give preference to the cylinder for research tests of concrete, the first important step was taken toward introducing an universal test shape for concrete tests. In this article the authors have reviewed the various factors by which cubes and cylinders may be judged. The authors contend that cylinders should be preferred for concrete testing, for reasons listed in the article.

AM-42-2
1/28/63 - 522

1050 257

1962 AM-42-2	Periodical	691.66 R45

Lyse, Inge and Johansen, Randulf
An Investigation on the Relationship Between the Cube and Cylinder Strengths of Concrete.
R.I.L.E.M. Bulletin (14) 125-133 (Mar. 1962).

This investigation presents the results of about 850 tests of concrete cubes and cylinders. Every precaution was taken for securing direct comparison between the various sizes and shapes of the test specimens. The results showed that within the field of this investigation the size of the test specimens did not have any effect upon the strength, and that the cylinder strength (standard vertical cylinders) was about 86% of the cube strength for all the different strengths of the concrete. There is therefore no reason for preferring one shape of test specimen for another one as far as strength results are concerned, but one shape (the cube) may have considerable practical advantages in the field as well as in the laboratories.

AM-42-2
4/30/62

1962 AM-42-2	Periodical	691.305 N75

Petersons, Nils
Relation Between Strengths of 15 cm Cubes and 15 X 30 Cylinders.
(IN SWEDISH, with English summary)
Nordisk Betong 6 (2) 159-170 (1962).

An account is given of the results obtained in strength tests on 15 cm cubes and 15 X 30 cm cylinders. Both cube and cylinder specimens were made on concrete taken from the same batch and cast in steel molds, which were provided with flat-ground end plates and partition plates. Strength consistency and curing conditions of the concrete were varied. Test results were submitted to a statistical analysis...when the strength was high, but also when it was comparatively low, the conversion factor for reducing the cylinder strength to the cube strength varied within wide limits depending on the method of treatment of test specimens. For the same grade of concrete, the differences in the observed values of the ultimate strength can be as high as 25%...Tests also showed that the compressive strength of 15 cm cubes exhibited a dispersion which was significantly smaller than that observed in the case of 15 X 30 cm cylinders...also the 15 cm cubes are simpler to make and to handle.

AM-42-2 . . . 8/8/62

1050 258

POOR ORIGINAL

1960 AM-42-2	Periodical	691.305 N73

Hansen, Henry; Kielland, Arvid; Nielsen, Knud E. C. and Thaulow, Sven

Compressive Strength of Concrete - Cube or Cylinder?

Nordisk Betong (4) 305-320 (1960). (IN NORWEGIAN, with Engl. summ.)

A review of the pros and cons of the two types of test specimens, cubes and cylinders, concludes that friction between the loading surfaces is the primary cause of the varying relationship between cube and cylinder strength. This relation is also affected by deformations in the heads of the testing machine. However, both sources of error can be eliminated. Friction can be counteracted by making the specimen sufficiently tall (h/d = 2.0); test head errors can be avoided by making the heads sufficiently rigid. Advantages of cylinder specimens are enumerated. 29 references.

(Abstr. by MC)

AM-42-2
2/9/61

A.S.? AM-42-2	Book	691.3 C55

Newman, K.

Concrete Control Tests as a Measure of the Properties of Concrete.

Great Britain. Cement & Concrete Assn. Symp. on Concrete Quality, 19pp. (Nov. 1964).

Factors affecting deformation and failure of concrete compression specimens show that the cube and cylinder strengths are strongly dependent on the state of stress induced in the specimen, its size and condition and the method of applying the load...results from the standard control tests are compared with data obtained from more fundamental tests under uniaxial and complex states of stress. Compression tests on cylinders and prisms, with a ratio of height to diam., or to width, greater than about $2\frac{1}{2}$, are direct measures of the uniaxial compressive strength of concrete, whereas cube tests are a measure more of the resistance of concrete to triaxial compression. The cylinder splitting test is a direct measure of the uniaxial tension strength while the flexural beam test gives an indication of the flexural tension strength of concrete...
[extensive data]

AM-40a, AM-42-2...1/6/65-43

1050 259

POOR ORIGINAL

1964 AM-42-2

Schneeweiss, G.
The Fundamental Laws Governing the Influence of Size and Volume of Concrete Specimens for Compression Tests. (IN GERMAN)
Oest. Ingen.-Arch. 18 (1/2) 22-46 (1964). Abstr. in Appl. Mech. Revs., 18 (4) Abstr. No. 2137 (April 1965).

A great number of test series from the literature are compared by plotting the compressive strengths against the volume of the test specimens, using logarithmic scales along both axis. A relatively uniform volume-influence is indicated. A general discussion is given concerning the influence of the size, the degree of hardening and the type of concrete on the indicated trend.

AM-42-2
6/2/65 - 1928

1963 AM-42-2 | Periodical | ~~691.36 423m~~

Wagner, W. K.
Effect of Sampling and Job Curing Procedures on Compressive Strength of Concrete.
Materials Res. & Standards 3 (8) 629-634 (Aug. 1963).

More than 1700 field compressive strength test were analyzed over a period of 8 years on nominal 3000-psi concrete of 2 aggregate sizes. Comparisons of contractor-made cylinders with lab.-made cylinders show that values reported on concrete improperly sampled, cured, and tested can cause considerable doubt as to the quality of the product. Other test data, covering a period of 16 months, compare the results of 6- x 12-in. cylinders at 7 and 28 days with a 4- x 8-in. diamond drilled cores taken from the same concrete after 28 days of field curing. In this specific case the core strengths were consistently below those of the cylinders at approx. the same age. The 2 sets of test data demonstrate the importance of proper sampling and curing of field specimens for realistic evaluation of the test results.

AM-22-3, AM-42-2
8/19/63-3742

1050 260

POOR ORIGINAL

1962 AM-42-2	Pamphlet	Serial File

Gaede, Kurt
On the Effect of Size of Specimens on the Cube Compressive Strength of Concrete. (IN GERMAN, with English summary)
Germany. Deutscher Ausschuss für Stahlbeton. Heft 144, pp.49-85 (1962).

The tests indicate that the apparent compressive strength of concrete does not decrease with an increase in size of specimens as long as all specimens are equally and uniformly compacted, and as long as the bearing blocks of the testing machine are sufficiently stiff. However, if the specimens are cast according to DIN 1048 the first requirement is not fulfilled so that the application of the relationship between cube strength and size of specimen is justified.

AM-42-2
9/5/62

1957 AM-42-2	Periodical	691.305 C33

Harman, A.B. et al.
Discussion of "The Influence of Size of Concrete Test Cubes on Mean Strength and Standard Deviation", by A.M. Neville.
Magazine of Concrete Research 9 (25) 52-55 (Mar. 1957).

Mr. Harman and Mr. Akroyd supply further information on the effect of cube size on the compression test results. A brief comparison is given of laboratory data with field data. A table gives results of mean deviation in kg/sq.cm. for three different sizes of concrete and mortar prisms, the number of specimens being 80 and 160.

AM-42-2
FCP-9-1-1
7-2-58

POOR ORIGINAL

1956 AM-42-2 | Periodical | 621.305 C33

Neville, A. M.
The Influence of Size of Concrete Test Cubes on Mean Strength and Standard Deviation.
Magazine of Concrete Research 8 (23) 101-110 (Aug. 1956).

Summary: It is suggested that the mean strength and the standard deviation of a sample of concrete cubes are functions of the cube size. The results of tests on over 300 cubes of three sizes are given, and from the statistical analysis of these results it is concluded that the smaller 2·78 in. cubes have a significantly higher mean strength and higher standard deviation than the larger 5 in. and 6 in. cubes. From these results, it is suggested that the standard deviation obtained from standard 2·78 in. mortar cubes gives an excessive estimate of the effect of the variation in cement quality as compared with the results obtained from 6 in. or 4 in. concrete cubes.

12/10/56
FCP-9-1-1
AM-42-2

1956 AM-42-2 | Periodical | 620.5 C50

Neville, A. M.
The Use of 4-In. Concrete Compression Test Cubes.
Civil Engineering & Public Works Review 51 (605) 1251-1252 (Nov. 1956). Abstract in Eng. Index, (1957).

Series of comparative tests on cubes of various sizes; it is suggested that 4-in. cubes be used as standard test cubes whenever maximum aggregate size is not greater than $^3/_4$ in.; by comparing 2.78-in. cubes cast as such, with $2^3/_4$-in. cubes obtained by cutting up 6-in. cubes, it is shown that $^3/_4$-in. aggregate can be successfully used even with this small size of cube.

AM-42-2
2/8/57

1050 262

1954 AM-42-2	Periodical	691.305 D 23

Efsen, A. and Glarbo, O.
Compressive Strength of Concrete Cylinders. (IN DANISH, with no English summary)
Beton og Jernbeton 6 (3) 91-93 (April 1954).

(1) The compressive strength of concrete cylinders was determined by the following methods:
  (a) the cylinders were capped with mortar;
  (b) a piece of soft wallboard was placed between the cylinder and the testing machine.
  No difference in strength was found.
(2) The ratio of cylinder to cube strength was found to be on the average equal to 0.827. This ratio decreased with increasing concrete strength.

(Abstract by J.M.)

AM-42-2
12-17-58

1925 AM-42-2	Periodical Periodical	666.906 L58 691.06 Am3p

Gonnerman, H. F.
Effect of Size and Shape of Test Specimen on Compressive Strength of Concrete.
Structural Materials Res. Lab., Lewis Institute, Chicago Bulletin No. 16, 16pp. (1925). Reprinted in Proc. Am. Soc. for Test. Mat. 25 (2) 237 (1925).

Compression tests were made at 7 days to 1 yr. on 1755 concrete specimens in a study of the compressive strength of: (1) cylinders $1^1/_2$ to 10-in. in diam. and 2 diam. in length with size, grading of aggregate, mix, consistency and age being the variables; (2) cylinders 12-in. in length and from 3 to 10-in. in diam.; (3) cylinders 6-in. in diam. and 3 to 24-in. long; (4) 6- and 8-in. cubes; (5) prisms, 6 by 12- and 3 by 16-in.
The 6 by 12-in. cylinder proved to be a satisfactory specimen. Aggregates should be limited to 2 in. or less in diam. for same.

(Abstr. by MC)

AM-42-2
12/26/56

1050 263

APPENDIX D

SUMMARY

"RATIO OF STRENGTH OF 2-in. CUBES TO 6x12-in. CYLINDERS"

Ratio of Strength of 2-in. Cubes to 6x12-in. Cylinders

Neville[1] has suggested that the ratio of strength of 6x12-in. cylinders to 6-in. cubes is about 0.83. This ratio being the average of the L/D correction factors of 0.91 and 0.75 from ASTM C-42 and British Standard BS1881, respectively. A factor of 0.81 was determined from an analysis from 11 investigations.

L'Hermite has also suggested a value of 0.83 with a range of 0.76 to 0.86 (see Neville Reference 13).

Other research data[2] indicate ratios of strength of cylinders to 6-in. cubes in the range of 0.80 to 1.10. RILEM and CEB recommend 0.80 and this value is specified in British Standard 1881. This reference[2] also sites other references (Table 7) to indicate the strength of 2, 4, and 6-in. diameter cores (L/D of 1) is approximately equal to the strength of cubes (4 and 6 in.). Applying the L/D correction factor of 0.91 the strength of cores is about 91% of the strength of cubes, or cubes 4 and 6 in. are about 10% stronger than cores.

In a later reference[3] Neville has summarized several investigations which lead to the conclusion that the compressive strength of 2-in. cubes is about 18% greater than the strength of 6x12-in. cylinders (see attached Figures 8.19 and 8.21).

Figure 8.19 shows that the strength of 2-in. cubes is about 8% greater than that of 6-in. cubes. Figure 8.21 shows that the strength of 6-in. cubes is about 10% greater than that of 6x12-in. cylinders. Therefore, considering these two together, the strength of 2-in. cubes is about 18% greater than 6x12-in. cylinders.

Gilkey[4] reported the ratio of strength of 6x12-in. cylinders to 2-in. cubes to be 0.88.

Other factors should be considered in estimating the strength of 6x12-in. cylinders from the strength of cubes cut from the remnants:

Reference 2 states that:

> "A core may be inherently weaker than a cylinder because the surface of a core includes cut pieces of aggregate, many of which will only be retained in the specimen by adhesion to the matrix. Such particles are likely to contribute little to the strength of the core."

Bloem[5] has shown that the operation of drilling can damage cores. The strength of cores was 7% lower than the strength of

push-out cylinders. It seems reasonable that the same might be said of sawed cubes.

It is generally accepted that the diameter of a cylinder or side of a cube should be 3 to 4 times the maximum size aggregate. Test samples with a smaller ratio of minimum dimensions to maximum size aggregate will produce lower compressive strengths. The 2-in. cube with 3/4-in. aggregate did not meet this recommendation.

The ACI Building Code[5] provides that if the strength of cores from the structure equals 85% of control cylinders the concrete is acceptable. It wculd appear that a similar factor would be appropriate for the cubes cut from the body of the cylinders to allow for potential damage to the samples.

In summary, research data do not reveal a precise relationship between strength of 6x12-in. cylinders and 2-in. cubes, but indicate a range of values from about 0.92 to 0.67 with an average of 0.80. This factor was used in our previous report dated April 19, 1978, and still seems appropriate.

J. J. Shideler, Director
Administrative and Technical Services

JJS/md
CT-0539

February 27, 1979

References

1. Neville, A.M., "A General Relation of Strength of Concrete Specimens of Different Shapes and Sizes," ACI Journal, October 1966, pp. 1095-1109.

2. Concrete Society Technical Report, "Concrete Core Testing for Strength," 1976, p. 34.

3. Neville, A.M., "Properties of Concrete" (book), pp. 490-492.

4. Gilkey, H.J., "Discussion of Modified Cube Test," Proc. ASTM Vol. 34, Part II, 1934, p. 415.

5. Bloem, D.L., "Concrete Strength in Structure," ACI Journal, March 1968, p. 176.

6. "Building Code Requirements for Reinforced Concrete - ACI 318-77," American Concrete Institute.

14. Brotchie, J. F., "General Elastic Analysis of Flat Slabs and Plates," ACI JOURNAL, *Proceedings* V. 56, No. 2, Aug. 1959, pp. 128-152.

15. Brotchie, J. F., "Direct Design of Plate and Shell Structures," *Proceedings*, ASCE, V. 88, ST6, Dec. 1962, pp. 1?-146.

16. Brotchie, J. F., "Direct Design of Prestressed Concrete Flat Plate Structures," *Constructional Review*, (Sydney), V. 37, No. 1, Jan. 1964, pp. 13-15.

This is Part 1 of an ACI two-part paper. The second part will not be published in the JOURNAL but xerographic or similar copies are available from American Concrete Institute headquarters, where it will be kept permanently on file, at a charge equal to cost of reproduction plus handling at time of request. For a time, 6 x 9 in. offset printed copies of Part 2 may be ordered at a substantial saving; see the News Letter for details. Part 2 contains details on ultimate strength of bonded balanced plates and load balancing versus moment balancing.

Received by the Institute Aug. 30, 1965. Title No. 63-51 is a part of copyrighted JOURNAL of the American Concrete Institute, Proceedings V. 63, No. 10, Oct. 1966. Separate prints are available at 60 cents each, cash with order.

American Concrete Institute, P.O. Box 4754, Redford Station, Detroit, Michigan 48219

Discussion of this paper should reach ACI headquarters in triplicate by Jan. 1, 1967, for publication in the Part 2 June 1967 JOURNAL. (See p. iii for details.)

Sinopsis—Résumé—Zusammenfassung

Diseño Racional de Placas

Se describen métodos de diseño óptimo desarrollados recientemente para placas de concreto reforzado y presforzado y se presentan métodos simplificados para determinar la carga de agrietamiento y la carga máxima de placas presforzadas optimizadas. Los métodos propuestos se comparan con otras técnicas de diseño.

Une Technique Rationnelle pour le Dimensionnement des Plaques

L'auteur décrit des méthodes de dimensionnement optimal récemment développées pour les plaques en béton armé et en béton précontraint et présente des méthodes simplifiées pour la détermination de la charge de fissuration et de la charge ultime pour les plaques précontraintes optimisées. Les méthodes proposées sont comparées avec d'autres techniques de dimensionnement.

Wirklichkeitsnahe Methoden zum Entwurf von Platten

Das Prinzip von in jüngerer Zeit entwickelten Methoden zum optimalen Entwurf von bewehrten und vorgespannten Platten wird beschrieben, und vereinfachende Methoden zur Bestimmung von Riss- und Bruchlast von optimal bemessenen vorgespannten Platten werden aufgezeigt. Die vorgeschlagenen Methoden werden mit anderen Entwurfsverfahren verglichen.

POOR ORIGINAL

1050 268

A General Relation for Strengths of Concrete Specimens of Different Shapes and Sizes

By ADAM M. NEVILLE

It is shown that the strengths of concrete test specimens (cylinders, cubes, and prisms) can be related to one another by simple expressions. Substantiating test results are presented. The secondary influence of the fineness modulus of aggregate on this relation is discussed.

Key words: compression tests; compressive strength; concrete; correlation; cubes; cylinders; fineness modulus; prisms.

THE NEED TO COMPARE OR CONVERT the strength of different types of concrete specimens arises from the fact that in different countries various standard test specimens are used. Furthermore, the use of cores (whose height to diameter ratio may not always be controlled) and of modified (equivalent) cubes makes conversion necessary. In some cases, standard conversion factors are available, e.g., ASTM Standard C42-64 or British Standard B.S. 1881: 1952. The problem has been investigated by several workers, notably Gonnerman,[1] Neville,[2] Murdock and Kesler,[3] and Kuczynski,[4] but a generalized treatment for any shape and size is believed not to have been attempted before.

The present paper is limited to concretes made with ordinary aggregate.

GENERAL RELATION

As a first attempt of finding an over-all, albeit gross, relation between the strength of a concrete specimen and its size and shape, it is suggested that strength is a function of three variables: V, the volume of the specimen; d, its maximum lateral dimension; and h/d, its height to lateral dimension ratio. These variables may not be independent of one another. The last of them is a well-known effect, recognized by various standards. The influence of d is probably in the form $P \propto 1/d'$ (where P is strength of the specimen) and arises from considerations of the probability of occurrence of an element containing a weakest link of a given level of strength. Lastly, V is thought to influence the

ACI member Adam M. Neville is dean of the Faculty of Engineering, University of Alberta, Canada. Dr. Neville was formerly professor of concrete technology at the University of Saskatchewan. Earlier he had served on the University of Manchester (England) faculty. In 1960 he was appointed dean of engineering at the Nigerian College of Technology. He received the 1960 Research Award of the Institution of Structural Engineers (England), the 1961 Medal of the Reinforced Concrete Association (England), and recently the University of London research degree of DSc (Eng). He also served as dean of Graduate Studies at University of Calgary. A frequent JOURNAL contributor, he is currently chairman of ACI Committee 209, Creep and Volume Changes in Concrete; a member of Committee 115, Research; a member of Committee 214, Evaluation of Results of Strength Tests of Concrete; and a member of the Standards Committee.

observed strength since a greater volume of the specimen leads to a more uniform stress distribution, and therefore a lesser likelihood of premature failure.

We can thus postulate:

$$P = F\left(\frac{V}{\frac{h}{d}, d^2}\right) \qquad (1)$$

More specifically:

$$P = F\left(\frac{V}{\frac{h}{d} \times d^2}\right)$$

or

$$P = F\left(\frac{V}{hd}\right) \qquad (2)$$

It is realized that the strength of a concrete specimen may also be influenced by other factors, such as the modulus of elasticity of the aggregate, its Poisson's ratio, the aggregate-cement ratio but since no experimental data on these factors are available they will perforce be ignored in the present approximate analysis.

Test results on cylinders with h/d ratio of 1 and 2, prisms with h/d ratio of 2 and 3, and cubes of 11 investigators, some of whom have not been concerned with the problem in hand but provided suitable data, were available to establish the form of Eq. (1). These are: Gonnerman[1] (1925); Blanks and McNamara[5] (1935); Gyengo[6] (1938); Cormack[7] (1956); Neville[2] (1956); Akroyd[8] (1957); Harman[9] (1957); Kuczynski[4] (1960); Hummel, Wesche, and Brand[10] (1962); Kankam[11] (1962); and U.S. Bureau of Reclamation[12] (1963). The data refer to many different concretes, cured in various ways and tested at a number of ages.

To make comparable the results of these different investigations on a wide variety of concretes, it is desirable to refer the strength of a specimen of any dimensions to the strength of a "standard" specimen. In the present case a 6-in. cube made of the same concrete was chosen

since this type of specimen was used by more investigators than any other. In three cases, Blanks and McNamara,[5] Hummel et al.,[10] and U.S. Bureau of Reclamation,[12] no results for 6-in. cubes were availab[illegible] In these cases the strength of a 6-in. cube was assumed to be 1/0.83 the strength of a 6 x 12-in. cylinder. The cylinder-cube ratio of 0.[illegible] is an average of the values prescribed by ASTM Standard C42-64 (0.9[illegible]) and by British Standard B.S. 1881:1952 (0.75). The same result [illegible] obtained from L'Hermite's[18] formula:

$$\frac{P_c}{P_k} = 0.76 + 0.2 \log_{10} \frac{P_k}{2840}$$

for $P_k = 6350$ psi, where

P_c = strength of cylinder, psi, and

P_k = strength of cube of same lateral dimension, psi

It should be noted that the relation developed later [Eq. (3)] f[illegible] the data of all the eleven investigators listed above yields a value [illegible] $P_c/P_k = 0.81$.

A general form of Eq. (2) can therefore be written in nondimension form:

$$\frac{P}{P_6} = F\left(\frac{V}{V_6}, \frac{h}{h_6}, \frac{d}{d_6}\right) \qquad (2a)$$

where the subscript 6 refers to a 6-in. cube.

It has been found empirically that a hyperbolic relation exists between P/P_6 and a dimensionless term:

$$\frac{\frac{V}{hd}}{\frac{V_6}{h_6 d_6}} + \frac{\frac{h}{d}}{\frac{h_6}{d_6}}$$

Since in a 6-in. cube $h_6 = d_6$, and $V_6/h_6 d_6 = 6$ in., the term reduces to:

$$\frac{V}{6hd} + \frac{h}{d}$$

with all dimensions in inches.

The relation between this quantity and P/P_6 is shown in Fig. 1, and Fig. 2 shows the rectified plot of:

$$\frac{P}{P_6} \text{ versus } \frac{d}{\frac{V}{6h} + h}$$

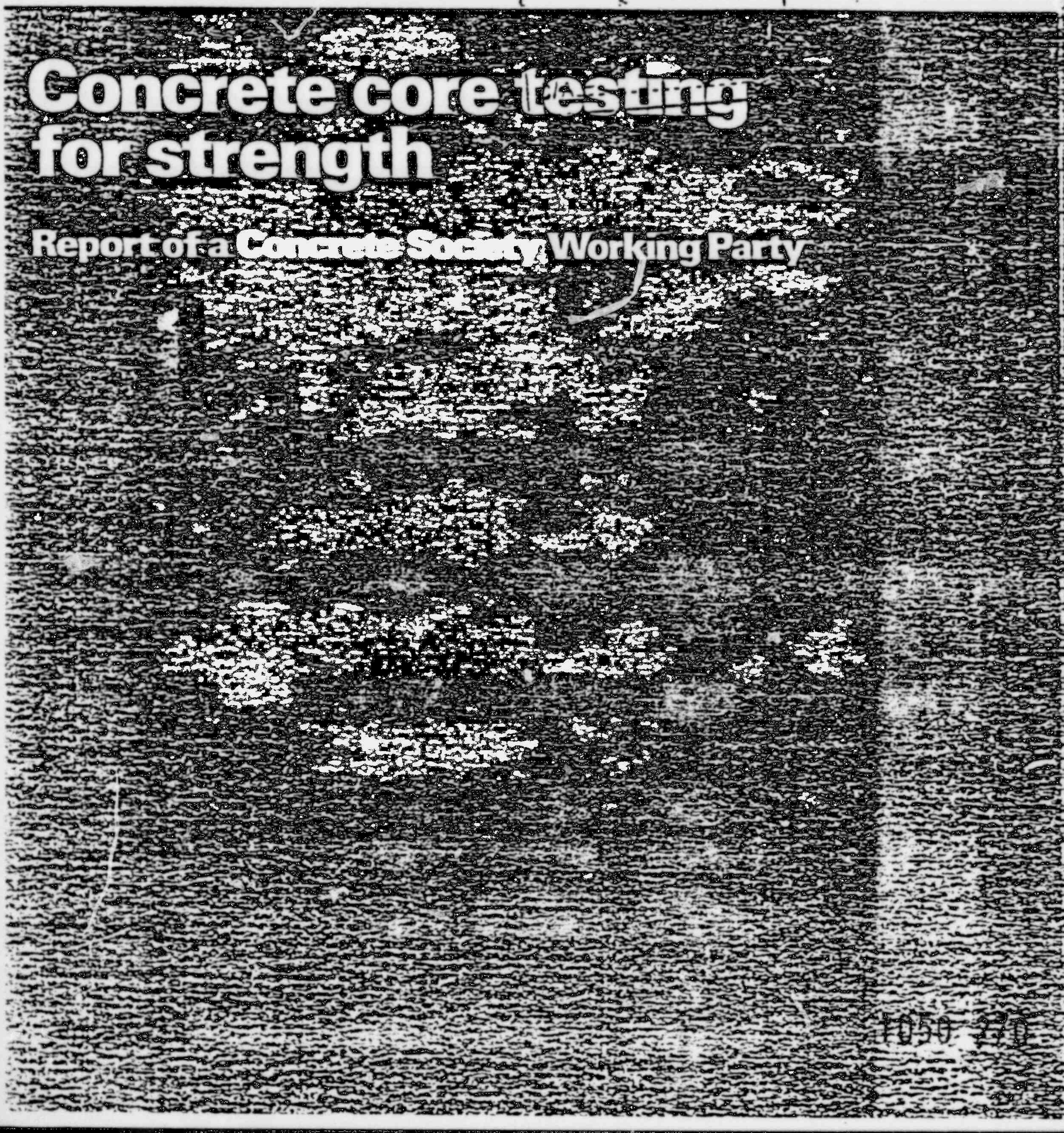
TABLE 1 — KEY TO SOURCES O[illegible] DATA FOR FIG. 1, 2, 3, AND [illegible]

Symbol	Investigator	Reference
▲	Gonnerman	1
▽	Neville	2
◻	Kuczynski	4
◊	Blanks and McNamara	5
-○-	Gyengo	6
△	Cormack	7
×	Akroyd	8
▼	Harman	9
♦	Hummel, Wesche, and Brand	10
○	Kankam	11
+	U.S. Bureau of Reclamation	12

Concrete Society Technical Report No. 11

Concrete core testing for strength

Report of a Concrete Society Working Party



Introduction

The procedures for estimating Actual and Potential Strength recommended in Part 3 are based upon information gained from practice and research. The object of this Part is to summarize the available knowledge, so enabling the validity and limitations of the recommendations to be assessed and indicating aspects of the subject which would merit further investigation.

Relationship between Core Strength and Actual Strength

The main factors which need to be considered when relating the Core Strength to the Actual Strength are:

(1) diameter of core;
(2) length/diameter ratio of core;
(3) direction of drilling;
(4) shape of specimen;
(5) method of capping;
(6) effect of drilling operation;
(7) reinforcement;
(8) curing of core;
(9) moisture condition of core;
(10) flaws in core.

4" + 6"

Diameter of core

British Standard 1881[1] states that cores shall have a diameter of either 100 or 150 mm. This standard does not relate the permissible diameter of the core to the maximum aggregate size, but standards[2-4] of other countries state that the diameter of the core should be at least three times the nominal maximum size of the aggregate.

Several investigators[5-11] have examined the results of drilling cores with a diameter of less than three times the nominal maximum size of the aggregate. For example, cores having a diameter of 50 mm have been taken from concrete made with aggregate of 20 mm maximum size[6]. For a given height/diameter ratio, little, if any, difference was noted between the mean strengths yielded by cores of 50 and 100 mm diameters, but the smaller cores tended to produce more variable results. Similar results were obtained during an investigation on the strengths of cores of 50, 100 and 150 mm diameter drilled from concrete with a maximum aggregate size of 30 mm[9]. In this case, it was shown that the testing error associated with 50 mm diameter cores was about twice that associated with 150 mm cores. This implies that, to obtain a similar degree of accuracy, more cores should be drilled if these are of small diameter.

Evidence is also available on the strengths of cores having a diameter equal to the maximum size of aggregate in the concrete. Cores of 150, 200 and 250 mm diameters were cut from concrete with aggregate of 150 mm maximum size; all yielded similar mean strengths[10]. The testing error again increased as the diameter of the cores was reduced.

Another investigation[11] involved the testing of cores of 35, 50, 75 and 100 mm diameter with mixes having maximum aggregate sizes of 4, 8 and 16 mm. It was found

Table 3 Relative strength of cores of different diameters.

Reference	Number of cores	Strength of 100 mm dia. cores / Strength of 150 mm dia. cores
6	50	0·98
9	716	1·04
28	48	0·80*
31	—	1·00
36	128	1·05

*Several investigators have commented upon this result but there seems to be no explanation for its contrasting with other evidence.

pressive strength of concrete with aggregate of 30 mm maximum size is permitted by the relevant Swiss standard[12].

Apart from tests on cores having a diameter less than three times the maximum aggregate size, the effect of size upon the compressive strength of different types of specimen, including cores, cylinders and cubes, has been studied by many investigators[6,8,9,11,13-34]. It is generally accepted that the strength tends to increase with decreasing size of specimen, there being several influencing factors which are discussed by various authors[8,17,25,37-41]. Any difference between the compressive strengths of 100 mm and 150 mm cubes is, however, so small that both RILEM[42] and CEB[43] suggest that it is of no significance.

Results of substantial programmes of tests on cores of 100 and 150 mm diameter, given in Table 3, indicate that, generally, the diameter has little, if any, effect upon the measured strength.

Length/diameter ratio of cores

The measured strength of a core decreases as the ratio of its length to its diameter, λ, increases. This report recommends that, when capped ready for test, a core should have a length/diameter ratio of between 1·0 and 1·2. It is, therefore, convenient to correct the measured strength of any core to obtain the strength which would have been obtained had the core a length/diameter ratio of 1·0.

The effect of the length/diameter ratio upon the strength of a cast cylinder or a core has been studied by many investigators[13,19,20,27,29,35,36,38,40,44-49]; the results of the tests are summarized in Table 4, all the data being based upon a specimen having a length/diameter ratio of 1·0. It is evident that there is a considerable range in the findings; it seems clear, however, that the relationship given in BS 1881[1] underestimates the difference in measured strength associated with a change in length/diameter ratio.

A detailed study of the results obtained in the various investigations suggests that the strength, f_1, of a core having a length/diameter ratio of 1, can be estimated from the strength, f_λ, of a core having a length/diameter ratio of λ, by the formula:

$$f_1 = \frac{2{\cdot}5 f_\lambda}{1{\cdot}5 + 1/\lambda}$$

1050 271

It follows from this formula that the strength, f_2, of a core having a length/diameter ratio of 2, is yielded by the

 Cor **POOR ORIGINAL**

Introduction

The procedures for estimating Actual and Potential Strength recommended in Part 3 are based upon information gained from practice and research. The object of this Part is to summarize the available knowledge, so enabling the validity and limitations of the recommendations to be assessed and indicating aspects of the subject which would merit further investigation.

Relationship between Core Strength and Actual Strength

The main factors which need to be considered when relating the Core Strength to the Actual Strength are:

(1) diameter of core;
(2) length/diameter ratio of core;
(3) direction of drilling;
(4) shape of specimen;
(5) method of capping;
(6) effect of drilling operation;
(7) reinforcement;
(8) curing of core;
(9) moisture condition of core;
(10) flaws in core.

4" + 6"

Diameter of core

British Standard 1881[1] states that cores shall have a diameter of either 100 or 150 mm. This standard does not relate the permissible diameter of the core to the maximum aggregate size, but standards[2-4] of other countries state that the diameter of the core should be at least three times the nominal maximum size of the aggregate.

Several investigators[5-11] have examined the results of drilling cores with a diameter of less than three times the nominal maximum size of the aggregate. For example, cores having a diameter of 50 mm have been taken from concrete made with aggregate of 20 mm maximum size[6]. For a given height/diameter ratio, little, if any, difference was noted between the mean strengths yielded by cores of 50 and 100 mm diameters, but the smaller cores tended to produce more variable results. Similar results were obtained during an investigation on the strengths of cores of 50, 100 and 150 mm diameter drilled from concrete with a maximum aggregate size of 30 mm[9]. In this case, it was shown that the testing error associated with 50 mm diameter cores was about twice that associated with 150 mm cores. This implies that, to obtain a similar degree of accuracy, more cores should be drilled if these are of small diameter.

Evidence is also available on the strengths of cores having a diameter equal to the maximum size of aggregate in the concrete. Cores of 150, 200 and 250 mm diameters were cut from concrete with aggregate of 150 mm maximum size; all yielded similar mean strengths[10]. The testing error again increased as the diameter of the cores was reduced.

Another investigation[11] involved the testing of cores of 35, 50, 75 and 100 mm diameter with mixes having maximum aggregate sizes of 4, 8 and 16 mm. It was found

Table 3 Relative strength of cores of different diameters.

Reference	Number of cores	Strength of 100 mm dia. cores / Strength of 150 mm dia. cores
6	50	0·98
9	716	1·04
28	48	0·80*
31	—	1·00
36	128	1·05

*Several investigators have commented upon this result but there seems to be no explanation for its contrasting with other evidence.

pressive strength of concrete with aggregate of 30 mm maximum size is permitted by the relevant Swiss standard[12].

Apart from tests on cores having a diameter less than three times the maximum aggregate size, the effect of size upon the compressive strength of different types of specimen, including cores, cylinders and cubes, has been studied by many investigators[6,8,9,11,13-38]. It is generally accepted that the strength tends to increase with decreasing size of specimen, there being several influencing factors which are discussed by various authors[8,17,28,37-41]. Any difference between the compressive strengths of 100 mm and 150 mm cubes is, however, so small that both RILEM[42] and CEB[43] suggest that it is of no significance.

Results of substantial programmes of tests on cores of 100 and 150 mm diameter, given in Table 3, indicate that, generally, the diameter has little, if any, effect upon the measured strength.

Length/diameter ratio of cores

The measured strength of a core decreases as the ratio of its length to its diameter, λ, increases. This report recommends that, when capped ready for test, a core should have a length/diameter ratio of between 1·0 and 1·2. It is, therefore, convenient to correct the measured strength of any core to obtain the strength which would have been obtained had the core a length/diameter ratio of 1·0.

The effect of the length/diameter ratio upon the strength of a cast cylinder or a core has been studied by many investigators[13,19,20,27,29,35,36,38,40,44-49]; the results of the tests are summarized in Table 4, all the data being based upon a specimen having a length/diameter ratio of 1·0. It is evident that there is a considerable range in the findings; it seems clear, however, that the relationship given in BS 1881[1] underestimates the difference in measured strength associated with a change in length/diameter ratio.

A detailed study of the results obtained in the various investigations suggests that the strength, f_1, of a core having a length/diameter ratio of 1, can be estimated from the strength, f_λ, of a core having a length/diameter ratio of λ, by the formula:

$$f_1 = \frac{2{\cdot}5 f_\lambda}{1{\cdot}5 + 1/\lambda}$$

1050 272

It follows from this formula that the strength, f_2, of a core having a length/diameter ratio of 2, is yielded by the

able 4 Relative strength of cores of different length/diameter ratios.

	Relative strength										
	Cylinders						Cores				
5	1·53	1·52	1·33	1·30	1·52	—	1·39	—	1·37	—	—
0	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00
5	0·88	0·88	0·89	0·90	—	0·87	0·83	0·82	0·88	0·84	0·95
0	0·85	0·86	0·83	0·87	0·86	0·84	0·84	0·75	0·81	0·82	0·92
0	—	0·81	0·78	—	0·84	—	—	—	—	0·80	—
eference	44	13	20	46	47	29	46	48	36	38	BS 1881

irection of drilling

ny heterogeneity in the concrete which is related to the rection of casting may have a different effect upon the rength of the core, depending upon the direction of drilling. Evidence regarding the effect is conflicting. The esults of an investigation[29,30] on cores drilled from olumns indicated that the strength was about 12% less if e cores were tested at right-angles to the direction of lacing. More extensive tests by the same author[32] indicated a difference of only 3%, which is not statistically gnificant.

Johnson[45] found that cylinders cast with their axes orizontal had a compressive strength about 5% less than at of cylinders cast in the normal manner; Bloem[51] ound the difference to average 15%. Other results[15,52-54] ndicate that the compressive strength of cubes tested in e direction of casting may be similar to that of cubes ested at right-angles to the direction of casting or up to 0% higher.

Recognizing the discrepancies between results reported y the various investigators, Johnston[55] cast prisms from range of 23 mixes. The findings from this carefully controlled programme indicated that the strength of prisms vas 8% higher if these were tested in the same orientation s cast. The magnitude of this difference was similar for all ormal-weight structural concrete.

This finding was in accord with results obtained by the Bureau of Reclamation[56,57] from a total of 237 cores rilled vertically and horizontally from two dams. These wo investigations indicated that, on average, vertically rilled cores were stronger than horizontally drilled cores y 7 and 9% respectively.

Shape of specimen

Most of the available information relating the strengths of cylindrical and cubical test specimens is based upon tests on cast specimens rather than samples cut from a larger concrete mass. The measurements are usually made on standard test cubes and cylinders and so any observed elationship includes the orientation effect.

The considerable volume of information[5,15,20,30,36,48-50,58-71] indicates that the relationship between cylinder and cube strengths is not unique but depends upon factors such as the concrete mix and the precise methods of test. A summary paper produced by RILEM[19] shows that the ratio between the strengths of cubes and of cylinders with a ength/diameter ratio of 2 has been found to vary from 0·9 and 1·5. A study of the information suggests that it is difficult to be more precise than to assume that the trength of a cube is 1·25 times that of a cylinder having a recommendations made by RILEM[42] and CEB[43] and is specified in BS 1881 for converting a corrected cylinder strength, obtained from a core test, to the equivalent cube strength.

Method of capping

Before being tested in accordance with BS 1881, the two ends of a core must be capped with a high-alumina-cement mortar, a sulphur–sand mixture or by other suitable means. The thickness and composition of the caps have some influence upon the strength of a core, as evidenced by several authors[15,16,27,32,49,71-84] but the effect is generally of no practical significance, provided that the capping material is not inherently weaker than the concrete and that the caps are sound and flat and perpendicular to the axis of the core, within the tolerances quoted in BS 1881. This conclusion is in agreement with the finding[74,85] that the same compressive strength is yielded by cylinders capped with neat cement or a mixture of sulphur and fire clay as is obtained from cylinders having ground end faces. It has been reported[83], however, that filled polyester resins are not suitable for capping, as they reduce the strength by up to 20%. It has also been found[32] that the use of filled polyester resins increases the variation in measured strengths.

Effect of drilling operation

It has been suggested that the operation of drilling can damage a core and hence reduce its compressive strength. Such damage is sometimes apparent when drilling immature or inherently weak concrete, but normally it is not possible to see any deleterious effects on the cut surface of a core.

A core may be inherently weaker than a cylinder because the surface of a core includes cut pieces of aggregate, many of which will only be retained in the specimen by adhesion to the matrix. Such particles are likely to contribute little to the strength of the core.

In the course of two investigations, sleeved cylinders have been cast within concrete slabs. Campbell and Tobin[28] cast 150 mm diameter metal sleeves in each of four 300 mm thick slabs. At ages of 28, 56 and 91 days, the strengths of pairs of these cylinders were compared with the strengths of pairs of cores of the same size and shape. On average, the cylinders had a strength 5% greater than the strength of the cores.

Similar tests are described by Bloem[86]. Pairs of slabs were cast from each of three concrete mixes, one being well cured and one poorly cured. Each slab was provided with 36 plastics inserts to enable cylinders to be abstracted

of 36 corresponding cores taken from each slab. The correlation between the strengths of the push-out cylinders and the cores was good and indicated that the compressive strength of the cylinders was 7% greater than the strength of the corresponding cores.

Reinforcement

The effect of reinforcing bars upon the strength of cylinders has been studied in the United States[87]. A total of 66 cylinders was cast, some unreinforced, some with one bar perpendicular to the axis and others with two mutually perpendicular bars, both perpendicular to the axis. The particular location of the bars was found to have little effect upon the strength of the cylinders. The average reductions in strength are given in Table 5.

Similar tests[69,71] have been conducted on 170 cylinders, 300 mm long x 150 mm diameter, some of which contained single bars of 10 or 20 mm diameter, set at various depths and distances from the axis. The cylinders were tested after being stored for 26 days in air followed by 2 days in water. The average percentage reductions in strength are given in Table 6.

A series of tests conducted in Germany[58] involved the testing of more than 300 cores, 151 mm high and 99 mm in diameter, cut in a vertical direction from slabs. Variables included the percentage reinforcement, the number of bars, the positions of the bars and the strength of the concrete. The results indicated that as much as 3·4% by volume of reinforcement (two 18 mm bars) had little effect upon the measured strength, the maximum reduction being 3%.

Table 5 Average reduction in strength due to presence of one or two bars.[87]

Diameter of bar (mm)	Number of bars	Reduction in strength (%)
12	1	8
	2	11
25	1	9
	2	13

Table 6 Average reduction in strength due to presence of bars at different positions.[69,71]

Diameter of bar	Distance from axis	Reduction in strength (%) at distance from top of cylinder of		
(mm)	(mm)	50 mm	150 mm	250 mm
10	0	1·5	2·6	3·8
	50	3·3	1·6	−0·4
20	0	3·5	11·6	−0·1
	50	10·4	8·6	5·4

Curing of core

Once a core has been cut, the method of curing, and hence the rate of strength development, will differ from that of the parent concrete. The difference in strength at the time of test will depend upon the maturity of the concrete at the time of drilling and any difference in the subsequent hydration of the specimen and the parent concrete is likely to be small; in any case, it will be very difficult to make a realistic allowance for the effect any difference may have upon the relative strengths of the core and of the concrete it represents.

Moisture condition of core

The measured strength of a core is dependent upon its moisture condition[86]. BS 1881 requires that a core shall be immersed for a period of at least 48 h prior to test and that it shall still be wet when tested; this requirement is similar to that which applies to compressive tests on other concrete specimens including cubes. In principle, the effect of the moisture content at the time of test is not considered to be a characteristic of the concrete affecting its inherent strength but to be a parameter associated with the testing technique. Thus, it is akin to the rate of loading, which similarly affects the measured strength and is, therefore, also standardized. Provided a core is tested wet, therefore, it is not necessary to allow for the difference in moisture content when inferring the strength of the parent concrete.

Some authorities[3,4,33,35,89] do not share this opinion and advocate that the core at the time of test should be dry or have a moisture condition similar to that of the parent concrete in the structure. Account must be taken of the moisture condition at the time of test when reviewing results quoted by various investigators.

Flaws in core

There are many faults which can occur in a core; these include cracks due to a variety of causes, voids due to water gain beneath horizontal reinforcement and voids left upon removal of an immersion vibrator from a mix of low workability. The information gained upon examining such a core can be of considerable value, but the measured strength of the core is likely to be low and not indicative of the Actual Strength of the concrete.

Estimation of Actual Strength

The definition of the Actual Strength of the concrete within an element must be related to a specific test method. It would be possible to base the strength upon tests on a core of a given length/diameter ratio or on a sawn cube. The results of tests on the latter type of specimen would not, however, be directly comparable with strengths measured on cast cubes. Differences between Actual and Potential Strength would reflect both real differences between the two materials and effects of the different specimens. The latter effect can only be eliminated by expressing the Actual Strength in terms of tests on cast cubes, although these are hypothetical test specimens in that they cannot be produced from the concrete in the element.

The Actual Strength can be assessed from the Core Strength by considering the six specimens illustrated in Figure 5. These are:

1(a) core drilled horizontally*, length/diameter = λ
1(b) core drilled vertically, length/diameter = λ
1(c) core drilled vertically, length/diameter = 2
2(a) cylinder with top layer removed, length/diameter = 2
2(b) cylinder as cast, length/diameter = 2 ...

1050 274

POOR ORIGINAL

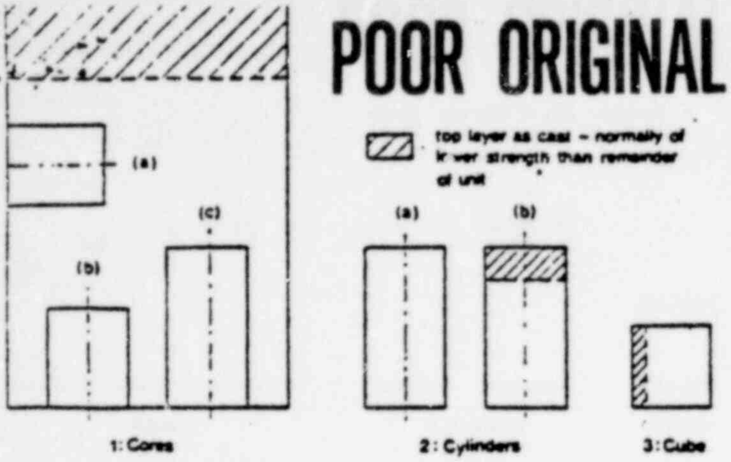


Figure 5: Types of specimen used in relating Core Strength and Actual Cube Strength.

The conversion process is as follows.

1(a) to 1(b) The difference between the strengths of these specimens is associated with the direction of drilling. On average, the strength of a core drilled vertically is about 8% greater than that of a core drilled horizontally. If the strength of 1(a) is p, the estimated strength of 1(b) is $1{\cdot}08p$.

1(b) to 1(c) The effect of the length/diameter ratio upon core strength is such that

$$\text{the strength of 1(c)} = \frac{2}{1{\cdot}5 + 1/\lambda} \times \text{the strength of 1(b)}$$

$$= \frac{2{\cdot}16p}{1{\cdot}5 + 1/\lambda}$$

1(c) to 2(a) The difference between the strengths of these specimens is associated with the fact that the cylinder has a cast, rather than a cut, surface. Experiments have indicated that a specimen with a cast surface has a strength about 6% greater than the core. Therefore,

$$\text{the strength of 2(a)} = 1{\cdot}06 \times \text{the strength of 1(c)}$$

$$= \frac{2{\cdot}29p}{1{\cdot}5 + 1/\lambda}$$

2(a) to 2(b) The strength of the latter is lower because of the presence of the weaker material near the top. There is little direct evidence on the magnitude of this decrease but a general examination of the reduction in strength towards the top of a layer of concrete, the strengths of cores drilled from cubes and the relationship between actual and potential strength suggests that a value of 15% will yield results consistent with the available evidence. On this basis, it can be estimated that

$$\text{the strength of 2(b)} = \text{the strength of 2(a)} \times \frac{1}{1{\cdot}15}$$

$$= \frac{2p}{1{\cdot}5 + 1/\lambda}$$

2(b) to 3(a) There is a considerable volume of data on the relationship between the strength of a cube, tested on its side, and a cylinder. The best average estimate is that the cube strength is 25% greater than the cylinder strength. Hence

$$\text{the strength of 3(a)} = 1{\cdot}25 \times \text{the strength of 2(b)}$$

$$= \frac{2{\cdot}5p}{1{\cdot}5 + 1/\lambda}$$

It may be noted that if $\lambda = 1$, the strength of 3(a) $= p$. This means that the strength of a core of length/diameter ratio 1, drilled horizontally, is similar to that of a cube; this is in line with evidence provided by tests made upon cores drilled from cubes. This is summarized in Table 7.

The Estimated Actual Strength, f_{act} is, therefore, yielded by the equations:

$$f_{act} = \frac{2{\cdot}5f_\lambda}{1{\cdot}5 + 1/\lambda}$$

if cores are drilled in a horizontal direction;

$$f_{act} = \frac{2{\cdot}3f_\lambda}{1{\cdot}5 + 1/\lambda}$$

if cores are drilled in a vertical direction.

Table 7 Evidence on relationship between core strength and cube strength.

Ref.	Cube size (mm)	Core diameter (mm)	L/D of cores, λ	Core strength / Cube strength	Approximate cube strength (N/mm^2)
5	200	50	1·12	1·04*	10 to 50
30	150 and 200	100 and 150	1	1·02 to 1·05 0·86 to 1·16	31 68 and 80†
49	150	100	1	1·03 0·97	60 30
36	200	100 150	1	1·05 1·00	12 to 70 12 to 70
32 and 35	150	70 and 100	1	1·04	25 and 60

1050 275

Table 11 Relative strength of cores from structures and test cubes.

Direction of drilling	Core strength / Cylinder strength	Core strength / Cube strength	28 day cube strength (N/mm²)	Age of cores (days)	Ref.
core L/D = 2	0·89	(0·71)	16 to 39	28	10
	0·94	0·89	16		
	0·84	0·74	31	28	48[1,2]
	0·75	0·64	49		
	0·91	(0·73)	44	93	81
	0·79	(0·63)			
Vertical	0·81	(0·65)	28	90	102[3]
	0·63	(0·50)	47		
	0·70	(0·56)	36	30	86[1]
	0·77	(0·62)	32		
	0·82	(0·66)	27	93	6
	0·88 0.81	(0·70)	44	91	114[2]
	(0·88)	0·71	35	34	70[4]
	0·85	(0·68)	37	93	81
	0·81	(0·65)			
	0·73	(0·58)	27	93	6
Horizontal	(1·13)	0·91	68	40	104[5]
	(1·10)	0·88	52		
	(0·89)	0·71	45 to 75	28	32[6]
	0·85	(0·68)	37	91	114
Both	(0·85)	0·68	—	28	121[7]

Notes
(1) Cores taken from full depth of slab
(2) Cores tested in moist condition
(3) Core strengths corrected from results of tests on cores with λ = 1·0
(4) Core strengths corrected from results of tests on cores with λ = 1·1
(5) Core strengths corrected from results of tests on cores with λ = 3·0
(6) Cores tested in dry condition
(7) Results based upon tests on 24 sites

Table 12 Relative strength of standard cylinders and cores from structures.[49]

Strength of standard cylinders (N/mm²)	Strength of cores (N/mm²)	Reduction in strength (%)
20	19	5
30	27	10
40	36*	15*
50	42·5	15

*Figures mathematically inconsistent

Table 14 Relative strength of concrete from actual structures and in cubes.[107]

Element	Number of sites	Mean ratio of Actual Strength to Potential Strength
Columns	3	0·68
Walls	2	0·59
Slabs	2	0·45

Table 13 Comparison of strength values yielded by use of formulae recommended here for Potential Strength and by use of data in BS 1881.

Method	Direction of drilling: Horizontal			Vertical		
	λ = 1*	λ = 1·2*	λ = 2	λ = 1*	λ = 1·2*	λ = 2
A: Formulae	1·30f_λ	1·39f_λ	1·62f_λ	1·20f_λ	1·29f_λ	1·50f_λ
B: BS 1881	1·15f_λ	1·17f_λ	1·25f_λ	1·15f_λ	1·17f_λ	1·25f_λ

Neville Reference 3

in indirect tension.[8.44] Fig. 8.19 shows the relation between mean strength and specimen size for cubes, and Table 8·4 gives the relevant values for

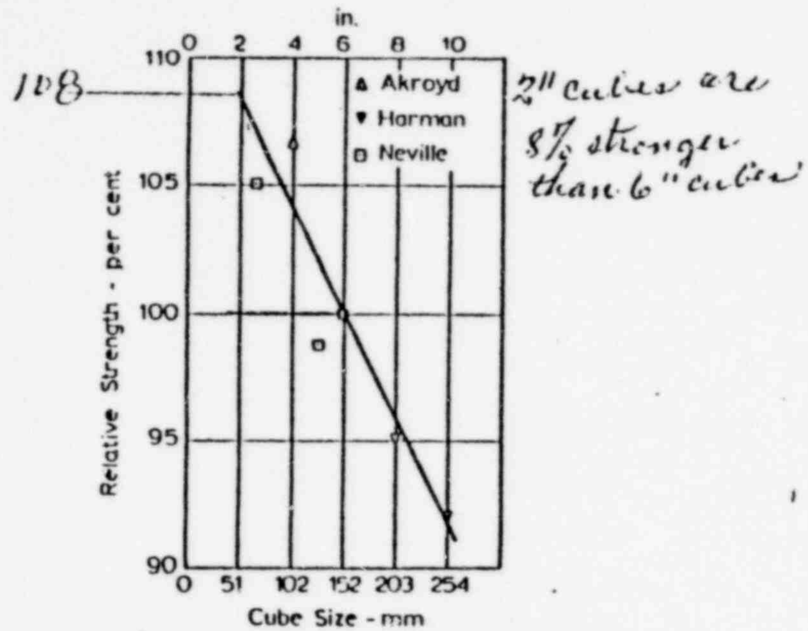


Fig. 8.19. *Compressive strength of cubes of different sizes*[8.38]

standard deviation. Prisms[8.36, 8.37] and cylinders exhibit a similar behaviour (Fig. 8.20). The size effects are, of course, not limited to concrete, and have been found also in anhydrite[8.38] and other materials.

It is interesting to note that the size effect disappears beyond a certain size so that a further increase in the size of a member does not lead to a decrease in strength. According to the Bureau of Reclamation,[8.77] the strength curve becomes parallel to the size axis at a diameter of 457 mm (18 in.), i.e. cylinders of 457 mm (18 in.), 610 mm (24 in.), and 914 mm (36 in.) diameter all have the same strength. The same investigation indicates that the decrease in strength with an increase in size of the specimen is less pronounced in lean mixes than in rich ones. For instance, the strength of 457 mm (18 in.) and 610 mm (24 in.) cylinders relative to 152 mm (6 in.) cylinders is 85 per cent for rich mixes but 93 per cent for lean (167 kg/m^3 (282 lb/yd^3)) mixes (*cf.* Fig. 8.20).

These experimental data are of interest as it could be speculated that, if the size effect is extrapolated to very large structures, a dangerously low strength might be expected. Evidently this is not so.

The various test results on the size effect are of interest because in the

POOR ORIGINAL

in a greater number to give the same precision of the mean: five to six 100 mm (4-in.) concrete cubes would be required instead of three 150 mm (6-in.) cubes;[8.42] or five 13 mm (½-in.) mortar cubes instead of two 100 mm (4-in.) cubes from the same batch or four 100 mm (4-in.) cubes from nominally similar batches.[8.43]

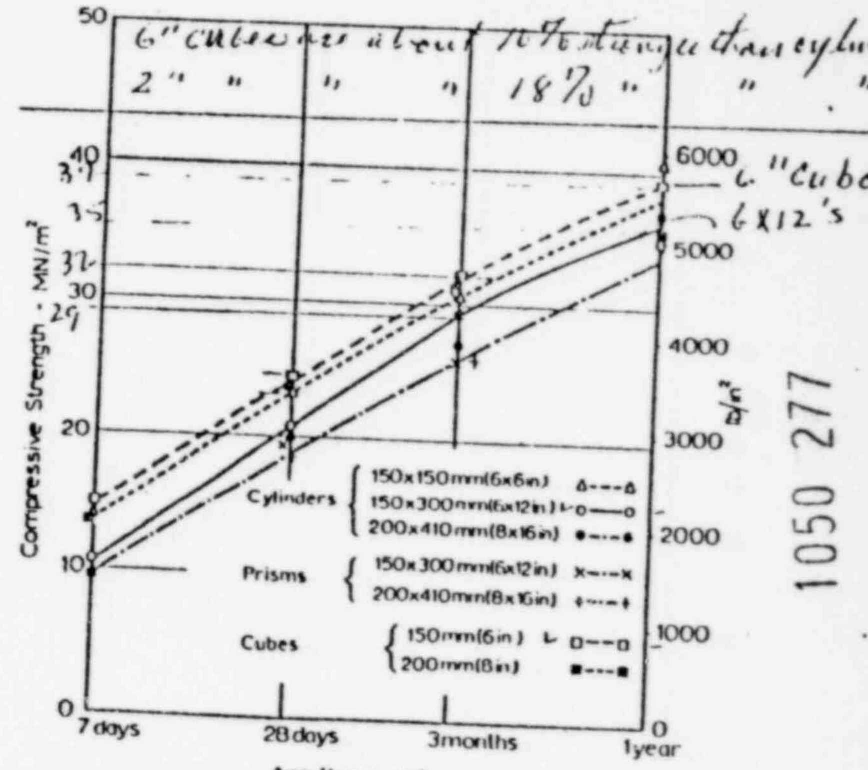


Fig. 8.21. *Effect of age on the compressive strength of specimens of different shape and size*[8.40] *(mix 1:5 by volume)*

Specimen Size and Aggregate Size

It is clear that a test specimen has to be appreciably larger than the largest size of the aggregate particles in the concrete. Various authorities recommend different values for the ratio of the minimum dimension of the test specimen to the maximum aggregate size. For instance, B.S. 1881: 1970 prescribes a test cube not smaller than 100 mm (4 in.) when 25 mm (1 in.) aggregate is used, i.e. a ratio of 4. A.S.T.M. Standard C 192-69 limits the ratio of the diameter of the cylinder to the maximum aggregate size to 3, and the U.S. Bureau of Reclamation to 4. A value of between 3 and 4 is generally accepted as satisfactory.

The limitation of size arises from the "wall effect" (*l'effet de paroi*):

Proc. ASTM Vol. 34 Part II 1934
p 415

larger groups so that the relative uniformity possible of attainment by the two methods of test can be more definitely determined.

MESSRS. H. J. GILKEY[1] AND GLENN MURPHY[1] (*by letter*).—When this paper first became available, the writers were laying out a series of compression tests on a large number of 2-in. cubes, 3 by 6-in. cylinders and 2 by 2 by 4-in. prisms (side cast) along with a few 6 by 12-in. control specimens. A number of the prisms were allocated, therefore, to tests paralleling those described in the paper. Results from these tests are tabulated below:

POOR ORIGINAL

	7-day Tests			28-day Tests				
	Prisms, 2 by 2 by 4 in.	Prisms as Modified Cubes	Cubes, 2 in.	Prisms, 2 by 2 by 4 in.	Prisms as Modified Cubes	Cubes, 2 in.	Cylinders, 3 by 6 in.	Cylinders, 6 by 12 in.
Number of tests	12	16	24	24	8	60	8	2
Average strength, lb. per sq. in.	3035	3020	2950*	5575	5750	6040	5590	5280
Ratio to prism strength	1.00	1.00	0.97*	1.00	1.03	1.08	1.00	0.95
Max. strength any specimen, lb. per sq. in.	3370	3400	3460	6175	6200	6825	5800	5330
Min. strength any specimen, lb. per sq. in.	2500	2800	2740	5100	5325	5000	5410	5220

* Probably out of line on the low side. Cubes are usually somewhat stronger than prisms and cylinders of height twice the lateral dimension.

6" cyl ÷ 5.5 2" cube
Mortar specimens

From these limited tests the following comments are ventured. Support is found for conclusions Nos. 1, 2, 3, 4, and 8 of the paper. As a check on conclusion No. 1, for half of the 24 prisms tested as cubes the modified cube was taken as the middle 2 in. of the 4-in. length and for the others, as the end 2 in. Moreover the zone of damage does not (for the mortar used) extend beyond the boundary picked for the cube. For tests in which the modified cube was taken as an end 2 in. of the prism, the other 2 in. was undamaged and gave virtually the same strength as the end tested first. Sometimes the strength of the fragment was higher rather than lower. Still more striking was the fact that the two end fragments resulting from the test when the middle 2 in. were used as the cube gave a strength which equalled that of the middle 2 in. at the original test.

It is difficult to understand why a prism tested as a modified cube should be weaker than a cube. It is common experience, as mentioned at the bottom of page 409 of the paper, that cubes are stronger than standard cylinders (our 7-day test results to the contrary notwithstanding). Thus while the evidence available seems to support conclusion No. 3, a satisfactory explanation is not yet apparent.

[1] Professor and Head, and Assistant Professor, respectively, Department of Theoretical and Applied Mechanics, Iowa State College, Ames, Iowa.

APPENDIX E

"POSSIBLE CAUSES OF RETROGRESSION OF STRENGTH OF CONCRETE"

Possible Causes of Retrogression of Strength of Concrete

There are several possible causes of retrogression of strength of concrete.

1. Unsound cement due to an excess of free lime, magnesia, and/or calcium sulfate.

2. Alkali-silica and alkali-carbonate reactions.

3. Sulfate attack.

4. Leaching of lime and soluble alkali salts from the concrete.

5. Other deteriorating exposures, i.e., freeze-thaw, acid, etc.

None are considered to be pertinent to the reported retrogression of strengths of concrete cylinders between the ages of 28 and 90 days.

Neville[1] discusses Item 1 in his book "Properties of Concrete," p. 50, copy attached. The autoclave expansion test specified in ASTM C-150 guards against excess magnesia and free lime, and the SO_3 requirement guards against excessive sulfate. The Ash Grove cement used in the construction satisfied all requirements of ASTM C-150.

Item 2 - Alkali-silica and alkali-carbonate reactions can cause loss of strength at later ages, generally noted after a good number of years. ASTM C-342 "A Test Method for Potential Volume Change of Cement-Aggregate Combinations" is a method designed to accelerate such reactions, if any, so that they occur within a period of about one year. We did not run this test because low alkali cement was specified and used and no evidence of deleterious reactions was revealed by microscopic examination.

Item 3 - Sulfates from soil and water may react with hydrated calcium aluminate to form calcium sulfoaluminate, causing expansion and deterioration of concrete. The concrete under discussion was not subjected to these conditions and no evidence of such reactions was observed.

Items 4 & 5 - There was no opportunity for leaching or deleterious exposures in the subject concrete cylinders.

Items 2, 3, 4, and 5 are briefly discussed in the BuRec Concrete Manual, Pages 7-11, attached.

Conclusions

We do not have any explanation for the reported retrogression of strength between 28 and 90 days, other than faulty handling and testing procedures and we can not readily identify these.

J. J. Shideler, Director
Administrative and Technical Services

JJS/md
CT-0539

February 27, 1979

Soundness

It is essential that a cement paste, once it has set, does not undergo a large change in volume. In particular, there must be no appreciable expansion, which under conditions of restraint could result in a disruption of the hardened cement paste. Such expansion may take place due to the delayed or slow hydration or other reaction of some compounds present in the hardened cement, namely free lime, magnesia, and calcium sulphate.

If the raw materials fed into the kiln contain more lime than can combine with the acidic oxides, the excess will remain in a free condition. This hard burnt lime hydrates only very slowly, and since slaked lime occupies a larger volume than the original free calcium oxide, expansion takes place. Cements which exhibit this expansion are known as unsound.

Lime added to cement does not produce unsoundness because it hydrates rapidly before the paste has set. On the other hand, free lime present in clinker is intercrystallized with other compounds and is only partially exposed to water during the time before the paste has set.

Free lime cannot be determined by chemical analysis of cement since it is not possible to distinguish between unreacted CaO and $Ca(OH)_2$ produced by a partial hydration of the silicates when cement is exposed to the atmosphere. On the other hand, a test on clinker, immediately after it has left the kiln, would show the free lime content since no hydrated cement is then present.

A cement can also be unsound due to the presence of MgO, which reacts with water in a manner similar to CaO. However, only periclase (crystalline MgO) is deleteriously reactive, and MgO present in glass is harmless.

Calcium sulphate is the third compound liable to cause expansion: in this case calcium sulphoaluminate is formed. It may be recalled that a hydrate of calcium sulphate—gypsum—is added to cement clinker in order to prevent flash set, but if gypsum is present in excess of the amount that can react with C_3A during setting, unsoundness in the form of a slow expansion will result. For this reason, B.S. 12:1958 limits very strictly the amount of gypsum that can be added to clinker, but the limits are well on the safe side as far as the danger of unsoundness is concerned.[1.40]

Since unsoundness of cement is not apparent until after a period of months or years it is essential to test the soundness of cement in an accelerated manner: a test devised by Le Chatelier is prescribed by B.S. 12:1958. The Le Chatelier apparatus, shown in Fig. 1.23, consists of a small brass cylinder split along its generatrix. Two indicators with pointed ends are attached to the cylinder on either side of the split; in this manner the widening of the split, caused by the expansion of cement, is greatly magnified and can be easily measured. The cylinder is placed on a glass plate, filled with cement paste of standard consistence, and covered

with another glass plate. The whole assembly is then immersed in water at 18 to 20°C (64 to 68°F) for 24 hours. At the end of that period the distance between the indicators is measured, and the mould is immersed in water again and brought to the boil in 30 minutes. After boiling for one hour the mould is removed, and after cooling the distance between the indicators

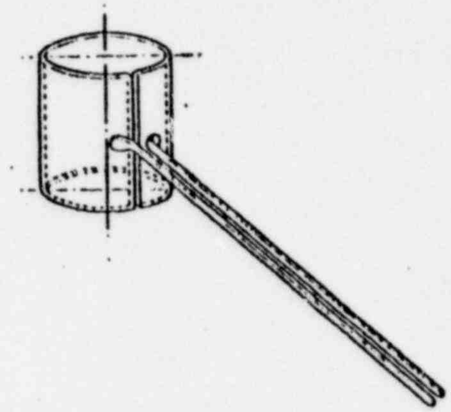


Fig. 1.23. *The Le Chatelier apparatus*

is again measured. The increase in this distance represents the expansion of the cement, and for Portland cements is limited to 10 mm. If the expansion exceeds this value a further test is made after the cement has been spread and aerated for 7 days. During this time some of the lime may hydrate or even carbonate, and a physical breakdown in size may also take place. At the end of the 7-day period, the Le Chatelier test is repeated and the expansion of aerated cement must not exceed 5 mm. A cement not satisfying at least one of these tests should not be used.

The Le Chatelier test detects unsoundness due to free lime only. Magnesia is rarely present in large quantities in the raw materials from which cement is manufactured in England, but is encountered in other countries.* For this reason, in the United States for instance, soundness of cement is checked by the autoclave test, which is sensitive to both free magnesia and free lime. In this test, prescribed by A.S.T.M. Standard C 151-71, a neat cement bar 25 mm (or 1 in.) square in cross-section and with a 250 mm (or 10 in.) gauge length is cured in humid air for 24 hours. The bar is then placed in an autoclave (a high pressure steam boiler), which is raised to a temperature of 216°C (420°F) (steam pressure of

* An example is India, where low-magnesia limestone occurs only to a limited extent. The resulting cement has therefore a high MgO content but expansion can be significantly reduced by the addition of active siliceous material such as pulverized fuel ash or finely ground burnt clay.

2 ± 0·07 MN/m² (295 lb/in²)) in one hour, and maintained at this temperature for 3 hours. The expansion of the bar due to autoclaving must not exceed 0·5 per cent. The high steam pressure accelerates the hydration of both magnesia and lime.

The results of the autoclave test are affected by, in addition to the compounds causing expansion, the C_3A content, and are also subject to other anomalies. The test gives, therefore, no more than a broad indication of the risk of long-term expansion in practice.[1.1]

No test is available for the detection of unsoundness due to an excess of calcium sulphate, but its content can be easily determined by chemical analysis.

Strength of Cement

The mechanical strength of hardened cement is the property of the material that is perhaps most obviously required for structural use. It is not surprising, therefore, that strength tests are prescribed by all specifications for cement.

The strength of mortar or concrete depends on the cohesion of the cement paste, on its adhesion to the aggregate particles, and to a certain extent on the strength of the aggregate itself. This last is not considered at this stage, and is eliminated in tests on the quality of cement by the use of standard aggregates.

Strength tests are not made on a neat cement paste because of difficulties of moulding and testing with a consequent large variability of test results. Cement-sand mortar and, in some cases, concrete of prescribed proportions and made with specified materials under strictly controlled conditions are used for the purpose of determining the strength of cement.

There are several forms of strength tests: direct tension, direct compression, and flexure. The latter determines in reality the tensile strength in bending because, as is well known, cement paste is considerably stronger in compression than in tension. Since the flexure test is not used in Great Britain and little used elsewhere it will not be further discussed.

The direct tension test used to be commonly employed but pure tension is rather difficult to apply so that the results of such a test show a fairly large scatter. Furthermore, since structural techniques are designed mainly to exploit the good strength of concrete in compression, the tensile strength of cement is often of lesser interest than its compressive strength. For these reasons the tension test has gradually given way to compression tests.

However, the tension test has been retained in B.S. 12:1958 as a permitted test for a one-day strength of rapid hardening Portland cement. In this test a 1:3 cement-sand mortar with a water content of

8 per cent of the weight of the solids is mixed and moulded into a briquette of the shape shown in Fig. 1.24. The sand is the standard Leighton Buzzard sand obtained from a quarry near the village of that name in Bedfordshire. This sand consists of pure siliceous material and is practically all of one size; all particles are nearly spherical and are smaller than a 850 μm (No. 18 B.S.) sieve and at least 90 per cent of the sand is retained on a 600 μm (No. 25 B.S.) sieve.

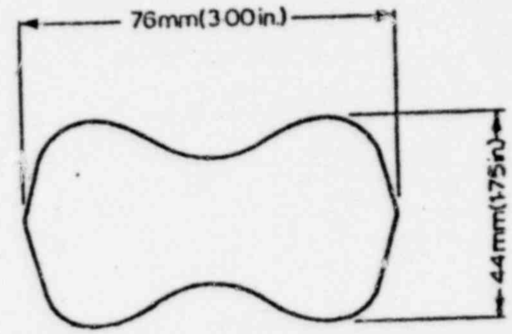


Fig. 1.24. *Briquette for the tension test of mortar*

The briquettes are moulded in a standard manner, cured for 24 hours at a temperature between 18 and 20°C (64 and 68°F) in an atmosphere of at least 90 per cent relative humidity and tested in direct tension, the pull being applied through special jaws engaging the wide ends of the briquette. B.S. 12: 1958 prescribes the minimum one-day strength of rapid hardening Portland cement as 2·1 MN/m² (300 lb/in²), taken as the average value for six briquettes.

There are two standard methods of testing the compressive strength of cement: one uses mortar, the other concrete.

In the mortar test, a 1:3 cement-sand mortar is used. The sand is again the standard Leighton Buzzard sand, and the weight of water in the mix is 10 per cent of the weight of the dry materials. Expressed as a water/cement ratio this corresponds to 0·40 by weight. A standard procedure, prescribed by B.S. 12:1958, is followed in mixing, and 70·6 mm (2·78 in.) cubes are made using a vibrating table with a frequency of 200 Hz applied for two minutes. The cubes are demoulded after 24 hours and further cured in water until tested in a wet-surface condition. The B.S. 12: 1958 requirements for minimum strengths (average values for three cubes) are given in Table 1.10.

The vibrated mortar test gives fairly reliable results but it has been suggested that mortar made with one-size aggregate leads to a greater scatter of strength values than would be obtained with concrete made under similar conditions. Moreover, the values of strength obtained in a

To Old Hallam

Properties of Concrete

A M Neville

MC, TD, DSc(Eng), PhD, MSc, CEng, PEng, FICE, FIStructE, MSocCE(France), FAmSocCE, FACI, FIArb

Professor and Head of Department of Civil Engineering, University of Leeds, formerly Dean of Engineering, University of Calgary

Pitman Publishing

the same slump. In the two views at the right, the specimens have been tapped with the tamping rod as prescribed in designation 22. The concrete in the upper view is a harsh mix, with a minimum of fines and water. It may be efficient for use in slabs, pavements, or mass concrete where it can readily be consolidated by vibration, but it would be quite unsuitable for a complicated and heavily reinforced placement. The concrete in the lower view is a plastic, cohesive mix; the surplus workability is needed for a difficult placement. However, if it is used where it can be easily placed and vibrated, such a mix would be inefficient because it contains excesses of cement, fines, and water. Thus, it is evident that, while measurement of slump gives a valuable indication of consistency, workability and efficiency of the mix can be judged only by how the concrete goes into place in each part of the structure and how it responds to consolidation by good vibration. Efficient mixes do not have much surplus workability over that needed for good results with thorough vibration.

The influence of temperature on the slump of concrete is indicated in figure 3.

For Bureau of Reclamation work, the maximum permissible slump of concrete, after the concrete has been deposited but before consolidation,

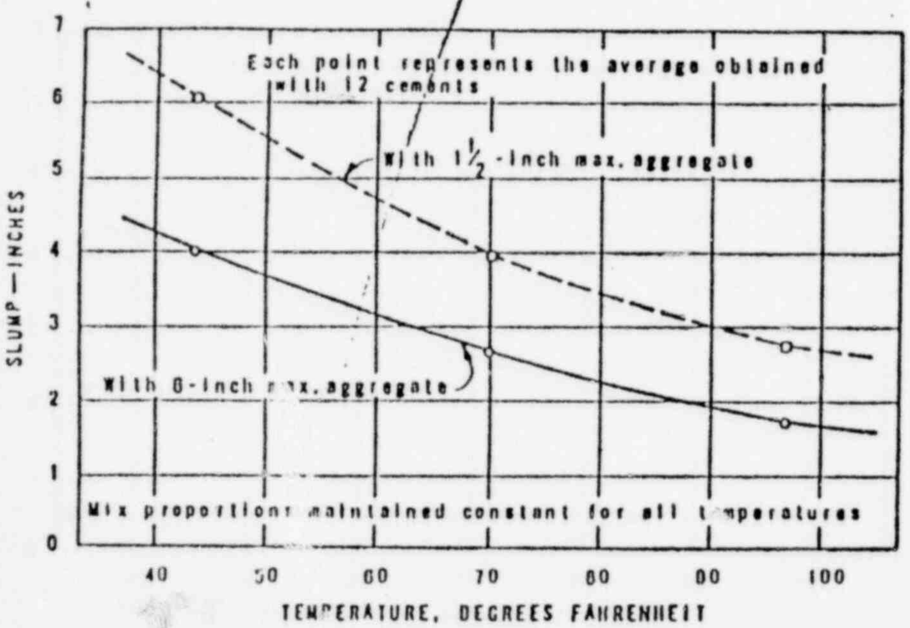


Figure 3.—Relationship between slump and temperature of concrete made with two maximum sizes of aggregates. As the temperature of the ingredients increases, the slump decreases. 288-D-1080.

is restricted by specifications to 2 inches for concrete in tops of walls, piers, parapets, curbs, and slabs that are horizontal or nearly horizontal; 4 inches for concrete in arch and sidewalls of tunnels; and 3 inches for concrete in other parts of structures and in canal linings. The slump of mass concrete is usually restricted to a maximum of 2 inches. If concrete cannot be placed without exceeding specified slump limitations, it may be concluded that the mix proportions are in need of adjustment. The minimum slump that can be used, commensurate with desired workability, requires the least amount of cement and water. In general, the wetter the consistency, the greater the tendency toward bleeding and segregation of coarse aggregate from the mortar.

6. Durability.—A durable concrete is one that will withstand, to a satisfactory degree, the effects of service conditions to which it will be subjected, such as weathering, chemical action, and wear. Numerous laboratory tests have been devised for measurement of durability of concrete, but it is extremely difficult to obtain a direct correlation between service records and laboratory findings.

(a) *Weathering Resistance.*—Disintegration by weathering is caused mainly by the disruptive action of freezing and thawing and by expansion and contraction, under restraint, resulting from temperature variations and alternate wetting and drying. Concrete can be made that will have excellent resistance to the effects of such exposures if careful attention is given to the selection of materials and to all other phases of job control. The purposeful entrainment of small bubbles of air, as discussed in section 14(b), has also helped to improve concrete durability by decreasing the water content and improving placeability characteristics. It is also important that, where practicable, provision be made for adequate drainage of exposed concrete surfaces.

Much has been learned regarding the resistance of air-entrained concrete to frost action, especially with respect to the influence of internal pore structure on durability. Dry concrete, with or without entrained air, sustains no damaging effects from freezing and thawing. Non-air-entrained concrete with high cement content and low water-cement ratio (0.36±) develops good resistance to freezing and thawing primarily because of its relatively high density and attendant high impermeability (or watertightness) which reduce the free (or freezable) water available to the capillary system and/or through inflow under pressure. However, within the usual range of water-cement ratio specified for exposed structural concrete (maximum 0.47 to 0.53), greatly increased resistance to freezing and thawing is effected by the purposeful entrainment of air. This entrainment, in the form of multitudinous air bubbles ranging in size from less than 20 micrometers (submicroscopic) to about 3,000

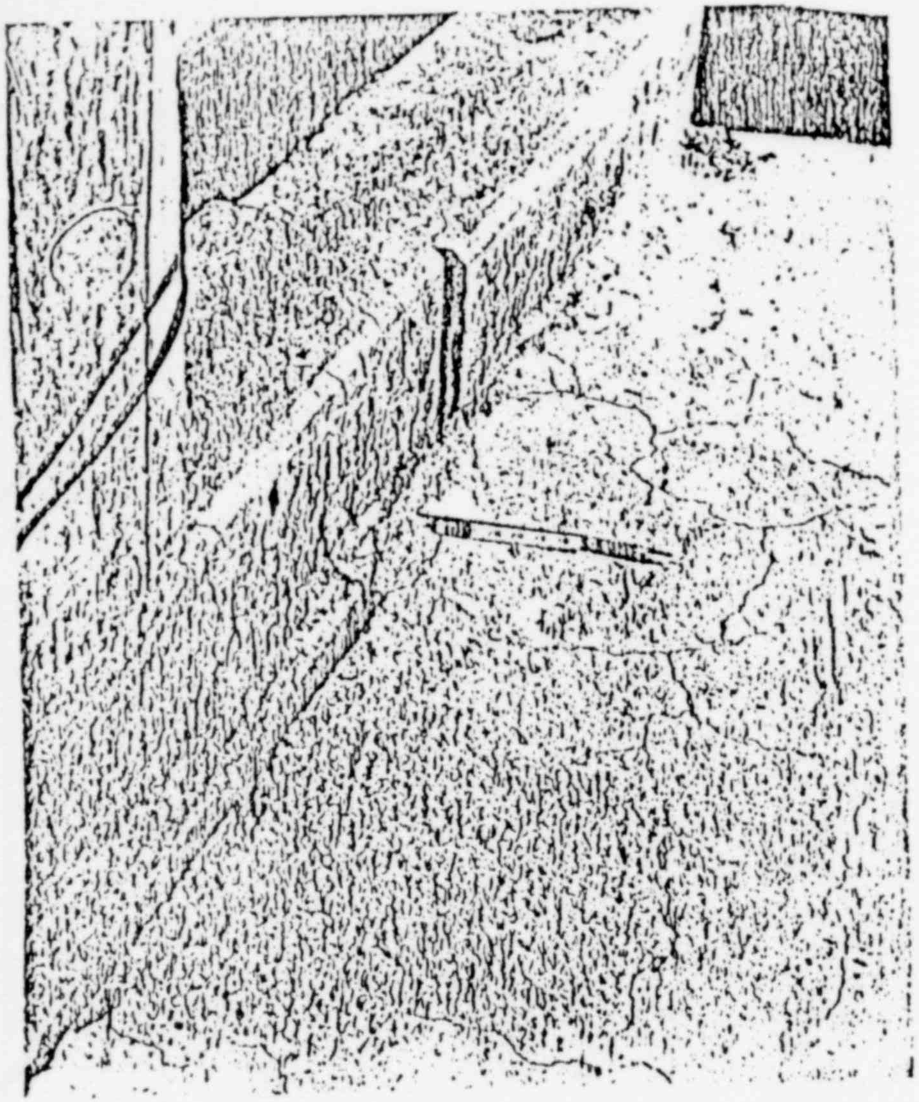


Figure 4.—Typical pattern cracking on the exposed surface of concrete affected by alkali-aggregate action. PX-D-32049.

micrometers (macroscopic), provides relief for pressures developed by free water as it freezes and expands.

(b) *Resistance to Chemical Deterioration.*—Concrete deterioration, attributable in whole or in part to chemical reactions between alkalies in cement and mineral constituents of concrete aggregates, is characterized by the following observable conditions: (1) Cracking, usually of random pattern on a fairly large scale (see fig. 4); (2) excessive internal and overall expansion; (3) cracks that may be very large at the concrete

surfaces (openings up to 1½ inches have been observed) but which extend into the concrete only a distance of from 6 to 18 inches; (4) gelatinous exudations and whitish amorphous deposits, on the surface or within the mass of the concrete, especially in voids and adjacent to some affected pieces of aggregate; (5) peripheral zones of reactivity, alteration, or infiltration in the aggregate particles, particularly those particles containing opal and certain types of acid and intermediate volcanic rocks; and (6) lifeless, chalky appearance of the freshly fractured concrete.

Deterioration of concrete also results from contact with certain chemical agents. The chemical action of a number of substances on unprotected concrete is shown in table 1. The table is intended to provide general guidance only, and salts listed as having no action might be aggressive at high concentrations or at high temperatures. Attack may assume one of several forms:

(1) Erosion of concrete results from the formation of soluble products which are removed by leaching. Attack by organic and inorganic acids is in this class. Attack by acids is seldom encountered at sites of Bureau work. This is a fortunate circumstance because no type of portland cement offers resistance to the forms of acid corrosion listed in table 1. Where likelihood of acid corrosion is in-

Table 1.—Effects of various substances on hardened concrete

Substance	Effect on unprotected concrete
Petroleum oils, heavy, light, and volatile	None.
Coal-tar distillates	None, or very slight.
Inorganic acids	Disintegration.
Organic materials:	
Acetic acid	Slow disintegration.
Oxalic and dry carbonic acids	None.
Carbonic acid in water	Slow attack.
Lactic and tannic acids	Do.
Vegetable oils	Slight or very slight attack.
Inorganic salts:	
Sulfates of calcium, sodium, magnesium, potassium, aluminum, iron.	Active attack.
Chlorides of sodium, potassium	None.
Chlorides of magnesium, calcium	Slight attack.
Miscellaneous:	
Milk	Slow attack.
Silage juices	Do.
Molasses, corn syrup, and glucose	Slight attack.
Hot distilled water	Rapid disintegration.

dicated, an appropriate surface covering or treatment should be employed.

When cement and water combine, one of the compounds formed is hydrated lime, which is readily dissolved by water (often made more aggressive by the presence of dissolved carbon dioxide) passing through cracks, along improperly treated construction planes, or through interconnected voids. The removal of this or other solid material by leaching may seriously impair the quality of concrete. The white deposit, or efflorescence, commonly seen on concrete surfaces is the result of leaching and subsequent carbonation and evaporation.

(2) Certain agents combine with cement to form compounds which have a low solubility but which disrupt the concrete because their volume is greater than the volume of the cement paste from which they were formed. Disintegration may be attributed to a combination of chemical and physical forces. In dense concretes this type of attack would be largely superficial. Porous concrete would be affected throughout the mass. Most prominent among aggressive substances which affect Bureau concrete structures are the sulfates of sodium, magnesium, and calcium. These salts which are known as white alkali are frequently encountered in the alkali soils and ground waters of the western half of the United States.

The stronger the concentration of these salts the more active the corrosion. Sulfate solutions increase in strength in dry seasons when dilution is at a minimum. The sulfates react chemically with the hydrated lime and hydrated calcium aluminate in cement paste to form calcium sulfate and calcium sulfoaluminate, respectively, and

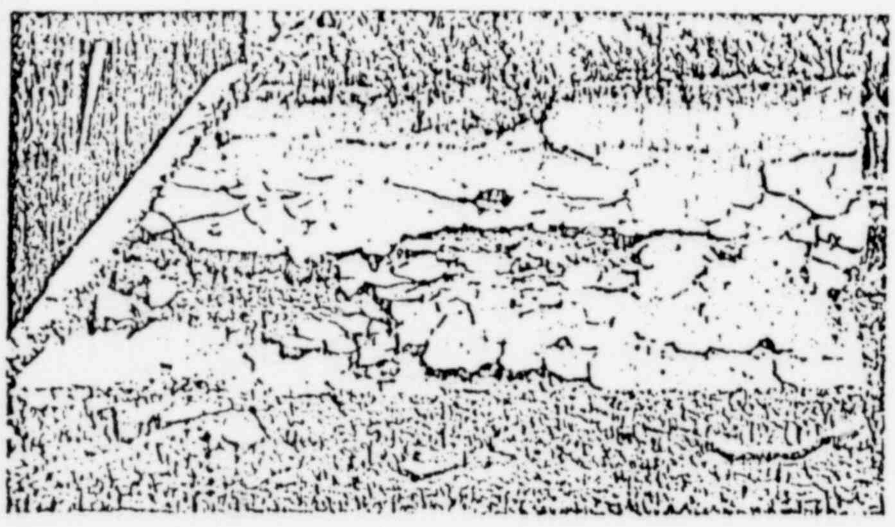


Figure 5.—Disintegration of concrete caused by sulfate attack. PX-D-32050.

Table 2.—Attack on concrete by soils and waters containing various sulfate concentrations

Relative degree of sulfate attack	Percent water-soluble sulfate (as SO_4) in soil samples	P/m sulfate (as SO_4) in water samples
Negligible	0.00 to 0.10	0 to 150
Positive [1]	0.10 to 0.20	150 to 1,500
Severe [2]	0.20 to 2.00	1,500 to 10,000
Very severe [3]	2.00 or more	10,000 or more

[1] Use type II cement.
[2] Use type V cement, or approved portland-pozzolan cement providing comparable sulfate resistance when used in concrete.
[3] Use type V cement plus approved pozzolan which has been determined by tests to improve sulfate resistance when used in concrete with type V cement.

these reactions are accompanied by considerable expansion and disruption of the paste. Figure 5 illustrates the effect of sulfate attack on concrete in a canal lining and a turnout wall. Concrete containing cement with a low content of the vulnerable calcium aluminate is highly resistant to attack by sulfate-laden soils and waters. (See sec. 15(b).) The relative degrees of attack on concrete by sulfates from soils and ground waters are given in table 2.

(3) Where concrete is subjected to alternate wetting and drying, certain salts, such as sodium carbonate, may cause surface disintegration by crystallizing in the pores of the concrete. Such action appears to be purely physical.

(4) In environments such as flash distillation chambers of desalination plants where concrete is exposed to condensing cool-to-hot water vapors or the resulting flowing or dripping of distilled water, the concrete is rapidly attacked by this mineral-free liquid. The liquid rapidly dissolves available lime and other soluble compounds of the cement matrix. Subsequent rapid deterioration and eventual decomposition result. The only palliative known at this time is complete insulation of the concrete from the mineral-free water by coatings or lining materials which are not affected by the water.

(5) Concrete in desalination plants is adversely affected by the feed water, sea water, or brine from wells. At these plants, high-quality concrete has been found unsuitable for use in brine exposures at temperatures of 290° F but suitable at 200° to 250° F provided adequate sacrificial concrete is made available for surface deterioration. Below about 200° F no provision for sacrificial concrete is generally required. Deterioration such as occurs at the higher temperature is a chemical alteration of the peripheral concrete paste which results in extensive microfracturing with resultant reduction of compressive strength, effective cross-sectional area of the member, and