Engineering Analyses and Tests

A STUDY OF TIME RELATED PROPERTIES
OF CONCRETE

MASTER

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FORWARD

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TABLE OF CONTENTS

Abstract

1.0 Introduction

2.0 Summary and Conclusions

3.0 Long Time Tests on Reinforced Concrete

3.1 Fifty-year Properties of Concrete

3.2 Cement Performance in Concrete

3.3 Long-time Creep Tests of Concrete

3.3.1 Effect of Stress/Strength Ratio on Creep of Concrete at Different Temperatures

3.3.2 Concrete Creep Under Temperature and Pressure Differentials

3.3.3 Creep and Shrinkage Under Drying Conditions

3.3.4 Geometrical Effects of Concrete Creep

3.4 Corrosion of Concrete Reinforcement Bars

3.4.1 Corrosion By Sea Water

3.4.2 Corrosion By Soils

References

Figures and Tables

ABSTRACT

The results of a literature survey conducted on the long time properties of reinforced concrete are presented as a means of evaluating the integrity of the high level neutralized waste tank vaults at the Nuclear Fuel Services (NFS) site. The long time behavior of reinforced concrete under conditions of humidity, moisture, temperature, and pressure differentials is discussed. An evaluation of the degree of NFS tank vaults' structural integrity degradation with time is made.

1.0 Introduction

The objective of this study is to investigate the integrity of the reinforced concrete used in the construction of radioactive waste storage tank vaults at the Nuclear Fuel Services (NFS) site using data from long time tests on reinforced concrete.

An extensive literature survey was performed to collect data on the full spectrum of concrete types under different loading conditions and environments in order to establish the time dependent properties of reinforced concrete (1-42).

The tank vaults are buried almost eight feet below ground level, in artificially maintained saturated clay. The inside of the tank has a temperature of approximately 82°C (180°F) and that of the soil is approximately 10°C (50°F). The steel tank inside the concrete vault is resting on perlite blocks and gravel. Assuming the presence of small amounts of water in the pan due to the permeability of the concrete, and considering the temperature of the tank vault, we may conservatively assume that the inside of the vault has a relative humidity of 100%.

The vaults house tanks 8D-2 and 8D-1. Tank 8D-2 contains neutralized high level radioactive waste from the purex processing of nuclear fuels. Tank 8D-1 is a spare tank partially filled with water.

The vaults are approximately 78 feet in diameter. The base slab is 2 feet, 3 inches in thickness with thicker sections under the six columns supporting the vault roof. The base slab rests on the leveling slab. Under the concrete vault is a 4 foot layer of gravel which is kept water-saturated at all times.

The vault roof is 2 feet thick and is supported by six concrete columns contained within 30 inch steel pipes (see table 1). Reinforcement of the concrete is provided with A432 carbon steel reinforcement bars. The concrete used in the vault construction is type F.

The information generated in this study is to be used to assess the maximum earthquake acceleration level that the existing vaults can withstand now and within the next 25 years.

2.0 Summary and Conclusions

The information presented in this study on the full spectrum of concrete types indicates that the structural integrity of the reinforced concrete used in the construction of tank vaults 8D-2 and 8D-1 at Nuclear Fuel Services can be assured for at least several decades. Central to the support of this statement is the fact that the tensile and compressive strengths of concrete increase with time for all concrete mixes. Creep of the concrete vault is expected to occur with negligible significance on the structural integrity. Corrosion of the reinforcement bars is not expected to significantly affect structural strength.

3.0 Long Time Tests on Reinforced Concrete

A variety of different types of long time test data has been generated on reinforced concrete. For this study it was necessary to determine the long time effects on the structural integrity of reinforced concrete due to temperature gradients, high levels of relative humidity, and moisture. The structural parameters investigated include tensile and compressive strength, creep, shrinkage, corrosion of the reinforcement bars, and the long time chemical stability of the cement.

3.1 Fifty-year Properties of Concrete

Results of a fifty-year study (1923-1973) of concrete (7) with different aggregate types, environments, and water cement ratios, show that the tensile and compressive strengths increase with time for all aggregate types, environmental conditions, and water cement ratios for a period up to 25 years. For the period of 25 to 50 years, the increasing rate of strength decelerates. However, the final values of strength, tensile and compressive, measured after 50 years are 1.5 to 2.5 times the original values. The results of this study and a plot of the data are presented in Tables 2 through 5 and Figures 8 and 9.

3.2 Cement Performance in Concrete

A long time study of cement performance in concrete has been done by Klieger (9). A variety of cement types were used in the study, and flexural strengths of the specimens as well as their compressive strengths were determined for up to 3 years. The tests were performed in a moist air environment as well as in aqueous storage. The results are presented for both conditions in Tables 6 through 18 and in Figure 10. Observation of the results at the end of the 3 years show that the strengths, flexural and compressive, are equal to or exceed their value at 28 days. The elastic properties (dynamic) of the test specimens were also determined in the study and are tabulated. Note that the study also covers testing of concrete with varying cement content and also with different additives such as air entrainment.

3.3 Long-time Creep Tests of Concrete

The creep of concrete for a wide range of water/cement (w/c) and aggregate/cement (a/c) ratios and also its dependence on composition and fineness of cement, mineralogical character of aggregate, maximum size of aggregates, and magnitude of compressive stress, has been studied by Troxell (22).

In this study a typical creep-time curve (Figure 20) was constructed by computing for each group of specimens included in Figures 12 to 19, the percent of twenty year total creep at each plotted time division. The several test series embrace a variety of conditions of mix, water-cement ratio, consistency, rock type, storage, load intensity, and age at loading.

If the slope of the creep curve on a semi-logarithmic plot is termed the creep coefficient, K , then the total creep, ϵ , in time, t , can be expressed as:

$$\epsilon = K \log_e (t+1)$$

With some idealization, the average creep-time curve of Figure 20 could be expressed as two straight lines on the semilogarithmic plot as

follows:

$$\epsilon = 0.149 \log_e (t+1) \text{ for } 0 < t < 730 \text{ days}$$

$$\text{and } \epsilon = 0.86 + 0.0665 \log_e (t-730) \text{ for } 730 < t < \infty \text{ (20 years)}$$

3.3.1 Effect of Stress/Strength Ratio on Creep of Concrete at Different Temperatures

The relation between creep and stress-strength ratio for various temperatures has been studied by Nasser, K.W. (10) for stress-strength ratios of up to 70% in the temperature range of 70 to 205°F. The experimental results show that at any stress-strength ratio, creep generally increases with an increase in temperature up to about 160°F where it is approximately 3.5 times the rate at 70°F. Above 160°F the rate drops off steadily until at 205°F the rate of creep is the same as it is at approximately 125°F. Experimental results are tabulated and presented in Table 20. Included in Figure 21 is a plot of stress-strength ratio vs. ratio of creep at time t to the final value of creep. To be noted is the linearity which exists between stress-strength ratio and creep.

3.3.2 Concrete Creep Under Temperature and Pressure Differentials

To determine the effect of temperature gradients and pressure differentials in circular cylindrical concrete structures, a study was done (14) on a circular cylinder with O.D. = 40", I.D. = 20" and $h = 1"$. The temperature inside the ring was 66°C (150°F) and outside was 27°C (81°F). The inside of the model had a pressure of 200 psi and the outside pressure was 500 psi. This temperature range closely approximates the temperature found inside and outside of the vault and the pressure simulates soil pressure on the vault. The study had the following limitations:

- 1) The mathematical model for analyzing the cylinder was developed for sealed specimens only.
- 2) The model was developed for temperature ranges of $68-100^{\circ}\text{F}$ ($20-93.3^{\circ}\text{C}$) and for ages of loading varying between 28 and 400 days.
- 3) The results are only valid for stress-strength ratios up to 0.45.
- 4) The instantaneous and time dependent behavior of concrete is assumed to be the same in tension and compression.
- 5) The coefficient of thermal expansion, α , is considered to be constant, independent of temperature and stress conditions.
- 6) Poisson's ratio is considered constant.

The variations of stress and strain in the concrete for the model structure is present in Figure 6. Note that the thickness of the concrete used in the model is close to that of the vault under investigation (20" vs. 18").

3.3.3 Creep and Shrinkage Under Drying Conditions

Reference (3) uses the rate theory and experimental data for determination of time dependent deformation of concrete. Actual test data is available for creep of hollow cylinders of hardened cement paste carried out under sealed conditions at 100% R.H. as well as for concrete under drying condition (100% to 65% R.H.). Creep of concrete for 100% R.H. has been calculated and plotted (Figure 7 - broken line).

3.3.4 Geometrical Effects of Concrete Creep

Size and shape of concrete members also affects the near term creep of concrete structures. For circular cylinders the effect has been studied (13). The results show that for volume to surface ratios

above 2.0 the effect on creep is constant and creep increases with time only. However, for v/s less than 2, creep increases with decreases of v/s at any given time. As the age of concrete increases this effect decreases and test results have shown that at an age beyond 1200 days the size and shape has negligible effects on the creep rate.

For the vault under investigation, the volume to surface ratio is 12.72" and its age exceeds 1200 days. So, it can be assumed that the effect of size and shape of the vault members on the present creep rate is negligible. However, the experimental results are indicative of the fact that the higher the volume/surface ratio, the lower the rate of creep and hence it takes more time before creep reaches its final value.

Final values of creep of various concrete specimens can be projected from the test data by assuming that the creep-time curves can be represented by the following hyperbolic function:

$$\epsilon_c = \frac{\epsilon_c^\infty t}{N_c + t}$$

where

ϵ_c = creep at time t

ϵ_c^∞ = final value of concrete creep

N_c = constant = time at which creep strain becomes equal to half its final value.

The parameter (N_c) is obtained by the empirical formula,

$$N_c = 26.0e^{0.156} (v/s)$$

where v/s = volume to surface ratio (in inches).

The actual test results are presented in figure 11 and table 19. The creep coefficient, ϕ , is defined as the ratio of actual creep, ϵ_c , to initial deformation, ϵ_i .

3.4 Corrosion of Concrete Reinforcement Bars

The NFS tank vault is situated in saturated soil. It is conceivable that sufficient cracking of the concrete might have occurred to expose a significant fraction of the reinforcement bars to corrosive attack. For this reason, corrosion of mild steel by both soil and sea water was investigated.

3.4.1 Corrosion By Sea Water

Illustrative data for steel and iron, largely from long time tests collected in Table 21 show a uniformity of rates of attack (as expressed in inches penetration per year) for specimens exposed under conditions of continuous immersion (39). The spread is between 0.001 and 0.0077 IPY, with an average of 0.0043. The data show that normal corrosion rates stay within rather narrow practical limits irrespective of the water temperature, salinity, etc. Consequently, for a rough estimate in the absence of data applying to a particular locality or condition of exposure, it would be reasonable to use a figure of about 0.005 IPY,

(inches penetration per year) or about 25 mdd, (milligrams persquare decimeter per day), for the expected average rate of corrosion of steel continuously immersed in sea water under natural conditions. The weight loss of steel continuously immersed in sea water is for all practical purposes a linear function of time.

3.4.2 Corrosion By Soils

If the depths of the maximum pits on specimens of commonly used ferrous materials are averaged for a number of soils, the differences in the rates of corrosion of most of them lie within a standard deviation (40). This is illustrated in Figure 22. It should be noted that the pit depths on the 1½ inch diameter specimens are less than those on 3 inch diameter specimens, (i.e. the pit depth is a function of the area of the specimen) (40).

Table 22 shows the pit depth for low alloy steels after four years exposure to fourteen soils. With one exception, each material appears best for

at least one soil condition and worse for some other soil conditions.

Table 23 shows the performance of some high-alloy steels. None was free from pits in all soils. The weight losses indicate that the diameters of pits were small.

References

1. "Comparison of Approximate Linear Methods for Concrete Creep", ASCE, Structural Division Journal, Sept. 73, 1851-1871.
2. "Characteristics and Predictions of Creep of a Saturated Mortar Under Variable Temperature", Magazine of Concrete Research, vol. 26 #88, Sept. 74, 169-179.
3. "The Application of Rate Theory to Time Dependent Deformation of Concrete", Magazine of Concrete Research, vol. 26 #89, Dec. 74, 191-197.
4. "Time Dependent Strains in Sealed Concrete Under Systems of Variable Multiaxial Stress", Magazine of Concrete Research, vol. 23 #75 and 76, June and Sept. 71, 79.
5. "Time Dependent and Steady-state Stresses in Concrete Structures with Steel Reinforcement at Normal and Raised Temperatures", Magazine of Concrete Research, vol. 27 # 92, Sept. 75, 131.
6. "Prediction of Concrete Creep Effects Using Age Adjusted Effective Modulus Method", American Concrete Institute Journal, by Z.P. Bazant, Apr. 72 #4, Proc. V-69, 212.
7. "Fifty-year Properties of Concrete", ACI Journal, by G.W. Washa, et al. Jan. 75 #1, Proc. V-72, 20 and July 75, 369 (discussion).
8. "An Experimental Study of Multiaxial Creep in Concrete", Concrete for Nuclear Reactors, SP-34, ACI Journal, Detroit, 1972, 735-768.
9. "Long Time Study of Cement Performance in Concrete", ACI Journal Proceeding V-54, #6, Dec. 1957, 481-504.
10. "Creep of Concrete at Elevated Temperatures" by Nasser, Karim, W. et al., ACI Journal, Proc. V-62, No. 12, Dec. 1965, 1567-1580.
11. "Prediction of Creep of Concrete at Variable Temperatures", Hani M. Fahmi et al, ACI Journal, Oct. 73, 709.
12. "A Theoretical Method for Predicting the Shrinkage of Concrete" Norbert K. Becker et al, ACI Journal, Sept. 1973, No. 9, 652.
13. "Influence of Size and Shape of Member on Creep and Shrinkage of Concrete", ACI Journal, Proc. V-63, No. 2, Feb. 1966, 267-290.

14. "Creep Analysis of Concrete at Elevated Temperatures", M. Mokaddam, ACI Journal, Proc. V-71, Feb. 74, 72.
15. "Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures", Designing for Effects of Creep, Shrinkage, and Temperature in Concrete Structures, SP-17, ACI Journal, Detroit, 1971, 51-93.
16. "Influence of Temperature on the Creep of Mass Concrete", Temperature and Concrete, ACI Journal, SP-25, Detroit, 1971, 137-190.
17. "Creep and Shrinkage Law for Concrete at Variable Humidity", Bazant et al., ASCE, Engineering Mechanics Division Journal, Dec. 1974, 1183-1209.
18. "Dirichlet Series Creep Function for Aging Concrete", ASCE, Engineering Mechanics Division Journal, April 1973, 367-385.
19. "Changes in Characteristics of Portland Cement as Exhibited by Laboratory Tests from 1904-1950", STP-127, ASTM, Philadelphia, 1951, 56.
20. "Effects of Sustained and Cyclic Elevated Temperature on Creep of Concrete", Cement and Concrete Research, vol. 2, no. 5, Sept. 72, 591-606.
21. "Thermoviscoelasticity of Aging Concrete", Z.P. Bazant et al., ASCE, Engineering Mechanics Division Journal, June 1974, 575.
22. "Longtime Creep and Shrinkage Tests of Plane and Reinforced Concrete", ASTM, Proc., vol. 58, 1958, by Troxell, G.E. et al., 1101-1120.
23. "Computation of Age Dependent Relaxation Spectra", Cement and Concrete Research, vol. 4, by Z.P. Bazant et al., 1974, 567-579.
24. "Creep and Shrinkage in Plane, Reinforced and Prestressed Concrete, a General Method of Calculation", Proc. of the Institute of Civil Engineers, vol. 21, No. 7, 1973, 38-57.
25. "Strain Behavior of Concrete up to 95°C (203°F) Under Compressive Stress", Conference of Prestressed Concrete Pressure Vessels, London, 1967, Institution of Civil Engineers, London, 1968. Group C page 17, 57-71, also pages 177-191.
26. "Stress in Cylindrical Tanks due to Shrinkage", J.D. Davies, Concrete and Construction Engineering, May 1962, 193-196.
27. "A Thermodynamic Study of System Hardened Cement Paste and Water and its Dynamic Mechanical Response as a Function of Temperature", Stanford University, Dept. of Civil Engineering, May 1969, Tech., report no. 90, 349.

26. "The Effect of Temperature on Creep of Concrete". A literature review. Vicksburg (Miss.), Waterways Experimental Station, 1970, 16. Misc. paper C-70.
29. "Numerical Analysis of Longtime Deformation of a Thick Walled Concrete Cylinder", Report No. 69-12, Division of Structural Engineering and Structural Mechanics, U.C. Berkeley, Aug. 1969. Also in ACI, Supplement, paper SP-27-21, Detroit, Michigan.
30. "Computation of Age Dependent Relaxation Spectra", Cement and Concrete Research, vol. 4, 1974, 567-579.
31. "Rate Type Creep Law of Aging Concrete Based on Maxwell Chain", Z.P. Bazant, Materials and Structures, vol. 7, no. 37, 1974, 45-60.
32. "The Calculation of Time Dependent Stresses in PCPV's by an Approximate Method", G.L. England, et al., Proc. of an International Conference on Structural Mechanics in Reactor Technology, Berlin, 1971. Paper H3/8 (vol. 4, Sept. 71, 289-313).
33. "A note on Concrete Creep Analysis Under Static Temperature Fields", Materials and Structures (RILEM), vol. 7, no. 41, Sept.-Oct. 1974, 329-333.
34. "The Creep of Concrete in Terms of its Developing Structure and Moisture Condition". Structure, Solid Mechanics and Engineering Design, Proc. of Civil Engineering Materials Conference, Univ. of Southampton, 21-25, Apr. 1969. Editor: M. Te'ent, London, Wiley-Interscience, 1971, 1287-1297.
35. "A 10-year Study of Creep Properties of Concrete", Concrete Laboratory Report No. SP-38, U.S. Dept. of Interior, Bureau of Reclamation, Denver, Colorado. July 1953.
36. "A Comparison of Instantaneous and Sustained Modulus of Elasticity of Concrete", Concrete Laboratory Report No. 3-854, Division of Engineering Laboratories, U.S. Dept. of Interior, Bureau of Reclamation, Denver, Colorado, March 1958.
37. "Effect of Stiffness Degradation on Earthquake Ductility Requirements", R.W. Clough, Report No. 66-16, Structural Engineering Laboratory, U.C. Berkeley.
38. "On the Influence of Water Content and of Drying Conditions on the Lateral Creep of Plane Concrete." Materials and Structures, vol. 2, no. 8, Mar-Apr 1969, 125-131.

39. Uhlig, Herbert H., "Corrosion and Corrosion Control", John Wiley & Sons Inc., New York, 1967.
40. Uhlig, Herbert H., "The Corrosion Handbook", John Wiley & Sons Inc., New York 1948.
41. Evans, Ulick R., "The Corrosion and Oxidation of Metals", St. Martins Press, New York, 1968.
42. "Alternative Process For Managing Existing Commercial High-Level Radioactive Wastes," Battelle Pacific Northwest Laboratory, April 1976.

FIG. 1 -Fit of Creep Data of Hannant.²¹

FIG. 2 -Fit of Creep Data of York, Kennedy, and Perry.²¹

FIG. 3 -Fit of Creep Data of Browne.²¹

FIG. 4 -Fit of Hannant's Data Assuming Linearly Distributed Activation Energy.²¹

FIG. 5 -Extrapolated Creep Curves Obtained
in Fitting Data in Figs. 1, 2, 3 and 4.²¹

FIG. 6 -Predicted Stresses and Strains in the Ring.¹⁴

FIG. 7³ $\tau = 28$ days, $\sigma = 10.8$ N/mm²

FIG. 8 -Compressive Strength-Age Relations for Series A and B Concrete Stored Indoors and Outdoors.

FIG. 9 -Compressive Strength-Age Relations for Series A, B, and C Concrete.⁷

FIG. 10 -Comparison of Modulus of Elasticity of Concretes as Determined by Two Different Methods. Plotted Points Represent Data Shown in Table 13. Dynamic E by Flexural Vibration. Static E 6 x 12-in. Cylinders Using Compressometer, of 6 x 6 x 30-in. Beams by Deflection Method.⁹

FIG. 11 -Variation of Creep Coefficient With Volume/Surface Ratio at Different Ages (sandstone aggregate concrete cylinders).¹³

FIG. 12 -Effect of Aggregate-Cement Ratio and Water-Cement Ratio upon Creep.²²

FIG. 13 -Effect of Composition and Fineness of Cement upon Creep.²²

FIG. 14 -Effect of Age and Intensity of Loading upon Creep.²²

FIG. 15 -Effect of Mineralogical Character of Aggregates upon Creep.²²

FIG. 16 -Effect of Level of Stress Increment upon Creep.²²

FIG. 19 -Effect of Size of Specimen upon Creep and Expansion While in Moist Storage.²²

FIG. 20 -Creep-Time Ratio Curves.²²

FIG. 21 -Relation Between Creep After 91 Days under Load and Stress-Strength Ratio for Different Temperatures of Storage.¹⁰

TABLE 1
NFS NEUTRALIZED WASTE TANK
VAULT GEOMETRY⁴²

	feet
Height.	32
Diameter.	78
Wall Thickness.	.2
Roof.	.2
Column Diameter	.2.5
Base Slab	.2.25

TABLE 2 - TENSILE AND COMPRESSIVE STRENGTHS OF
MORTAR - SERIES B (1923)*⁷

Mix (weight)	Sand	Test	Tensile or compressive strength, psi**, at					
			7 days	28 days	1 yr	10 yr	25 yr	50 yr
Stored outdoors								
1:1	Janesville	T	510	655	715	810	845	770(17)
1:2	Janesville	T	435	555	660	720	765	710(16)
1:3	Janesville	T	370	465	530	640	740	610
1:1	Stnd. Ottawa	T	560	655	505	605	705	740(19)
1:2	Stnd. Ottawa	T	390	500	535	695	765	505
1:3	Stnd. Ottawa	T	275	365	410	405	460	425(24)
1:1	Janesville	C	5200	6860	8700	8950	9020	8880(5)
1:2	Janesville	C	3630	5430	7020	7530	7410	6910(14)
1:3	Janesville	C	2360	3870	5610	6890	6210	7120(5)
1:1	Stnd. Ottawa	C	4720	7620	8130	8890	10100	7870(25)
1:2	Stnd. Ottawa	C	3080	4950	6500	7320	7100	6590(27)
1:3	Stnd. Ottawa	C	1510	2600	4260	5190	4130	4970(11)
Stored in water								
Neat		T	630	655	620	580	675	690(15)
1:3	Stnd. Ottawa	T	280	390	400	320	285	230(23)
1:3	Stnd. Ottawa	C	1390	2460	2980	3140	2780	2220(21)

* Each result is the average of 4 cements and represents 12 specimens except where indicated in ().

**Values in psi may be converted to kgf/cm² by multiplying by 0.07031.

TABLE 3 - PROPERTIES OF SERIES B (1923),
CONCRETE DETERMINED OVER A 50-YEAR PERIOD

Mix variables a=mix prop(vol.) b=coarse aggregate c=storage d=cement content(s/cy) e=w/c(weight)		Compressive strength, psi ² at							Properties at 50 yr. Secant modulus Dec. Modulus of in weight of elasticity percent rupture X10 ⁻⁶ psi psi		
	Cement type	7 day	28 day	1 yr	5 yr	10 yr	25 yr	50 yr			
a 1:1½:3	3M	2325	3315	4580	6780	7260	7400	7110	0.59	756	5.72
b Janesville	4M	2620	3455	4910	6930	7195	7555	8660	0.32	828	6.72
c Outdoor	5M	2530	4035	5050	6960	6900	7990	7070	0.10	877	6.73
d 6.62	7M	2805	3095	5190	7145	7615	7850	8715	0.25	878	6.82
e 0.41											
Average		2570	3725	4930	6955	7240	7700	7890	0.32	835	6.50
a 1:2:4	3M	1575	2430	3815	5370	6295	6730	6465	0.11	765	6.16
b Janesville	4M	1425	2950	3680	5925	6115	6720	6340	0.50	777	6.35
c Outdoor	5M	1485	2945	3615	5395	5740	6535	5640	0.44	818	6.70
d 5.15	7M	1690	2800	3785	6190	6140	6970	6840	0.29	770	5.53
e 0.51											
Average		1545	2780	3725	5720	6070	6740	6320	0.33	782	6.18
a 1:2:4	3M			2980	3615	4145	5195	5645	1.24	843	4.78
b Janesville	4M			3415	3980	4410	5620	5630	1.30	966	5.19
c Indoor	5M			3220	3500	4165	5345	5090	1.17	766	4.80
d 5.15	7M			3280	3805	4135	5660	5605	1.42	972	4.86
e 0.51											
Average				3225	3725	4215	5455	5490	1.28	889	4.90
a 1:2:4	3M	820	1445	2580	3505	3810	4465	4635	0.46	519	5.47
b Janesville	4M	745	1780	2865	3815	4095	5350	4455	0.53	710	5.56
c Outdoor	5M	960	2125	2745	3640	3980	4790	3795	0.88	642	5.16
d 5.04	7M	870	1790	3130	4280	4395	5345	5260	0.86	703	5.48
e 0.67											
Average		850	1785	2830	3810	4070	4990	4535	0.68	644	5.42
a 1:2:4	3M			2440	2510	2540	3940	3975	1.73	584	4.90
b Janesville	4M			2350	2405	2940	3740	4030	2.57	662	4.38
c Indoor	5M			2570	2685	2745	3345	3185	2.65	707	4.44
d 5.04	7M			2975	2704	2860	3865	4785	1.97	816	4.90
e 0.67											
Average				2585	2575	2770	3720	3995	2.23	692	4.66

TABLE 3 - CONTINUED

Mix variables	Cement type	Compressive strength, psi ² at						Properties at 50 years			
		7 day	28 day	1 yr	5 yr	10 yr	25 yr	50 yr	Dec. in weight percent	Modulus of rupture, psi	Secant modulus of elast. (10 ⁻⁶)psi
a 1:3:6	3M	825	1340	2185	3140	3470	4340	3930	1.26	580	5.63
b Janesville	4M	785	1480	2445	3690	4095	4795	4055	1.51	629	6.33
c Outdoor	5M	800	1445	2290	3444	3810	4720	4590	1.39	559	6.10
d 3.58	7M	780	1560	2920	3050	4370	5155	4400	1.40	625	6.34
e 0.69											
Average		800	1455	2460	3610	3935	4750	4245	1.39	598	6.10
a 1:2:4	3M	1475	2490	4100	5990	5890	6555	7065	0.57	726	6.76
b Lannon Dolomite	4M	1555	2750	4290	6025	6515	7065	7320	0.46	753	6.72
c Outdoor	5M	1370	2565	3960	5325	5985	6560	6265	0.57	771	6.74
d 3.52	7M	1900	3285	4365	6270	6880	7395	7515	0.14	907	7.23
e 0.54											
Average		1575	2770	4180	5900	6320	6895	7040	0.44	789	6.86
a 1:2:4	3M	1475	1935	3295	4385	5425	6650	5350	0.07	820	5.42
b Red Granite	4M	1450	2440	3350	5390	5930	6960	6355	0.18	838	5.63
c Outdoor	5M	1575	2715	3495	5290	4990	6320	6520	0.00	832	5.73
d 3.41	7M	1685	2930	4350	6180	6810	7450	7810	0.05	837	5.62
e 0.51											
Average		1545	2505	3620	5310	5790	6845	6510	0.04	832	5.61

¹ Each compressive strength value is the average of five test results. Each modulus of rupture value and each decrease in weight is the average of three test results. Each secant modulus of elasticity is the average of two test results.

At test, average moisture content of specimens stored indoors was 0.45 percent, stored outdoors was 2.3 percent.

² Values in psi may be converted to kgf/cm² by multiplying by 0.07031.

TABLE 4 - A COMPARISON OF THE COMPRESSIVE STRENGTHS OF CONCRETES AT DIFFERENT AGES WITH THE COMPOUND COMPOSITIONS OF THE CONSTITUENT CEMENTS⁷

Test series	Coarse aggregate	Mix proportions		Cement content, sk/yd ³	Water cement		Method of molding
		by vol.	by wt.		by vol.	by wt.	
A 1910	Lower Mag. Limestone	1:2:4	1:2.18:3.50	5.75	0.94	0.63	Hand
		1:3:6	1:3.27:5.25	4.01	1.36	0.90	Hand
B 1923	Average of						Hand
	Janes. Gr.	1:2:4	1:2.4:4.47	5.15	0.76	0.51	Hand
	Lannon Dol.	1:2:4	1:2.4:3.92	5.52	0.81	0.54	Hand
	Red Granite	1:2:4	1:2.4:4.00	5.41	0.77	0.51	Hand
C 1937	Janesville Gravel	1:1.66:3.80	1:2:4.25	5.68	0.74	0.49	Hand
		1:1.66:3.80	1:2:4.25	5.82	0.60	0.40	Vib.
		1:2.09:4.78	1:2.51:5.34	4.73	0.74	0.49	Vib.
		1:1.66:3.80	1:2:4.25	5.65	0.74	0.49	Hand
		1:1.66:3.80	1:2:4.25	5.82	0.60	0.40	Vib.
		1:2.09:4.78	1:2.51:5.34	4.75	0.74	0.49	Vib.
		1:1.66:3.80	1:2:4.25	5.72	0.72	0.48	Hand
		1:1.66:3.80	1:2:4.25	5.84	0.59	0.39	Vib.
		1:2.09:4.78	1:2.51:5.34	4.76	0.71	0.47	Vib.
		1:1.66:3.80	1:2:4.25	5.67	0.74	0.49	Hand
		1:1.66:3.80	1:2:4.25	5.82	0.60	0.40	Vib.
		1:2.09:4.78	1:2.51:5.34	4.74	0.74	0.49	Vib.

¹All specimens stored outdoors after moist curing.

Series A test results adjusted to 12-in. (30 cm) cylinder length for purposed of comparison
($S_{12} = 1.05 S_{18}$)

Test series A results at 30 years.

TABLE 4 - CONTINUED

Cement	Compound composition of cement			Surface area, cm ² /gr	Compressive strength, psi ² at					
	C ₃ S	C ₂ S	C ₃ A		1 mo	1 yr	5 yr	10 yr	25 yr	50 yr
Atlas	28.9	44.4	11.4	1045	1920	3400	4250	4050	6250	6160
	28.9	44.4	11.4	1045	875	1920	2550	3010	3240	2975
3M	43.7	29.7	11.0	1100	2285	3735	5250	5870	6645	6295
4M	32.8	38.6	14.2	1285	2715	3775	5780	6185	6915	6675
5M	46.5	25.1	14.8	1235	2750	3690	5735	5570	6485	6140
7M	30.4	41.4	13.3	1295	3005	4165	6215	6610	7270	7390
3M7					3990	5195	7510	7865	7585	
3M7	53.1	21.5	10.4	1370	5030	6530	8780	8700	8200	
3M7					4285	5805	7400	7855	7840	
5M7					4525	6015	7540	8025	7885	
5M7	52.6	21.0	11.9	1780	6185	8195	9015	10465	9850	
5M7					4990	6240	7820	7885	8050	
5UM					5150	7395	7940	8525	8070	
5UM	37.5	34.0	4.53	1920	6265	8310	10145	10145	9915	
5UM					5130	7325	8860	9015	8250	
I					5145	6715	7640	7910	6835	
I	56.5	16.2	13.0	2110	7050	8695	9995	9515	8985	
I					5480	7360	8405	8180	7500	

²psi values may be converted to kgf/cm² by multiplying by 0.07031.

TABLE 5 - STRENGTH CHANGES FOR SERIES A, B, AND C ⁷

Series	Average surface area, cm ² /gm	Average C ₂ S content of cement, percent	Outdoor storage percent change from			Indoor storage percent change from		
			1 mo-10 yr	10 yr-25 yr	10 yr-50 yr	1 mo-10 yr	10 yr-25 yr	10 yr-50 yr
A-1910	1045	44.4	177	31*	42	97	44*	62
b) 1923	1230	33.7	130	15	9	55	32	37
C-1937	1795	23.2	67	-5	--	--	--	--

* 10 years to 30 years

TABLE 6 - TENSILE STRENGTH OF 1:3
STANDARD OTTAWA SAND BRIQUETS¹

Cement No.	Tensile strength, 1:3 mortar briquets, psi						
	Water storage (ASTM)						
	1 day	3 days	7 days	28 days	3 months	1 year	3 years
TYPE I CEMENTS							
11	210	385	465	525	470	455	430
11T ²	165	310	380	440	410	370	350
12	150	380	470	555	550	490	485
12T ²	125	340	480	525	545	500	470
13	190	375	455	550	565	550	485
14	230	370	460	545	540	495	475
15	245	480	525	555	535	510	445
16	250	400	475	505	515	490	465
16T ²	185	350	410	500	460	445	445
17	175	435	480	575	530	510	465
18	190	425	485	550	550	505	465
18T ²	100	320	430	500	480	470	395
19A	150	310	395	495	515	485	445
19B	155	340	445	505	495	480	455
19C	250	475	545	555	565	505	485
TYPE II CEMENTS							
21	110	325	435	525	565	530	540
21T ²	115	305	375	500	545	495	485
22	150	325	420	550	545	515	485
23	150	355	480	580	555	510	510
24	190	355	415	525	530	490	450
25	165	295	395	540	550	530	475
TYPE III CEMENTS							
31	350	545	605	590	555	510	490
33	365	500	570	555	550	460	465
33T ²	350	455	470	475	475	390	335
TYPE IV CEMENTS							
41	155	290	360	485	530	475	465
42	135	260	350	505	610	515	550
43	105	255	360	475	565	510	510
43A	130	220	335	535	575	510	495
TYPE V CEMENT							
51	160	345	430	545	585	580	515

1 Each value is the average of three specimens. Made and tested in accordance with ASTM C 190-49. Duplicate specimens prepared for curing in moist air at $73.4 \pm 3^\circ\text{F}$ and 100 percent relative humidity.

2 "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 6 - CONTINUED

Cement No.	Tensile strength, 1:3 mortar briquets, psi						
	Moist air storage						
	1 day	3 days	7 days	28 days	3 months	1 year	3 years
TYPE I CEMENTS							
11	210	375	475	555	560	480	460
11T ²	170	320	410	465	400	400	390
12	150	400	475	485	575	530	500
12T ²	115	355	490	550	510	500	485
13	185	380	470	535	535	520	520
14	220	360	465	565	590	505	515
15	240	495	550	610	575	560	520
16	245	430	490	575	535	535	520
16T ²	205	365	445	475	425	465	480
17	180	440	490	530	555	510	495
18	170	390	480	535	570	510	460
18T ²	100	365	405	515	505	450	430
19A	145	305	405	525	525	525	450
19B	155	335	455	560	565	480	460
19C	250	390	555	585	590	525	525
TYPE II CEMENTS							
21	110	325	430	545	585	575	575
21T ²	105	390	405	535	550	530	535
22	140	305	460	555	585	545	515
23	150	350	470	560	555	545	535
24	190	390	465	520	555	530	460
25	170	295	400	515	520	545	500
TYPE III CEMENTS							
31	340	550	655	610	605	530	530
33	385	525	580	570	570	495	480
33T ²	330	470	490	500	470	450	425
TYPE IV CEMENTS							
41	155	285	370	500	545	505	460
42	125	280	310	535	620	530	530
43	105	250	355	525	555	515	490
43A	120	330	335	515	595	545	595
TYPE V CEMENT							
51	150	345	405	575	595	590	605

2 "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 7 - COMPRESSIVE STRENGTH OF 1:2.75
GRADED OTTAWA SAND PLASTIC MORTAR CUBES (2-IN.)^{*,**}

Cement No.	Compressive strength, 1:2.75 mortar cubes, psi						
	Water storage (ASTM)						
	1 day	3 days	7 days	28 days	3 months	1 year	3 years
TYPE I CEMENTS							
11	650	1850	3340	5220	5540	5220	5460
11T*	520	1650	2950	4160	4270	4320	4270
12	490	1850	3280	5260	6080	5950	5860
12T*	350	1580	2910	4800	5450	5250	5330
13	720	1560	2350	4140	5330	5660	5810
14	690	1730	2880	4330	4950	5140	5210
15	1010	3060	4750	5870	5750	5530	2090
16	810	2170	3560	5100	5610	5580	5790
16T*	560	1420	2380	3350	3990	4030	4050
17	630	2160	3530	5610	5900	5700	5420
18	580	1920	3520	5480	6040	5990	5580
18T*	290	1730	2990	4620	4920	4650	4910
19A	460	1010	1610	2950	4050	4210	4390
19B	430	1180	2180	3700	4340	4370	4510
19C	750	2140	3460	5050	5260	5380	4780
TYPE II CEMENTS							
21	380	1380	2450	4330	5940	6670	6810
21T*	320	1200	1980	3750	5470	5890	5860
22	410	1200	2340	3000	5950	5960	6230
23	620	1660	2580	4580	5420	5810	5760
24	630	1530	2270	3670	4600	4790	4970
25	550	1160	1770	3790	5280	5640	5900
TYPE III CEMENTS							
31	1820	4000	5630	7010	7150	6900	6550
33	2010	4180	5910	6340	6460	6210	5850
33T*	1560	3330	4480	5190	5340	4900	4320
TYPE IV CEMENTS							
41	400	850	1840	3230	5070	5910	5880
42	390	940	1290	3070	6110	7110	7350
43	260	860	1480	3620	5440	5810	5650
43A	410	890	1320	3490	5990	6650	6920
TYPE V CEMENT							
51	620	1500	2180	3870	6090	6850	7190

* "Treated" cements. Comparable to present-day air-entraining cements.

** Each value is the average of three specimens. Made and tested in accordance with ASTM C 109-49. Duplicate specimens prepared for curing in moist air at $73.4 \pm 3^\circ\text{F}$ and 100 percent relative humidity.

TABLE 7 - CONTINUED

Cement No.	Compressive strength, 1:2.75 mortar cubes, psi						
	Moist air storage						
	1 day	3 days	7 days	28 days	3 months	1 year	3 years
TYPE I CEMENTS							
11	670	1890	3670	5430	5730	5630	5630
11T*	520	1600	3040	4150	4470	4430	4420
12	490	1840	3350	5520*	6360	6100	5940
12T*	340	1540	2910	4830	5770	5370	5400
13	720	1570	2410	4210	5530	5950	5880
14	720	1670	2870	4350	4990	5290	5540
15	1000	3110	4430	6130	5940	5890	5710
16	810	2120	3590	5170	5680	5920	5910
16T*	560	1450	2360	3560	4160	4100	4230
17	620	2110	3630	6000	6100	6100	5790
18	510	1900	3330	5530	6130	6050	6000
18T*	280	1740	2960	4700	5210	6010	4880
19A	350	1100	1610	2870	4170	4690	4680
19B	440	1180	2190	3820	4560	4600	4680
19C	760	2170	3580	5160	5430	5520	5680
TYPE II CEMENTS							
21	380	1350	2410	4450	6350	6850	7140
21T*	310	1240	2150	4020	5620	5630	5920
22	410	1200	2330	4980	6250	6290	6310
23	600	1650	2590	4720	6130	6480	6430
24	620	1480	2320	3760	4580	4880	5010
25	540	1160	1890	3910	5120	5690	6150
TYPE III CEMENTS							
31	1820	4310	6180	7640	7770	7540	7080
33	2030	4220	5670	6700	6810	6620	6240
33T*	1560	3460	4790	5500	5340	5220	4920
TYPE IV CEMENTS							
41	400	1010	1390	3350	5480	5890	6180
42	380	920	1250	3120	6270	7500	7680
43	270	910	1730	3680	5420	5710	5680
43A	400	840	1320	3690	6390	7060	7190
TYPE V CEMENT							
51	620	1470	2120	3810	6150	7300	7150

* "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 8 - FLEXURAL STRENGTH OF 1:2.75 GRADED OTTAWA SAND PLASTIC MORTAR PRISMS**

Cement No.	Flexural strength, 1:2.75 mortar prisms, psi									
	Water storage					Moist air storage				
	7 days	28 days	3 months	1 year	3 years	1 day	7 days	28 days	3 months	1 year 3 years
TYPE I CEMENTS										
11	610	790	750	740	755	195	655	815	765	755 745
11T*	565	660	655	615	635	160	600	680	670	625 625
12	665	840	815	815	795	140	695	880	885	845 825
12T*	580	735	785	725	735	95	630	795	800	730 730
13	545	755	815	830	830	200	585	790	885	885 890
14	560	755	785	765	805	180	575	700	750	775 800
15	765	895	795	785	775	290	795	900	880	825 810
16	675	810	820	800	855	230	685	815	855	845 850
16T*	585	715	715	740	765	205	605	735	750	760 745
17	655	835	800	755	755	255	665	825	810	810 825
18	655	810	830	795	795	265	660	830	855	790 860
18T*	590	725	725	700	725	95	610	775	755	735 695
19A	385	580	680	715	730	95	425	595	740	735 690
19B	525	700	765	745	765	130	550	745	780	760 755
19C	655	810	820	760	780	190	685	825	810	795 760
TYPE II CEMENTS										
21	535	785	910	915	890	105	555	785	915	950 935
21T*	475	665	810	915	855	95	485	730	855	860 850
22	520	800	850	800	840	125	565	830	925	855 880
23	570	820	865	865	900	145	610	860	870	870 895
24	550	685	765	775	805	170	570	740	785	755 785
25	480	775	895	860	920	175	510	760	865	855 815
TYPE III CEMENTS										
31	895	945	890	885	900	405	845	925	930	885 850
33	890	835	825	810	825	495	870	825	845	805 805
33T*	740	775	715	750	750	430	730	730	760	755 715
TYPE IV CEMENTS										
41	360	680	840	850	820	105	380	670	820	820 805
42	325	645	940	930	945	105	340	700	975	935 965
43	390	725	845	830	795	85	405	745	890	920 770
43A	375	725	915	900	920	115	390	740	945	890 925
TYPE V CEMENT										
51	505	790	945	975	990	165	490	785	1005	970 1055

* "Treated" cements. Comparable to present-day air-entraining cements.

** Each value is the average of the two tests on each of three specimens, total of six tests.

Specimens are 2X2X11 1/2-in. prisms tested with the load applied at the center of a 6-in span.

The specimens were prepared in accordance with ASTM C101-49, except as specimen size, molding, and testing. Duplicate specimens prepared for curing in moist air at 100 percent rel. humidity.

TABLE 9 - COMPRESSIVE STRENGTH OF 1:2.75 GRADED OTTAWA SAND PLASTIC MORTAR MODIFIED CUBES (2-IN.)***

Cement No.	Compressive strength, 1:2.75 mortar modified cubes, psi										
	Water storage					Moist air storage					
	7 days	28 days	3 months	1 year	3 years	1 day	7 days	28 days	3 mo.	1 year	3 years
TYPE I CEMENTS											
11	3470	4870	5320	5200	4920	700	3970	5050	5180	5440	5720
11T*	3000	4100	4150	5120	4220	560	3220	4220	4380	4380	4320
12	3670	5630	5850	5990	5980	520	3960	5800	6350	6350	6190
12T*	3960	4410	5210	4990	5330	360	3200	4880	5400	5400	5270
13	2600	4520	5210	5260	5580	730	2870	4660	5920	5920	6010
14	2920	4060	4580	4630	5040	660	3010	4090	5020	5020	5000
15	4700	6070	5380	5450	5260	1120	4810	6070	5700	5700	5780
16	3680	5160	5530	5530	5740	840	4190	5230	5810	5810	6150
16T*	2820	4050	4250	4430	5020	690	3110	4260	5010	5010	4950
17	3450	5290	5520	5320	5500	560	3780	5600	5730	5730	6000
18	3460	5230	5810	5720	5960	600	3820	5590	5860	5860	5910
18T*	3210	4540	4870	4860	5090	310	3170	4680	5070	5070	5010
19A	1520	2580	3420	3710	4310	280	1660	2910	4130	4130	4520
19B	2340	3630	4240	4150	4380	460	2690	3950	4740	4740	4810
19C	3280	4520	4800	4700	4880	690	3500	4810	5150	5150	5170
TYPE II CEMENTS											
21	2480	4560	5920	6240	6700	370	2800	4600	6990	6990	6990
21T*	2270	3980	5180	5720	6200	350	2260	4080	5950	5950	6140
22	2530	4770	5680	5440	5710	440	2820	5100	6170	6170	6530
23	2620	4700	5480	5850	5880	580	3030	5200	6370	6370	6130
24	2590	3710	4220	4410	4850	600	2780	3910	4740	4740	4780
25	2100	3240	5090	5350	5820	600	2290	4060	5350	5350	5550
TYPE III CEMENTS											
31	5900	7300	7420	6810	6880	1760	5780	7150	7060	7060	7130
33	5620	6100	6200	5820	5910	2030	5580	5810	6190	6190	6110
33T*	4320	5080	5260	5260	5370	1740	4250	5120	5300	5300	5320
TYPE IV CEMENTS											
41	1540	3330	4830	5380	5690	360	1610	3590	5620	5620	5670
42	1270	3100	5660	6200	6610	350	1360	3420	7070	7070	6930
43	1680	3700	5080	5460	5580	290	1760	3730	5520	5520	5510
43A	1520	3810	6040	6710	6730	390	1630	2850	6660	6660	6880
TYPE V CEMENT											
51	2400	4280		6880	7050	610	2320	4310	7420	7420	7220

* Treated cements. Comparable to present-day air-entraining cements.

**Each value is the average of tests on both ends of three 2K2K1K1 in. prisms prepared in accordance with ASTM C109-49, except as related to specimen size, molding, and testing. Duplicate specimens prepared for curing in moist air at 73.4 ± 3°F and 100 percent relative humidity.

TABLE 10 - CHARACTERISTICS OF CONCRETES MADE WITH LTS CEMENTS*

Cement No.	Nominal: 6 bags per cu yd					Actual Nominal: 4 1/2 bags per cu yd				
	Actual cement content, bags per cu yd	Net W/C gal/bag	Sand % by absolute vol.	Slump in.	Air content % (Press)	Actual cement content, bags	Net W/C gal/bag	Sand % by absolute vol.	Slump in.	Air content % (Press)
TYPE I CEMENTS										
11	6.01	4.63	37.0	1.0	1.30	4.50	6.26	40.0	2.5	1.42
11T*	5.95	4.46	32.9	2.4	6.66	4.49	5.28	36.4	2.3	7.58
12	6.00	4.61	37.0	2.3	1.52	4.50	6.15	40.0	2.9	1.73
12T*	6.00	4.55	35.8	2.2	2.77	4.48	5.94	38.7	2.3	3.58
13	6.01	4.80	37.0	2.5	1.12	4.53	6.41	40.0	2.4	1.9
14	6.00	4.63	37.0	2.4	1.63	4.53	6.15	40.0	2.4	1.7
15	6.01	5.07	37.0	2.4	1.24	4.52	6.56	40.0	2.4	1.3
16	6.01	4.03	37.0	1.9	1.38	4.51	6.26	40.0	2.1	1.55
16T*	6.03	4.25	32.7	2.2	5.59	4.47	5.16	35.3	2.4	7.52
17	6.02	5.22	37.0	2.3	1.24	4.50	6.83	40.0	2.2	1.34
18	6.02	4.98	37.0	2.8	1.15	4.53	6.49	40.0	2.6	1.24
18T*	6.01	4.80	35.2	2.5	3.07	4.51	5.77	37.6	1.9	3.93
19A	6.02	5.08	37.0	3.4	1.48	4.52	6.63	40.0	2.7	1.95
19B	6.02	5.09	37.0	2.9	1.28	4.50	6.73	40.0	2.6	1.59
19C	6.01	5.00	37.0	2.5	1.19	4.50	6.55	40.0	2.2	1.45
TYPE II CEMENTS										
21	6.01	4.88	37.0	2.6	1.14	4.54	6.29	40.0	2.5	1.29
21T*	5.99	4.41	35.1	2.0	3.87	4.50	5.53	37.7	2.1	4.88
22	6.01	4.57	37.0	2.5	1.40	4.51	6.11	40.0	2.7	1.67
23	6.01	4.74	37.0	2.5	1.29	4.53	6.14	40.0	2.3	1.46
24	6.02	4.73	37.0	2.7	1.60	4.53	6.33	40.0	2.8	1.76
25	6.02	4.76	37.0	2.2	1.56	4.55	6.35	40.0	2.4	1.73
TYPE III CEMENTS										
31	6.01	5.50	37.0	2.9	1.16	4.54	6.71	40.0	3.0	1.23
33	5.99	4.91	37.0	2.3	1.34	4.50	6.20	40.0	2.0	1.61
33T*	5.98	4.55	34.7	2.1	4.60	4.51	5.42	36.5	2.4	5.81
TYPE IV CEMENTS										
41	6.02	4.53	37.0	2.3	1.85	4.53	6.04	40.0	2.4	1.97
42	6.03	4.79	37.0	2.5	1.22	4.54	6.19	40.0	2.1	1.37
43	6.00	4.72	37.0	2.7	2.06	4.52	6.10	40.0	2.4	2.51
43A	6.00	4.65	37.0	2.7	1.90	4.51	6.14	40.0	2.7	2.21
TYPE V CEMENT										
51	6.01	4.57	37.0	2.1	1.29	4.50	6.07	40.0	2.4	1.4

* "T-treated" cements. Comparable to present-day air-entraining cements.
LTS = Long-Time Study

TABLE 11 - CHARACTERISTICS OF 3 BAGS PER CU YD
AIR-ENTRAINED CONCRETES MADE WITH LTS CEMENTS*

Cement No.	Cement type	Actual cement content, bags/cu yd	Net W/C, gal/bag	% sand, by absolute vol.	Slump in.	Air content, % (pressure)
12	I	3.00	9.12	41.0	2.9	4.83
23	II	3.02	8.03	41.0	2.4	4.30
43A	IV	3.02	8.81	41.0	2.1	4.30

* Neutralized Vinsol resin in solution added at the mixer as air-entraining agent.

LTS = Long-Time Study

TABLE 12 - STRENGTH OF CONCRETES MADE WITH
LTS CEMENTS, 6 BAGS PER CU YD**³

Cement No.	Net W/C, gal/bag	Flexural strength, psi					
		1 day	7 days	28 days	3 months	1 year	3 years
TYPE I CEMENTS							
11	4.63	240	640	765	840	905	855
11T*	4.46	180	500	500	660	660	710
12	4.61	180	640	790	910	925	965
12T*	4.55	160	595	730	850	885	865
13	4.80	260	525	690	845	885	915
14	4.63	250	620	725	800	915	890
15	5.07	320	660	755	865	865	870
16	4.63	265	675	755	890	920	935
16T*	4.25	230	510	625	720	780	800
17	5.22	210	600	685	855	870	935
18	4.98	220	585	720	830	915	895
18T*	4.80	140	530	655	760	785	830
19A	5.08	145	450	605	745	840	870
19B	5.09	195	555	670	810	835	875
19C	5.09	275	605	750	890	920	890
TYPE II CEMENTS							
21	4.88	140	525	710	845	940	925
21T*	4.41	140	490	640	740	870	920
22	4.57	170	580	735	910	935	945
23	4.74	215	565	750	870	950	945
24	4.73	240	565	715	780	865	870
25	4.76	220	510	715	850	905	925
TYPE III CEMENTS							
31	5.50	315	590	655	765	760	790
33	4.91	435	650	665	825	850	845
33T*	4.55	405	635	675	745	815	770
TYPE IV CEMENTS							
41	4.53	100	495	725	875	980	940
42	4.79	160	405	665	890	925	965
43	4.72	115	495	750	890	930	905
43A	4.65	160	430	650	870	935	965
TYPE V CEMENT							
51	4.57	215	520	705	860	945	965

** Flexure: 6X6X30 in. beams. Loaded at third points of 18-in span.
Two breaks per beam. Compression: 6-in. modified cubes and 6X12-in.
cylinders. Each value is the average of six for flexure and modified
cubes and three for cylinders. All concretes cured continuously
moist at 73.1± 3F

* "Treated" cements. Comparable to present-day air-entraining cements.
LTS = Long-Time Study

TABLE 12 - CONTINUED

Compressive strength, psi							6X12-in. cylinders
Cement No.	6-in. modified cubes						
	1 day	7 days	28 days	3 months	1 year	3 years	28 days
TYPE I CEMENTS							
11	1550	5680	7390	7610	9160	9810	7020
11T*	890	3690	5030	5380	5740	6390	4760
12	1120	5920	7490	8770	9170	9710	7370
12T*	860	4930	6920	7740	8720	9330	6700
13	1520	4320	6280	7560	8280	8620	5850
14	1490	5020	6460	7160	8730	9280	5920
15	2230	6080	7180	7820	8530	9290	7490
16	1820	6040	7230	8080	9540	10160	6780
16T*	1250	3850	5050	5710	6380	7390	4670
17	1340	5220	7040	7560	8700	9310	6740
18	1220	5290	7000	7600	8360	9110	6560
18T*	720	4750	6310	6500	7450	8080	5800
19A	770	3090	4810	6600	7350	7930	4320
19B	1110	4350	6560	7450	7740	8850	5720
19C	1540	5370	6860	7390	7960	9000	6530
TYPE II CEMENTS							
21	860	4110	6510	8160	9640	9580	6000
21T*	770	3590	5780	6950	8350	9460	4880
22	1060	5030	7540	8340	9240	9940	6560
23	1420	4530	6760	7550	9210	9540	5970
24	1270	4100	5530	6920	8170	8160	5310
25	1300	3740	5960	7710	8560	9300	5720
TYPE III CEMENTS							
31	2110	5730	6540	7350	7800	7970	6560
33	3690	6580	7360	8140	8840	9340	6100
33T*	2580	5330	6090	6390	7320	7870	5650
TYPE IV CEMENTS							
41	970	3290	5950	7730	9140	9630	5900
42	800	2460	4880	7720	9470	9640	4660
43	660	3340	5470	7280	8480	9500	5700
43A	880	2580	5470	7610	9220	9890	5180
TYPE V CEMENT							
51	1420	4400	6560	8300	8620	9990	6200

* "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 13 - STRENGTH OF CONCRETES MADE WITH
LTS CEMENTS, 4½ BAGS PER CU YD**

Cement No.	Net W/C, gal/bag	Flexural strength, psi					
		1 day	7 days	28 days	3 months	1 year	3 years
TYPE I CEMENTS							
11	6.26	135	520	625	710	690	730
11T*	5.28	140	445	515	595	585	595
12	6.15	100	530	705	795	755	770
12T*	5.94	60	495	645	765	790	760
13	6.41	165	420	595	705	765	765
14	6.15	150	490	630	740	765	745
15	6.56	215	580	650	710	710	665
16	6.26	165	535	655	760	770	775
16T*	5.16	155	415	550	635	605	665
17	6.83	120	490	640	735	760	720
18	6.49	130	510	650	750	740	730
18T*	5.77	100	485	585	710	720	720
19A	6.63	75	300	470	610	655	700
19B	6.73	105	415	580	680	725	715
19C	6.55	170	510	665	775	810	765
TYPE II CEMENTS							
21	6.29	75	380	590	745	825	825
21T*	5.53	90	420	575	700	810	800
22	6.11	95	425	640	760	755	815
23	6.14	130	445	615	765	800	765
24	6.33	130	440	585	690	735	745
25	6.35	105	325	545	730	790	760
TYPE III CEMENTS							
31	6.71	230	540	640	710	645	640
33	6.20	370	585	635	755	695	720
33T*	5.42	340	545	615	655	660	615
TYPE IV CEMENTS							
41	6.04	95	305	575	745	875	835
42	6.19	95	270	500	825	890	860
43	6.10	60	325	615	770	770	775
43A	6.14	80	265	525	745	845	815
TYPE V CEMENT							
51	6.07	125	380	595	745	780	795

** Flexure: 6X6X30-in. beams. Loaded at third points of 18-in. span.
Two breaks per beam. Compression: 6-in. modified cubes and 6X12-in.
cylinders. Each value is the average of six for flexure and modified
cubes and three for cylinders. All concretes cured continuously
moist at 73.4±3°F.

* "Treated" cements. Comparable to present-day air-entraining cements.
LTS = Long-Time Study

TABLE 13 - CONTINUED
Compressive strength, psi

Cement No.	6-in. modified cubes						6x12-in. cylinders
	1 day	7 days	28 days	3 months	1 year	3 years	28 days
TYPE I CEMENTS							
11	780	4210	5870	6390	7020	6910	5250
11T*	600	3010	4190	4460	4780	5080	2840
12	580	3800	5710	6650	7010	7380	5510
12T*	420	3680	6030	6580	7240	7560	5480
13	890	2740	4730	5760	6400	6750	3990
14	800	3480	5190	5700	6540	7030	4500
15	1260	4730	5830	6280	6440	6360	5590
16	1020	4000	5820	6520	7060	7640	5000
16T*	800	2940	4150	4480	4770	5490	3970
17	740	3480	5770	6410	6560	6890	4920
18	670	3600	5600	6230	6540	6810	5340
18T*	500	3980	5460	5770	6260	6570	5050
19A	410	1710	3100	4280	5060	5940	2750
19B	560	2640	4260	5140	5420	6000	3810
19C	890	3910	5520	6200	6580	6970	4720
TYPE II CEMENTS							
21	540	2600	4630	6080	7410	7630	4320
22T*	450	2650	4590	5900	6920	7080	4020
22	560	2850	5150	6000	6620	7170	4600
23	830	3220	5040	6200	6790	7100	4690
24	680	2800	4300	5360	5920	6060	3860
25	620	1980	4000	5630	5680	6820	3580
TYPE III CEMENTS							
31	1480	4820	5820	6490	6260	6370	5440
33	2290	4900	5560	6340	6600	6790	5310
33T*	1860	4320	4950	5370	5560	5880	4790
TYPE IV CEMENTS							
41	510	1760	3860	5920	6940	6830	3410
42	460	1490	3200	5930	7140	7850	2810
43	340	1780	3810	5560	6750	7070	3950
43A	460	1490	3450	5700	6820	7380	3010
TYPE V CEMENT							
51	780	2590	4220	6440	6850	7570	3890

* "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 14 - STRENGTH OF AIR-ENTRAINED CONCRETES MADE WITH
LTS CEMENTS - 3 BAGS PER CU YD (VINSOL RESIN ADDED)*²

Cement No.	Flexural strength, psi						Compressive strength, psi						
							6-in. modified cubes						6x12-in. cylinder
	1 day	7 days	28 days	3 months	1 year	3 years	1 day	7 days	28 days	3 months	1 year	3 years	28 days
12	35	250	420	490	500	485	170	1240	2550	2820	2780	2990	2360
23	50	225	370	440	440	450	270	1280	2240	2680	2860	2940	2010
43A	30	115	270	460	535	560	160	600	1400	2620	3150	3660	1280

* Flexure: 6X6X30-in. beams. Loaded at third points of 18-in. span. Two breaks per beam.
Compression: 6-in. modified cubes and 6x12-in. cylinders.
Each value is the average of six for flexure and modified cubes and three for
cylinders. All concretes cured continuously moist at 73.4±3F.

LTS = Long-Time Study

TABLE 15 - ELASTIC PROPERTIES (DYNAMIC) OF CONCRETES MADE
WITH LTS CEMENTS, 6 BAGS PER CU YD**

Cement No.	Young's modulus, psiX10 ⁻⁶						Shear modulus, psiX10 ⁻⁶		
	1 day	7 days	28 days	3 months	1 year	3 years	1 day	7 days	28 days
TYPE I CEMENTS									
11	3.23	5.29	5.86	6.38	7.18	7.09	1.33	2.15	2.31
11T*	2.52	4.21	5.04	5.40	5.85	6.06	1.08	1.76	2.04
12	2.67	5.40	5.99	6.41	7.06	7.60	1.12	2.12	2.34
12T*	2.43	5.14	5.85	6.28	6.87	7.39	0.99	2.03	2.31
13	3.39	4.97	5.73	6.30	7.57	7.41	1.39	2.01	2.24
14	1.37	5.07	5.67	6.20	6.86	7.00	1.39	2.04	2.25
15	3.65	5.08	5.65	6.23	6.91	7.07	1.48	2.04	2.25
16	3.26	5.25	5.89	6.35	6.98	7.36	1.36	2.06	2.28
16T*	3.02	4.49	5.16	5.67	6.26	6.52	1.22	1.87	2.09
17	2.77	4.56	5.51	6.21	6.52	7.12	1.13	1.87	2.14
18	2.89	4.88	5.47	6.24	7.01	7.33	1.16	1.92	2.19
18T*	2.26	4.87	5.42	6.00	6.49	6.88	0.93	1.92	2.18
19A	2.50	4.39	5.22	6.13	6.55	6.94	1.01	1.78	2.06
19B	2.89	4.88	5.77	6.19	6.88	7.04	1.19	1.90	2.22
19C	3.37	5.02	5.82	6.17	6.74	7.12	1.20	1.99	2.26
TYPE II CEMENTS									
21	2.33	4.56	5.65	6.22	6.96	7.33	0.92	1.83	2.17
21T*	2.32	4.63	5.49	6.05	6.80	7.21	0.96	1.88	2.17
22	2.75	5.21	6.01	6.49	7.31	7.50	1.14	2.00	2.38
23	2.99	4.94	5.72	6.43	6.93	7.15	1.20	1.92	2.24
24	3.25	4.94	5.43	6.10	6.48	6.77	1.28	1.93	2.16
25	2.93	4.50	5.41	6.11	6.79	6.97	1.21	1.81	2.14
TYPE III CEMENTS									
31	3.27	4.77	5.43	6.00	6.31	6.66	1.35	1.91	2.13
33	4.07	5.32	5.77	6.19	6.57	6.96	1.66	2.10	2.26
33T*	3.56	4.85	5.35	5.79	6.19	6.31	1.51	1.97	2.10
TYPE IV CEMENTS									
41	2.74	4.51	5.46	6.21	6.72	6.99	1.14	1.85	2.17
42	2.51	4.05	5.48	6.23	7.01	7.35	1.01	1.65	2.09
43	2.18	4.62	5.67	6.16	6.74	7.11	0.90	1.85	2.20
43A	2.56	4.27	5.41	6.20	6.81	7.42	1.02	1.71	2.15
TYPE V CEMENT									
51	3.12	5.07	5.72	6.51	7.27	7.56	1.24	1.97	2.24

** Specimens: 6X6X30-in. beams. Cured continuously moist. Each result is the average of tests of three specimens.

* "Treated" cements. Comparable to present-day air-entraining cements.

LTS = Long-Time Study

TABLE 15 - CONTINUED

Cement No.	Shear modulus, psiX10 ⁻⁶			Poisson's ratio					
	3 mo.	1 year	3 years	1 day	7 days	28 days	3 mo.	1 yr.	3 yrs.
TYPE I CEMENTS									
11	2.57	2.82	2.81	.21	.23	.27	.24	.27	.26
11T*	2.13	2.33	2.42	.17	.20	.24	.27	.25	.25
12	2.60	2.81	3.00	.19	.27	.28	.24	.25	.27
12T*	2.53	2.79	2.89	.23	.26	.27	.24	.23	.28
13	2.53	2.85	2.99	.22	.24	.28	.24	.33	.24
14	2.48	2.75	2.82	.21	.25	.26	.25	.25	.24
15	2.51	2.75	2.83	.23	.24	.26	.24	.26	.25
16	2.52	2.83	2.92	.20	.27	.29	.26	.22	.26
16T*	2.25	2.52	2.63	.24	.20	.23	.26	.24	.25
17	2.45	2.64	2.81	.22	.22	.28	.26	.24	.26
18	2.49	2.79	2.84	.25	.27	.25	.26	.25	.29
18T*	2.42	2.68	2.77	.21	.27	.24	.24	.21	.24
19A	2.40	2.56	2.76	.23	.23	.27	.28	.28	.26
19B	2.54	2.71	2.82	.21	.28	.30	.22	.27	.25
19C	2.47	2.68	2.83	.40	.26	.29	.25	.26	.25
TYPE II CEMENTS									
21	2.48	2.77	2.86	.26	.24	.30	.26	.26	.28
21T*	2.43	2.75	2.86	.21	.23	.27	.24	.24	.26
22	2.57	2.83	2.97	.21	.31	.26	.26	.29	.27
23	2.54	2.74	2.85	.24	.28	.28	.26	.26	.25
24	2.48	2.57	2.66	.27	.28	.25	.26	.26	.27
25	2.38	2.66	2.78	.20	.24	.27	.28	.28	.25
TYPE III CEMENTS									
31	2.30	2.51	2.64	.21	.25	.27	.30	.26	.26
33	2.18	2.61	2.78	.23	.27	.28	.25	.26	.25
33T*	2.20	2.45	2.53	.18	.23	.27	.31	.27	.25
TYPE IV CEMENTS									
41	2.47	2.72	2.78	.20	.22	.25	.26	.23	.26
42	2.45	2.81	2.89	.24	.25	.32	.27	.24	.27
43	2.44	2.64	2.80	.22	.25	.29	.26	.28	.27
43A	2.49	2.70	2.93	.25	.25	.26	.25	.26	.27
TYPE V CEMENT									
51	2.56	2.83	3.03	.26	.29	.28	.27	.29	.25

* "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 16 - ELASTIC PROPERTIES (DYNAMIC) OF CONCRETES MADE WITH
LTS CEMENTS, 4½ BAGS PER CU YD**

Cement No.	Young's modulus psi X 10 ⁻⁶						Shear modulus psi X 10 ⁻⁶		
	1 day	7 days	28 days	3 mo.	1 year	3 years	1 day	7 days	28 days
TYPE I CEMENTS									
11	2.41	4.85	5.53	6.03	6.47	6.66	0.96	1.90	2.15
11T*	2.22	4.02	4.75	5.16	5.66	5.82	0.90	1.63	1.90
12	2.02	4.73	5.64	6.19	6.48	6.94	0.85	1.89	2.21
12T*	1.68	4.61	5.39	5.85	6.53	6.82	0.69	1.83	2.15
13	2.71	4.44	5.38	6.01	6.53	6.83	1.12	1.83	2.10
14	2.57	4.70	5.38	5.81	6.26	6.53	1.05	1.86	2.05
15	2.98	4.87	5.34	5.98	6.33	6.46	1.20	1.94	2.13
16	2.60	4.69	5.46	5.98	6.37	6.66	1.05	1.87	2.15
16T*	2.47	4.13	4.87	5.17	5.74	6.13	1.06	1.65	1.96
17	2.17	4.31	5.19	5.89	6.22	6.52	0.87	1.71	1.98
18	2.33	4.52	5.37	5.99	6.50	6.60	0.93	1.79	2.07
18T*	1.97	4.49	5.32	5.83	6.39	6.65	0.86	1.85	2.15
19A	2.84	3.86	4.88	.64	6.13	6.61	0.74	1.55	1.91
19B	2.12	4.27	5.16	5.85	6.26	6.57	0.88	1.73	2.05
19C	2.68	4.64	5.49	5.92	6.43	6.66	1.14	1.87	2.17
TYPE II CEMENTS									
21	1.72	4.12	5.12	5.96	6.55	6.77	0.72	1.63	1.99
21T*	1.78	4.23	5.14	5.73	6.29	6.68	0.78	1.71	2.06
22	1.95	4.39	5.51	6.05	6.48	6.87	0.83	1.77	2.17
23	2.32	4.49	5.38	5.96	6.48	6.77	0.95	1.77	2.12
24	2.32	4.24	5.10	5.67	6.16	6.37	0.94	1.68	1.94
25	2.41	3.82	4.96	5.69	6.35	6.60	0.88	1.51	1.95
TYPE III CEMENTS									
31	2.88	4.78	5.22	5.79	6.19	6.40	1.19	1.89	2.07
33	3.09	4.93	5.43	5.96	6.26	6.57	1.50	1.94	2.16
33T*	3.33	4.47	4.97	5.43	5.83	5.93	1.35	1.94	1.97
TYPE IV CEMENTS									
41	1.92	3.74	4.95	5.86	6.35	6.69	0.80	1.50	1.93
42	1.90	3.52	4.89	5.81	6.61	7.14	0.83	1.42	1.92
43	1.63	3.87	5.20	5.86	6.30	6.79	0.64	1.60	2.08
43A	1.80	3.58	4.85	5.70	6.44	6.97	0.77	1.43	1.92
TYPE V CEMENT									
51	2.41	4.36	5.37	6.10	6.61	7.12	0.97	1.74	2.15

** Specimens: 6 X 6 X 30-in. beams. Cured continuously moist. Each result is the average of tests of three specimens.

* "Treated" cements. Comparable to present-day air-entraining cements.

LTS = Long-Time Study

TABLE 16 - CONTINUED

Cement No.	Shear modulus, psi X 10 ⁻⁶			Poisson's ratio					
	3 mo.	1 year	3 years	1 day	7 days	28 days	3 mo.	1 year	3 years
TYPE I CEMENTS									
11	2.39	2.56	2.64	.25	.28	.29	.26	.27	.26
11T*	2.05	2.17	2.36	.24	.23	.25	.25	.30	.23
12	2.46	2.55	2.74	.19	.25	.28	.26	.27	.27
12T*	2.32	2.60	2.73	.21	.26	.26	.26	.26	.25
13	2.41	2.63	2.75	.21	.22	.28	.25	.24	.24
14	2.27	2.49	2.58	.22	.26	.31	.28	.26	.27
15	2.33	2.49	2.54	.24	.26	.25	.28	.27	.27
16	2.36	2.57	2.65	.27	.25	.27	.26	.24	.26
16T*	2.05	2.26	2.42	.16	.25	.24	.26	.27	.26
17	2.26	2.47	2.49	.25	.26	.31	.30	.26	.31
18	2.36	2.56	2.67	.25	.26	.30	.27	.27	.25
18T*	2.31	2.54	2.62	.15	.22	.24	.26	.26	.27
19A	2.18	2.43	2.57	.24	.24	.27	.29	.26	.29
19B	2.26	2.49	2.59	.20	.24	.25	.29	.26	.27
19C	2.31	2.51	2.62	.18	.24	.27	.28	.28	.27
TYPE II CEMENTS									
21	2.30	2.57	2.73	.19	.27	.29	.30	.28	.24
21T*	2.30	2.52	2.66	.14	.24	.25	.24	.25	.25
22	2.43	2.57	2.73	.17	.24	.27	.24	.26	.26
23	2.32	2.53	2.67	.22	.27	.27	.29	.28	.27
24	2.19	2.38	2.48	.23	.26	.31	.29	.29	.29
25	2.23	2.51	2.55	.20	.27	.27	.27	.26	.29
TYPE III CEMENTS									
31	2.25	2.45	2.49	.21	.26	.26	.28	.26	.28
33	2.33	2.50	2.57	.23	.27	.26	.28	.26	.28
33T*	2.13	2.31	2.39	.24	.22	.26	.28	.26	.24
TYPE IV CEMENTS									
41	2.24	2.50	2.62	.20	.25	.28	.30	.27	.28
42	2.29	2.59	2.79	.15	.24	.27	.27	.28	.28
43	2.27	2.50	2.69	.28	.21	.25	.29	.26	.26
43A	2.29	2.55	2.76	.17	.25	.25	.26	.26	.26
TYPE V CEMENT									
51	2.46	2.66	2.85	.24	.25	.25	.24	.24	.25

* "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 17 - ELASTIC PROPERTIES (DYNAMIC) OF CONCRETES MADE WITH
LTS CEMENTS, 3 BAGS PER CU YD (AIR-ENTRAINED)*²

Cement No.	Test results at age indicated					
	1 day	7 days	28 days	3 months	1 year	3 years
	Young's modulus, psi X 10 ⁻⁶					
12	0.91	3.25	4.31	5.09	5.37	5.40
23	1.26	3.38	4.29	5.00	5.52	5.52
43A	0.92	2.38	3.80	5.18	5.73	5.95
	Shear modulus, psi X 10 ⁻⁶					
12	0.41	1.33	1.72	1.94	2.10	2.12
23	0.54	1.35	1.72	1.92	2.13	2.17
43A	0.40	0.99	1.55	2.01	2.22	2.34
	Poisson's ratio					
12	0.12	0.22	0.25	0.31	0.28	0.27
23	0.16	0.26	0.25	0.30	0.30	0.28
43A	0.14	0.21	0.23	0.29	0.29	0.27

* Specimens: 6x6x30-in. beams. Cured continuously moist. Each result is the average of tests of three specimens.

LTS = Long-Time Study

TABLE 18 - CONTINUED

		Young's modulus of elasticity, psi X 10 ⁻⁶					
		6 x 6 x 30-in. beams					
Cement No.	Cement type	Dynamic E			Static E		
		28 days	1 yr.	3 yrs.	28 days	1 yr.	3 yrs.
6 bags per cu yd							
11	I	5.86	7.18	7.09	5.46	6.96	7.27
11T	IT*	5.04	5.85	6.06	4.60	5.41	5.48
15	I	5.65	6.91	7.07	5.52	6.99	7.10
19A	I	5.22	6.55	6.94	4.37	6.79	6.44
19B	I	5.77	6.88	7.04	5.39	7.07	7.11
19C	I	5.82	6.74	7.12	5.47	6.92	6.98
21	II	5.65	6.96	7.33	5.12	7.05	6.93
21T	IIT*	5.49	6.80	7.21	5.36	7.08	7.14
31	III	5.43	6.31	6.66	4.91	6.05	6.33
41	IV	5.46	6.72	6.99	4.97	6.96	6.68
51	V	5.72	7.27	7.56	4.96	7.29	7.22
4½ bags per cu yd							
11	I	5.53	6.47	6.66	4.96	6.23	6.30
11T	IT*	4.75	5.66	5.82	4.28	5.15	5.24
15	I	5.34	6.33	6.46	4.96	6.03	6.07
19A	I	4.88	6.13	6.61	4.31	6.00	6.26
19B	I	5.16	6.26	6.57	4.55	5.70	6.20
19C	I	5.49	6.43	6.66	4.75	6.24	6.31
21	II	5.12	6.55	6.77	4.61	6.42	6.46
21T	IIT*	5.14	6.29	6.68	4.47	6.66	6.10
31	III	5.22	6.18	6.40	4.60	6.26	5.75
41	IV	4.95	6.35	6.69	4.36	6.28	6.24
51	V	5.37	6.61	7.12	4.57	7.33	7.06
3 bags per cu yd (air entrained)							
12	I	4.31	5.37	5.40	3.51	4.83	4.77
23	II	4.29	5.52	5.52	3.60	4.76	4.96
43A	IV	3.80	5.73	5.95	3.17	5.46	5.98

* "Treated" cements. Comparable to present-day air-entraining cements.

TABLE 19 - TEST DATA SUMMARY TABLE¹³

Specimen No.	Initial strain per psi of stress (millionths)	Modulus of elasticity at loading (10 ⁶ psi)	Projected final creep psi of stress (millionths)	Projected final value of creep coefficient	Days to reach half final creep strain
4nd	0.268	3.73	0.491	1.83	27
6nd	0.283	3.53	0.656	2.32	43
8nd	0.283	3.53	0.686	2.42	71
12nd	0.248	3.88	0.547	2.12	140
16nd	0.247	4.05	0.490	1.99	108
20nd	0.280	3.57	0.515	1.84	156
24nd	0.275	3.64	0.531	1.93	184
6nw	0.342	2.92	0.578	1.69	121
1 ₁	0.261	3.83	0.535	2.05	119
1 ₂	0.276	3.63	0.541	1.96	57
1 ₃	0.259	3.86	0.577	2.23	44
4sd	0.554	1.80	0.896	1.62	48
6sd	0.647	1.55	0.966	1.49	89
8sd	0.654	1.53	0.975	1.49	66
16sd	0.476	2.10	0.623	1.31	51
6sw	0.636	1.57	0.957	1.50	113
Sd	0.992	1.01	0.079	0.08	-
Sw	1.489	0.67	0.164	0.11	-

TABLE 20 - CREEP AFTER 15 MONTHS UNDER LOAD²²

Stress-strength ratio, percent	Creep at 70F 10^{-6}	Ratio of creep at temperature shown to creep at 70F		
		115F	160F	205F
35	640	1.32	1.75	1.96
60	1220	1.10	2.16	1.63
70	1560	1.07	2.23	1.42

TABLE 21 - RESULTS OF EXPOSURE OF STEEL AND IRON TO CORROSION BY
SEA WATER UNDER NATURAL CONDITIONS¹

Line	Steel Specimens--Continuously Immersed										Original condition of surface	Duration of Exposure, years	Weight Loss	
	Composition of steel, %												mdd*	ipy
	C	Mn	Si	S	P	Cu	Ni	Cr	Other					
1	.07	.31	.02	.06	.11	--	--	--	--	Pickled	2	31	.0058	
2	.20	.69	.005	.005	.06	.04	--	--	--	Mill scale	4	23	.0042	
3	.08	.40	.05	.02	.024	.09	--	--	--	Pickled	1	21	.0038	
4	.08	.40	.05	.02	.024	.09	--	--	--	Pickled	1	18	.0033	
5	.08	.40	.05	.02	.024	.09	--	--	--	Pickled	1	23	.0042	
6	.08	.40	.05	.02	.024	.09	--	--	--	Pickled	1	42	.0077	
7	Average of carbon steels included in tests										Pickled	15	26	.0048
8	"										Mill scale	15	23	.0043
9	"										Pickled	15	17	.0030
10	"										Mill scale	15	18	.0033
11	"										Pickled	15	13	.0024
12	"										Mill scale	15	13	.0024
13	"										Pickled	15	20	.0036
14	"										Mill scale	15	21	.0039
15	Average of 9 mild steels submitted										Machined	3	27	.005
16	.20	.59	.02	--	.04	.02	--	--	--	Sandblasted	1.2	27	.0049	
17	.21	.61	.03	--	.04	.48	--	--	--	Sandblasted	1.2	28	.0051	
18	.21	.61	.03	--	.04	.48	--	--	--	Mill scale	0.5	33	.0060	
19	--	--	--	--	--	--	--	--	--	Pickled	1	23	.0041	
20	--	--	--	--	--	--	--	--	--	Pickled	0.5	36	.0066	
21	--	--	--	--	--	--	--	--	--	Pickled	1	20	.0038	
22	.16	.60	.017	.032	.025	--	--	--	--	Pickled	1	27	.005	
23	.16	.60	.017	.032	.025	--	--	--	--	Mill scale	1	22	.004	
24	.13	.51	--	.021	.013	.05	--	--	--	Pickled	5	33	.0060	
25	.13	.51	--	.021	.013	.05	--	--	--	Mill scale	7.5	23	.004	
26	.10	.52	.10	.04	.05	.34	--	--	--	Pickled	6.5	30	.005	
27	.08	.61	.27	.04	.05	--	--	--	--	Pickled	6.5	13	.002	
28	.08	.40	.19	.04	.05	--	--	--	--	Pickled	6.5	13	.003	

*mdd = milligrams per square decimeter per day

TABLE 21- CONTINUED

Line	Maximum Depth of Pitting, inches	Geographical Location
1	--	Sandy Hook, N.J.
2	.009	Briston Channel, Weston- super-Mare
3	.018	Dunkerque, France
4	.017	Concarneau, France
5	.031	Le Havre, France
6	.031	Brest, France
7	.075	Halifax, N.S.
8	.068	"
9	.043	Aukland, N.Z.
10	.147	"
11	.065	Plymouth, Eng.
12	.156	"
13	.064	Colombo, Ceylon
14	.240	"
15	--	Eastport, Me.
16	--	Gosport, Eng.
17	--	"
18	.050	"
19	--	Kill-van-Kull, N.J.
20	--	San Francisco, Calif.
21	.030	Cape May, N.J.
22	.028	Freeport, Texas
23	.080	"
24	.115	Kure Beach, N.C.
25	.25	"
	(Perf.)	
26	.21	"
27	.035	"
28	.091	"

TABLE 21 - CONTINUED

Steel Specimens--Continuously Immersed										Original condition of surface	Duration of Exposure, years
Line	Composition of steel, %										
	C	Mn	Si	S	P	Cu	Ni	Cr	Other		
29	.06	.39	--	.03	.016	--	2.15	--	--	Mill scale	7.5
30	.18	.66	.27	.016	.016	--	1.80	.26	--	Mill scale	7.5
31	1.35	11.92	.23	--	--	--	--	--	--	Mill scale	4
32	Carbon steel pipe, 6 ft. diam.									Mill scale	10
33	Steel piling									Mill scale	31
34	Steel piling									Mill scale	7.5
Wrought Iron Specimens--Continuously Immersed											
35	.04	.10	.10	.028	.018	.06	--	--	--	Mill scale	4
36	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
37	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
38	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
39	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
40	.03	.02	.12	.017	.08	--	--	--	--	Mill scale	6.5
41	.025	.05	.15	.014	.031	.01	--	--	--	Mill scale	4
42	--	--	--	--	--	--	--	--	--	Pickled	0.5
43	--	--	--	--	--	--	--	--	--	Sandblasted	6
44	--	--	--	--	--	--	--	--	--	Mill scale	7.5
Cast Iron Specimens -- Continuously Immersed											
45	3.52	.88	1.5	.09	.17	--	--	--	--	As cast	4
46	3.41	.74	1.73	.07	.48	--	--	--	--	As cast	15
47	3.41	.74	1.73	.07	.48	--	--	--	--	As cast	15
48	3.41	.74	1.73	.07	.48	--	--	--	--	As cast	15
49	Average of 8 cast irons in test									--	3
50	--	--	--	--	--	--	--	--	--	Machined	0.5
51	--	--	--	--	--	--	--	--	--	Machined	0.2

TABLE 21 - CONTINUED

Line	Weight Loss		Maximum Depth of Pitting, inches	Geographical Location
	md	ipy		
29	26	.005	.094	Kure Beach, N.C.
30	23	.004	.063	"
31	19	.0035	.029	Briston Channel Weston- super-Mare
32	--	.0045	.084	Kure Beach, N.C.
33	--	.001	--	Dry Tortugas Island
34	--	.0037	.098	Boston, Mass.
35	19	.0035	.031	Bristol Channel, Weston-super-Mare
36	25	.0046	.060	Halifax, N.S.
37	12	.0022	.040	Aukland, N.Z.
38	11	.0020	.061	Plymouth, Eng.
39	17	.0031	.108	Colombo, Ceylon
40	28	.0051	.139	Kure Beach, N.C.
41	28	.0052	.022	Briston Channel, Weston-super-Mare
42	33	.0061	--	San Francisco, Calif.
43	35	.0065	.191	"
44	37	.0069	.164	Kure Beach, N.C.
45	21	.0040	.25	Bristol Channel,
46	32	.0059	G	Weston-super-Mare
47	14	.0026	.059	Halifax, N.S.
48	46	.0085	.198	Plymouth, Eng.
49	24	.0048	G	Colombo, Ceylon
50	34	.0068	--	Eastport, Me.
51	32	.0065	--	San Francisco, Calif.
			--	East River,
			--	New York, N.Y.

TABLE 21 - CONTINUED

Line	Composition of steel, %									Original condition of surface	Duration of Exposure, years
	C	Mn	Si	S	P	Cu	Ni	Cr	Other		
	Cast Iron Specimens--Continuously Immersed										
52	--	--	--	--	--	--	--	--	--	As cast	6
53	3.0	1.2	1.7	--	--	6.5	15.0	2.0	--	"	6
54	2.8	1.0	1.7	--	--	--	20.0	2.5	--	"	6
Steel Specimens--Exposed at Half-Tide Level											
55	.13	.55	.12	.06	.04	--	--	--	--	Mill scale	3
56	Average of carbon steels included in test									Pickled	15
57	Average of carbon steels included in test									Mill scale	15
58	Average of carbon steels included in test									Pickled	15
59	Average of carbon steels included in test									Mill scale	15
60	Average of carbon steels included in test									Pickled	15
61	Average of carbon steels included in test									Mill scale	15
62	Average of carbon steels included in test									Machined	3
63	.17	.52	--	.03	.02	--	--	--	--	Sandblasted	1
64	Steel piling									Mill scale	21
65	Steel piling									Mill scale	7.5
66	Carbon steel									Pickled and with mill scale	1
67	.09	.63	.14	.028	.098	.58	.36	.50	--	"	1
68	.09	.37	.68	.028	.141	.39	--	1.00	--	"	1
69	.09	.47	.14	.022	.008	1.02	1.80	--	--	"	1
70	.09	.78	--	.020	.010	1.10	1.32	--	.10 Mo	"	1
71	.10	.40	.03	.025	.08	.60	.70	--	.08 Mo	"	1
72	Copper steel									"	1
73	Carbon steel									"	1
74	.09	.63	.14	.028	.098	.58	.36	.50	--	"	1
75	.09	.37	.68	.028	.141	.39	--	1.00	--	"	1
76	.09	.47	.14	.022	.008	1.02	1.80	--	--	"	1
77	.09	.78	--	.020	.010	1.10	1.32	--	.10 Mo	"	1
78	.10	.40	.03	.025	.08	.60	.70	--	.08 Mo	"	1
79	Carbon steel									"	1

TABLE 21 - CONTINUED

Line	Weight Loss		Max. Depth of Pitting, inches	Geographical Location
	mdd	ipy		
52	103	.021	G	Kure Beach, N.C.
53	4	.0008	0	"
54	8	.0016	0	"
55	9.4	.0017	--	Southampton, Eng.
56	15	.0028	.124	Halifax, N.S.
57	16	.0029	.126	"
58	5	.0009	.023	Aukland, N.Z.
59	3	.0006	.022	"
60	23	.0042	.049	Plymouth, Eng.
61	14	.0026	.082	"
62	17	.0031	--	Eastport, Me.
63	71	.013	--	Pacific Ocean, Panama
64	--	.0044	--	Glenwood Landing, N.Y.
65	--	.0055	--	Boston Mass.
66	52	.0096	--	Seabright, N.S.
67	42	.0077	--	"
68	48	.0086	--	"
69	39	.0072	--	"
70	44	.0081	--	"
71	38	.0070	--	"
72	53	.0098	--	"
73	29	.0053	--	"
74	25	.0046	--	Esquimalt, B.C.
75	20	.0037	--	"
76	26	.0048	--	"
77	28	.0051	--	"
78	28	.0051	--	"
79	28	.0051	--	"

TABLE 21 - CONTINUED

Steel Specimens--Continuously Immersed										Original condition of surface	Duration of Exposure, years
Line	Composition of steel, %										
	C	Mn	Si	S	P	Cu	Ni	Cr	Other		
Wrought Iron Specimens--Exposed at Half-Tide Level											
80	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
81	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
82	.015	.02	.15	.013	.11	--	--	--	--	Pickled	15
83	.06	.10	.12	.03	.27	.06	--	--	--	Mill scale	3
Cast Iron Specimens--Exposed at Half-Tide Level											
84	3.41	.74	1.73	.07	.48	--	--	--	--	As cast	15
85	3.41	.74	1.73	.07	.48	--	--	--	--	As cast	15
86	Average of 9 cast irons in test									Machined	3

For reference, see reference 40, pp. 384.

TABLE 21 - CONTINUED

Line	Weight Loss		Max. Depth of Pitting, inches	Geographical Location
	mdd	ipy		
80	13	.0024	.059	Halifax, N.S.
81	4	.0007	.026	Auckland, N.Z.
82	19	.0035	.043	Plymouth, Eng.
83	7	.0014	--	Southampton, Eng.
84	15	.0015	.052	Halifax, N.S.
85	15	.0020	.180	Plymouth, Eng.
86	3	.0015	--	Eastport, Me.

G = severe graphitic corrosion

TABLE 22 - MAXIMUM PENETRATION OF ALLOY IRON AND STEEL PLATES
EXPOSED FOR FOUR YEARS*⁴⁰
In Mils

Soil		Open Hearth Iron			Low-Alloy Steel	
No.	Type	Open hearth steel	.45% Cu, .07% Mo	.54% Cu, .13% Mo	.95% Cu, .52% Ni	Cr-Si- Cu-P steel, 1.02% Cr
53	Cecil clay loam	76	74	72a	57	56
55	Hagerstown loam	54	44	51	50	52
56	Lake Charles clay	100b	116	100	96	139b
58	Muck	61b	48b	44	64b	52b
60	Rifle peat	40	28	26a	40b	38
61	Sharkey clay	50b	66	54	63	56
62	Susquehanna clay	47	38	49	60	69
63	Tidal marsh	26d	48a	47	28	25
64	Docas clay	78	75	76	84	88
65	Chino silt loam	51	65	57a	60	84a
66	Mohave fine gravelly loam	188+d,e	84	98	85	73
67	Cinders	132+a,b,f	55f,g,h	74a,f	90b,g,h	84b,g,h
69	Houghton muck	22	20	16	15	12
70	Merced silt loam	77b	97a	122a	82	78

* K.H. Logan and Melvin Romanoff, "Soil-Corrosion Studies, 1911," J. Research Natl. Bur. Standards, 33:145 (1944), R.P. 1602.

a Data for the individual specimens differed from each other by more than 50%.

b No original surface; impossible to measure true penetration.

d Data on one specimen only.

e The + mark in all cases indicates one or more specimens penetrated.

f Severe corrosion at one end.

g Plate entirely destroyed at one end.

h Data for one specimen--impossible to obtain data from other specimen because of loss of original surface caused by corrosion.

i Hole from both sides.

For reference, see reference 40, pg. 387.

TABLE 22 - CONTINUED

No.	4 to 6% Chromium Steel			High-Alloy Steel	
	2.01% Cr, .57% Mo	5.02% Cr	4.67% Cr, 0.51% Mo, .030% Al, .022% Ti	5.76% Cr, .43% Mo, .027% Ti	18% Cr
53	52	57	50	57	--
55	52	48	47	39	--
56	60b	95	80b	90b	--
58	42b	44b	46b	44b,d	42d
60	26b	51b	36	32	--
61	35	36	36	32	--
62	56	52	46	58	--
63	24	70	73	72	--
64	70	60	66b	72	--
65	55	46	48	56	--
66	130+	99b	88	117	--
67	68b, f	57b	52b, f	44b, g, h	--
69	27	39	26	33	--
70	94	121	106b	94	--

TABLE 23 - AVERAGE LOSS OF WEIGHT AND MAXIMUM PENETRATION OF
HIGH-ALLOY SHEETS EXPOSED FOR NINE* YEARS**⁴⁰

M, shallow metal attack, roughening of surface, but no definite pitting.
P, definite pitting, but no pits greater than 6 mils.
U, apparently unaffected by corrosion.
+, one or more specimens contained holes because of corrosion, rendering the computation of the exact penetration impossible. The thickness of the specimen has been used as the maximum pit in this case.

Soil No.	(5) 11.95%Cr, .48%Ni, .38%Mn		(5) 17.08% Cr, .09% Ni, .36% Mn		(2) 17.72% Cr, 9.44% Mn	
	Loss, ave.	Maximum Penetration, ave.	Loss, ave.	Max. Penet. ave.	Loss, ave.	Max. Penet. ave.
	mdd	mils	mdd	mils	mdd	mils
53	--	--	--	--	--	--
55	.00039	M	.0013	U	--	--
56	--	--	--	--	--	--
58	--	--	--	--	--	--
59	.00078	P	.0015	P	--	--
60	.00018d	P(5,7)d	.14f	P(5)f	--	--
61	--	--	--	--	--	--
62	--	--	--	--	--	--
63	--	--	--	--	--	--
64	2.95	63+(2,5,7)	1.04	63+(2,5,7)	.45	63+(2,5,7)
65	.037	53+(2,7)	.22f	43+(2,5,7) d,f	--	--
66	.52	55+(2,5,7)	.65	63+(7)	--	--
67	--	--	--	--	.00061	M(7)d

For reference, see reference 40, pg. 389.

TABLE 23 - CONTINUED

Soil No.	(2) 17.2% Cr, 8.95% Ni, .44% Mn		(5) 18.69% Cr, 9.18% Ni, .36% Mn		(5) 22.68% Cr, 12.94% Ni, 1.5% Mn	
	Loss ave. mdd	Max. Penet. ave. mils	Loss ave. mdd	Max. Penet. ave. mils	Loss ave. mdd	Max. Penet. ave. mils
53	.00093	U	--	--	--	--
55	--	--	.00049	P	.0014	P
54	.012c	25+(5,7)e	--	--	--	--
58	.0010	U	--	--	--	--
59	.013	M	.00069	P	.0020	P
60	.0011	M(5)	.0011	P	.0022	--
61	.0015	P	--	--	--	--
62	.0010	M	--	--	--	--
63	--	--	--	--	--	--
64	.72f	14+f	.0024	P	.0058	P
65	.0013	P(2,7)d	.0014	P(2)	.0019	P(2)
66	.23f	14+(5,7)f	.00049	M	.11f	14+f
67	.0014	P	--	--	--	--

* In this table, the weight losses are expressed as average rates for the given time of exposure. It should be remembered that these rates combine in most instances, but not always, a higher initial rate with a lower final rate and hence in any extrapolation represent the maximum expected corrosion. Values of maximum penetration are for the total period of exposure.

** K.H. Logan and Melvin Romanoff, "Soil-Corrosion Studies, 1941," J. Research Natl. Bur. Standards, 33:145 (1944). R.P. 1602.

a The number in parentheses indicates the number of specimens removed from each test site.

b Polished surface.

c Data for one specimen only.

d Average loss of weight or pit depth of 1939 removal is greater.

e The number in parentheses after the pit depth indicates that at least one specimen of a previous removal was punctured, e.g., (2) indicates a puncture after two years.

f Data for the individual specimens differed from each other more than 50%.

mdd = milligrams per square decimeter per day