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Highway Materials Engineering

Module VI: Concrete

National Highway Institute

Notice

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16. Abstract

This student workbook and instructor's guide is one of six prepared for an intensive 6-week "Highway Materials Engineering" course. The course was developed primarily for State highway agency (SHA) engineers who require a basic knowledge of highway materials. The workbook/ guides were developed by national experts in the various materials areas under the guidance of SHA materials engineers and FHWA materials experts.

This module focuses on the basic knowledge of concrete needed by highway materials engineers. Topics discussed include the role of cement and water in concrete, admixtures, fresh concrete behavior, hardened concrete behavior and properties, freeze-thaw and other durability problems, and corrosion of reinforcing steel.

This workbook/guide is the sixth in a series. The others in the series are:

Module No.	FHWA No.	Title
I	90-004	Materials Control and Acceptance -- Quality Assurance
II	90-005	Soils and Foundations
III	90-006	Steels, Welding, and Coatings
IV	90-007	Aggregates and Unbound Bases
V	90-008	Asphalt Materials and Paving Mixtures

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

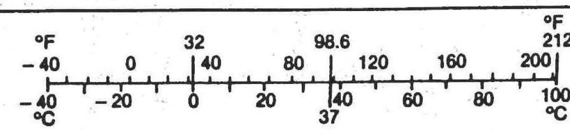
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

Preface

The Highway Materials Engineering course is a concentrated program of classroom and laboratory education designed to meet the needs of Federal, State, and local highway and transportation agencies through comprehensive academic training of qualified engineers for service in materials engineering positions.

The American Association of State Highway and Transportation Officials' (AASHTO) Subcommittee on Materials and the Federal Highway Administration (FHWA) have stressed the need for civil engineers with academic training in highway materials engineering. The urgency of this need was most recently restated by AASHTO in its policy resolution PR-25-89, which was approved October 7, 1989.

Training materials for the 6-week course were prepared as part of a contract between the FHWA's National Highway Institute and Purdue University.

A combination student workbook and instructor's manual has been assembled for each of the six modules which make up the course. The modules, which address specific materials areas, are as follows:

I - Materials Control and Acceptance -- Quality Assurance
II - Soils and Foundations
III - Steels, Welding, and Coatings
IV - Aggregates and Unbound Bases
V - Asphalt Materials and Paving Mixtures
VI - Concrete

Six expert panels, each consisting of two State materials representatives and two FHWA specialists, were formed to direct development of the modules. A team of nationally recognized consultants was selected by each of the panels and retained by Purdue University to perform the work.

The course is designed to be presented either in a single, continuous 6-week session or in as many as six individual sessions with suitable intervals between modules.

Acknowledgment

Appreciation is hereby expressed to the following agencies for their contributions and support in the development of this program:

Florida Department of Transportation

Illinois Department of Transportation

Indiana Department of Transportation

Iowa Department of Transportation

Kansas Department of Transportation

New Hampshire Department of Transportation

New Jersey Department of Transportation

New Mexico State Highway and Transportation Department

New York State Department of Transportation

Oregon Department of Transportation

South Carolina Department of Highways and Public Transportation

West Virginia Department of Highways

Wisconsin Department of Transportation

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MODULE VI: Concrete

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
8:30 9:30	Introduction	Admixtures	Mechanical Properties of Hardened Concrete	Other Durability Problems Break	Laboratory 6.3 (cont.) Testing of Hardened Concrete
	Break	Break	Break		Break
10:30 11:30	Role of Cement and Water in Concrete	Construction Processes and Fresh Concrete Behavior	Freeze-Thaw Durability	Corrosion of Reinforcing Steel	Analysis of Laboratory Results
12:30			LUNCH		
1:30 2:30 3:30 4:30	Laboratory 6.1 Testing of Plastic Concrete	Field Trip: Batch Plant, Precast, Prestressing	Laboratory 6.2 Mix Design Workshop and Miscellaneous Testing	Laboratory 6.3 Testing of Hardened Concrete	Concrete Module Wrap-Up Break Evaluation and Examination
5:00					

Chapter 1

Introduction

Instructional Objectives:

1. Introduce course material.
2. Determine background and composition of student group.
3. Deal with current issues and problems in concrete construction and quality control/quality assurance.
4. Find out what concrete-related problems and concerns the participants are currently facing.

Desired Student Achievements:

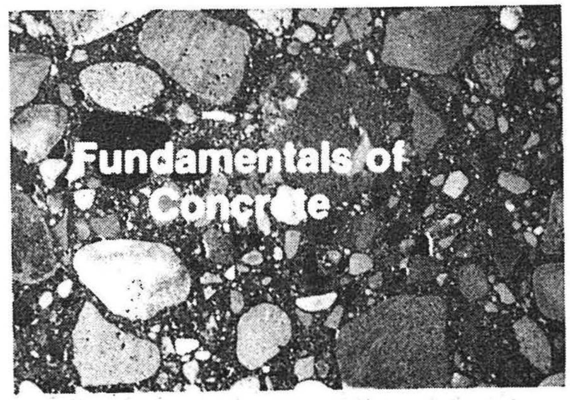
1. Become familiar with the plan of activities for the concrete module.
2. Become familiar with the facilities.
3. Learn the instructor's background and perspective.
4. Understand the purposes and objectives of the concrete module.
5. Understand how the concrete module fits in to the balance of the course.
6. Understand the scheme to be used for performance evaluation.

Chapter 1

Introduction

1. Questions to Students

- What has your experience consisted of in the highway or transportation department?
- How have you encountered concrete?
- What problems are you aware of in concrete?
- Based on your present knowledge, how would you solve the problems?
- What is concrete?
- What holds it together?
- What gives it durability?
- What do we expect from concrete? Owner? Designer? Supplier? Contractor?

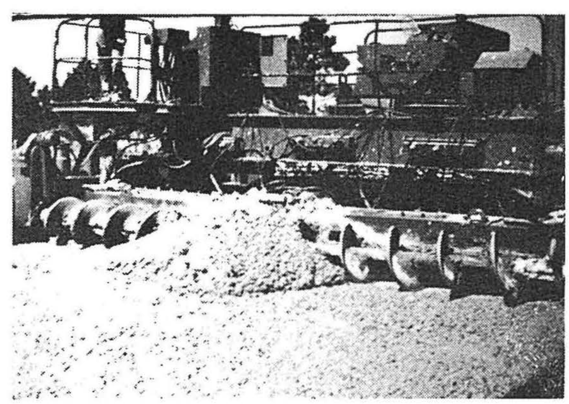


2. Concrete

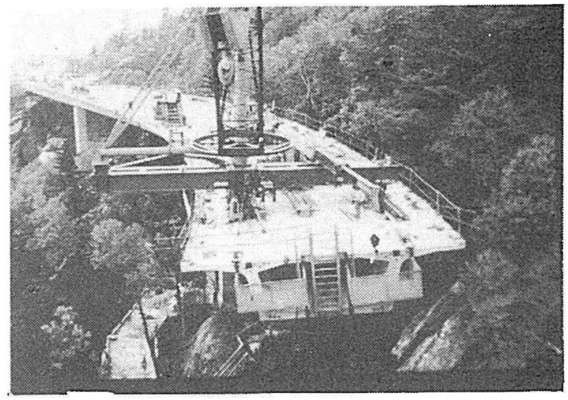
2.1 General Comments on Concrete Construction

Concrete is the most widely used construction material.

Concrete is unique in that it is usually manufactured at the site and cannot be tested and approved in advance.

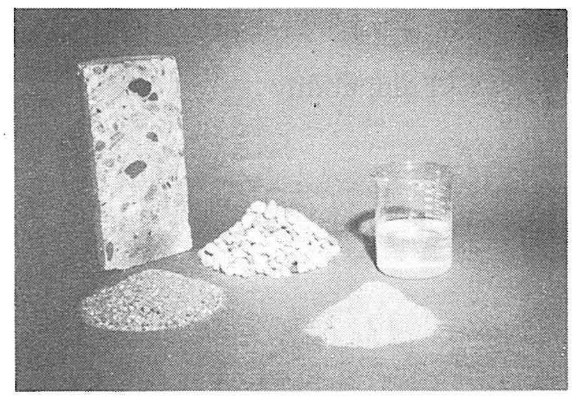


Concrete can be molded into virtually any shape conceived by the designer.

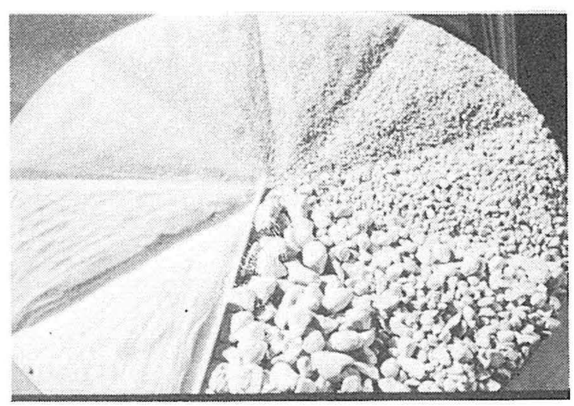


2.2 Composition of Concrete

Concrete is a composite material whose important properties result from the chemical reaction between cement and water.



If concrete was made from cement and water only, it would be very expensive. To reduce cost, natural rock is added (natural sand, gravel, crushed quarried rock). The resulting volume of cement and water is about a quarter of the total volume of the concrete.



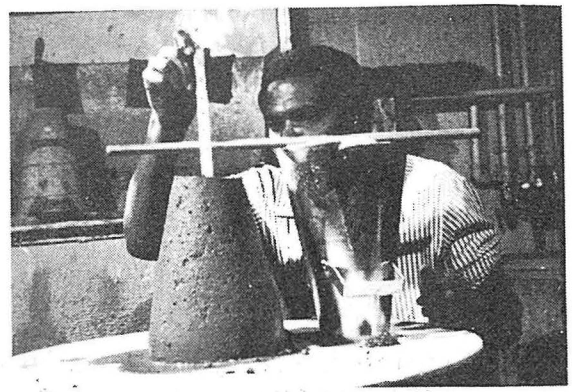
As we shall see, economy is not the only reason to reduce the quantity of cement and water to the lowest practical volume.

2.3 Concrete Properties of Interest

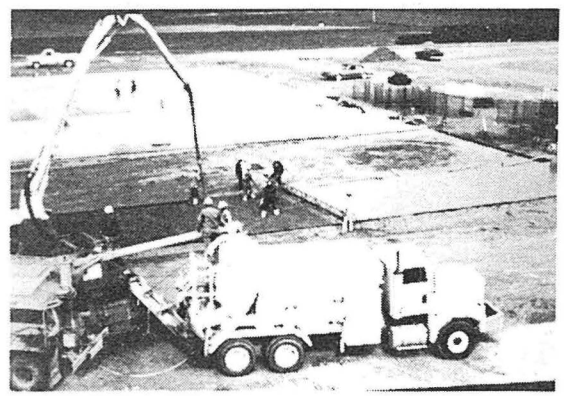
2.3.1 Concrete in the plastic state

Workability

Slump

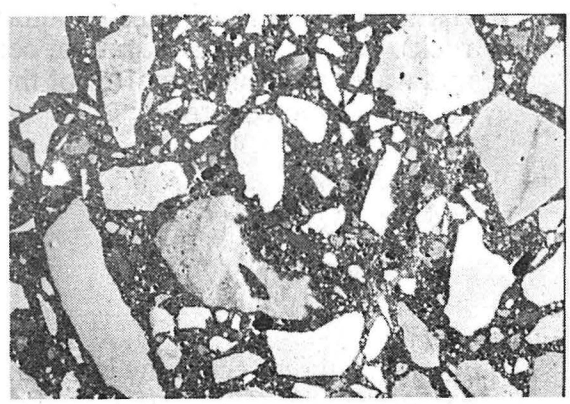


Pumpability

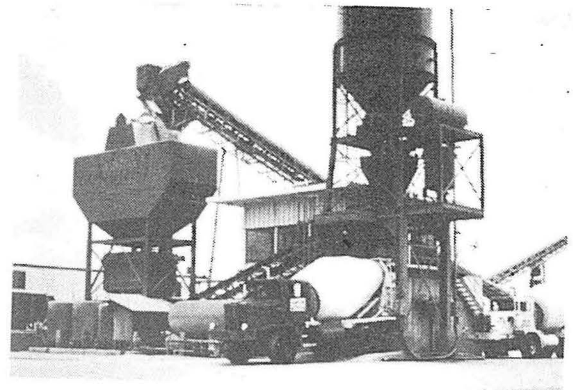


Finishability

Air content



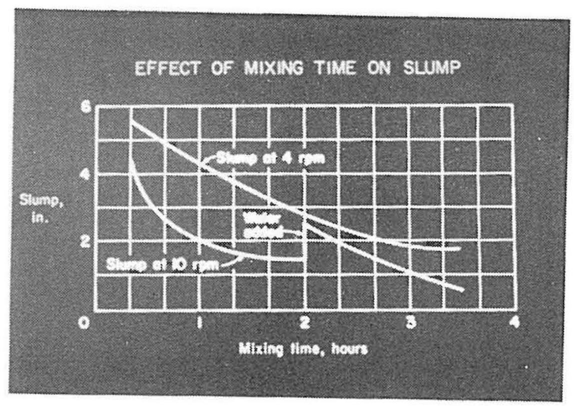
Mixing



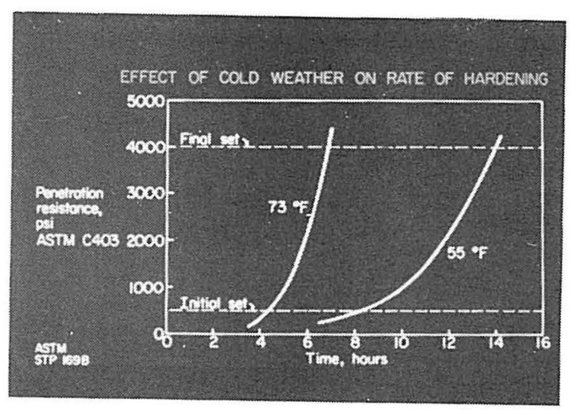
Uniformity

2.3.2 Concrete in the transitional state

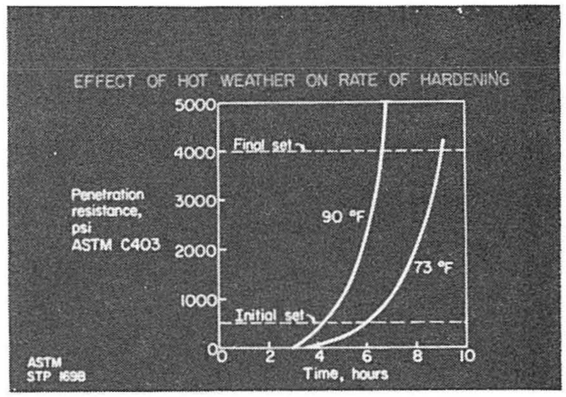
Rate of slump loss



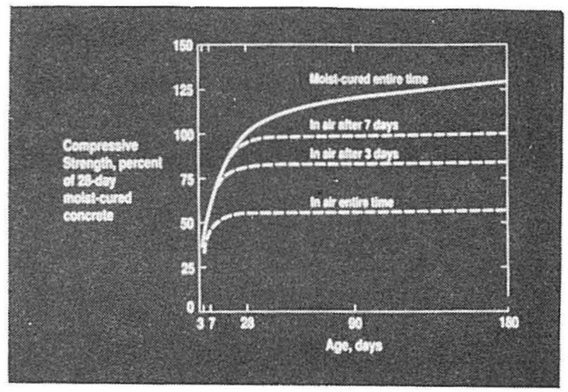
Setting time



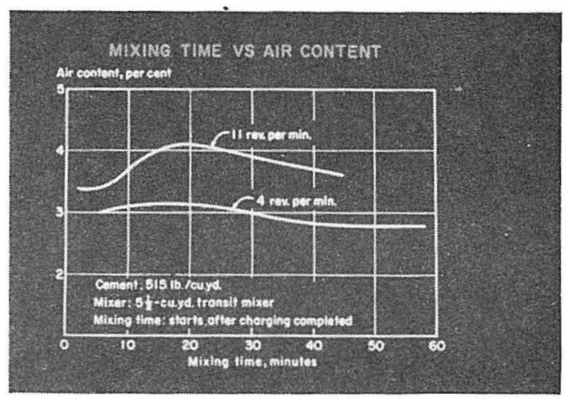
Rate of hardening



Strength versus time

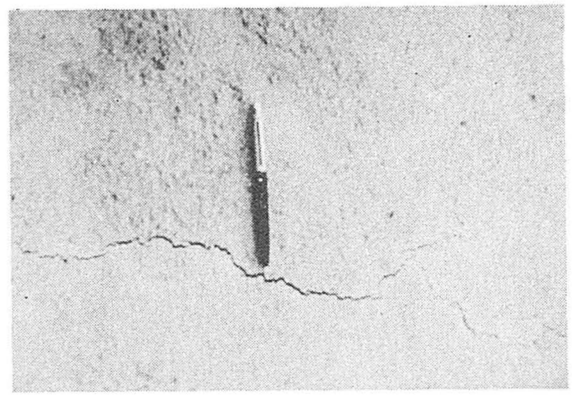


Air loss



Segregation

Plastic shrinkage



Drying shrinkage

2.3.3 Concrete in the hardened state

Compressive strength

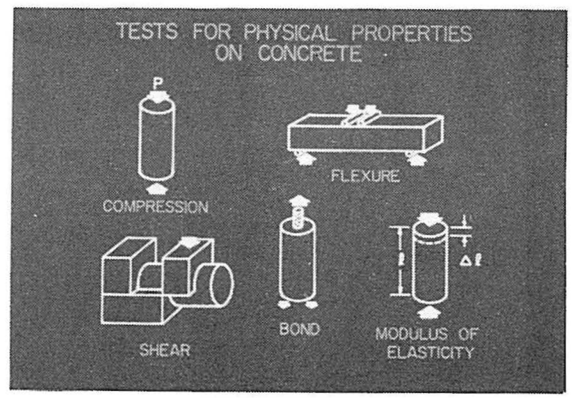
Tensile strength

Flexural strength

Shear strength

Fracture toughness

Elasticity

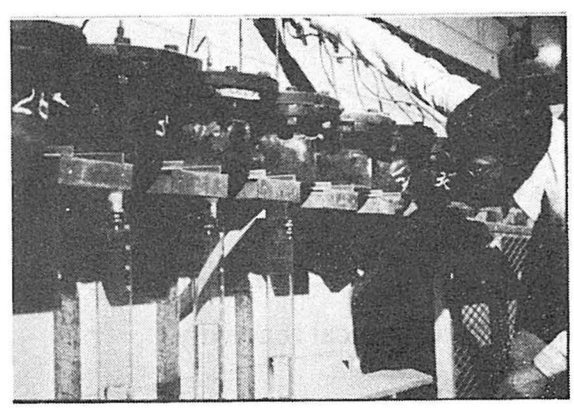


Poisson's ratio

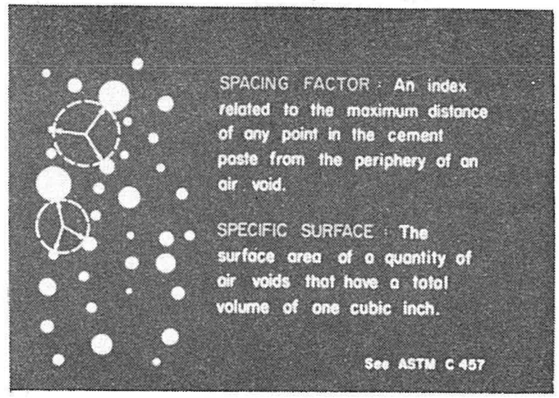
Porosity

Pore size distribution

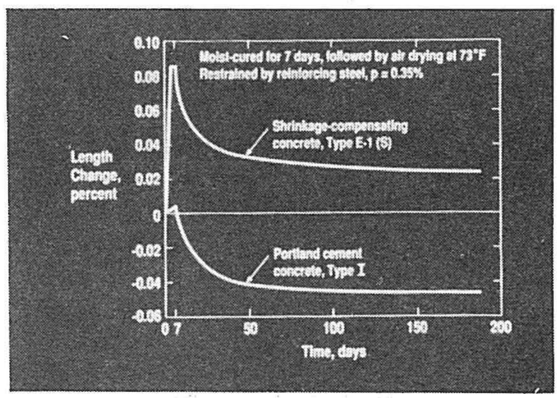
Permeability



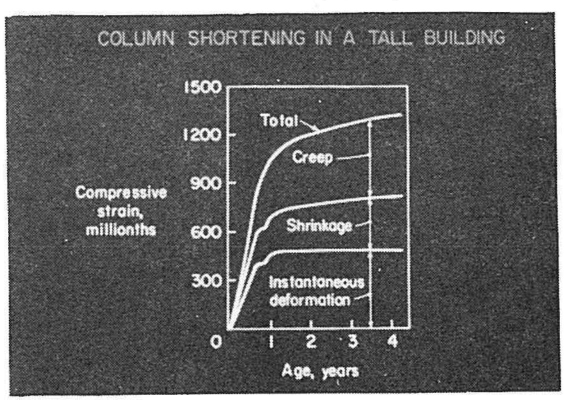
Air void system



Shrinkage



Creep

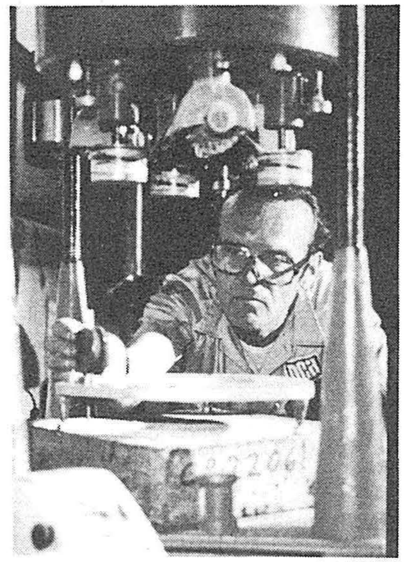


Fatigue

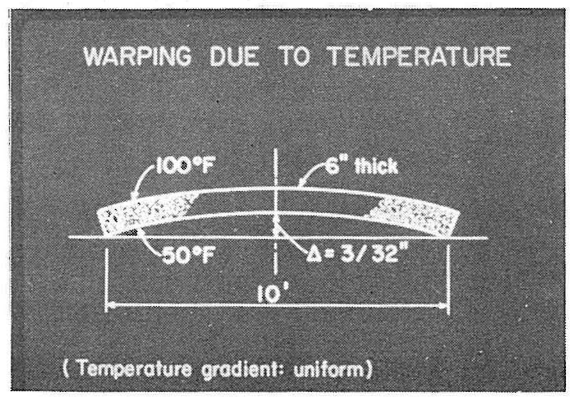
Dynamic properties

Chemical reactivity

Abrasion resistance



Thermal volume change



Heat capacity

Thermal conductivity

Electrical conductivity

Density

Atomic absorption

Color

Texture

Cost

2.4 Concrete Quality and Water-Cement Ratio

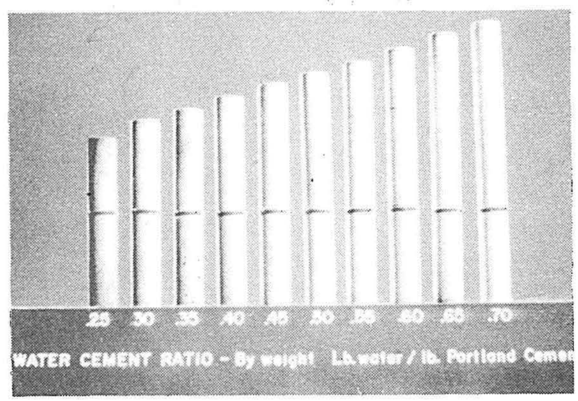
2.4.1 Introduction

The **water-cement ratio** (w/c ratio) is the weight of water divided by the weight of cement.

Concrete quality is most often characterized by the w/c ratio of the mix.

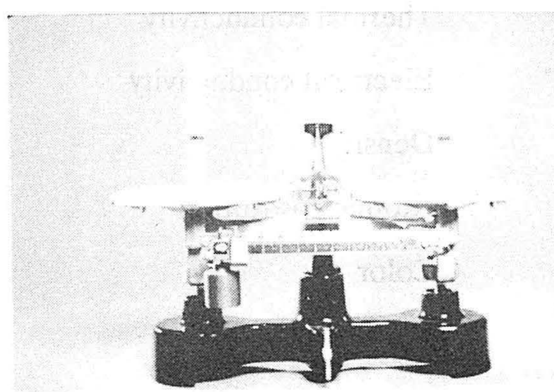
2.4.2 Effect of the w/c ratio

The quantity of voids in hydrated cement paste depends on the w/c ratio.



A unit volume of cement produces 2.2 volumes of hydrated material; therefore, if the w/c ratio exceeds 1.2 by volume, there will be unfilled space (voids) even after all the cement has hydrated.

If the w/c ratio is less than 1.2 by volume, there will be insufficient space to accommodate all the potential hydration products; thus, there will be unhydrated cement in the system after all void space has been eliminated.



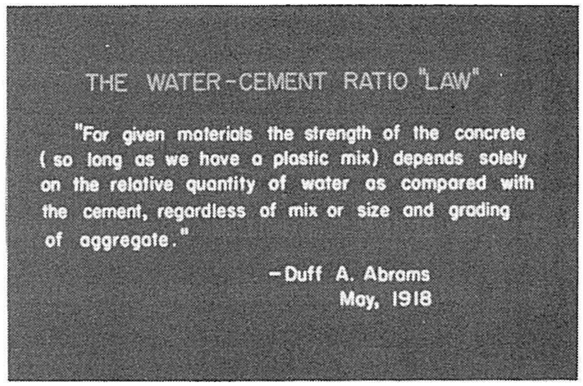
A w/c ratio of 1.2 by volume translates to .38 by weight.

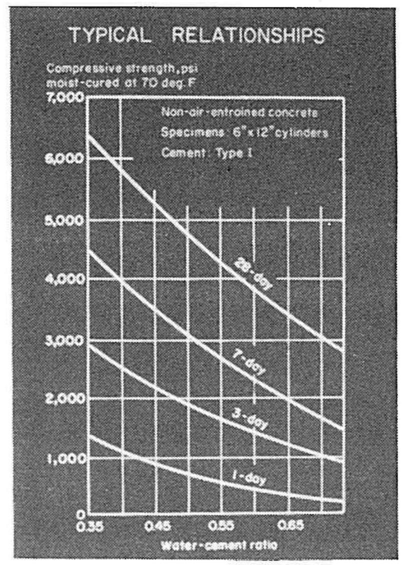
As the w/c ratio increases above .38 by weight, concrete becomes progressively weaker and

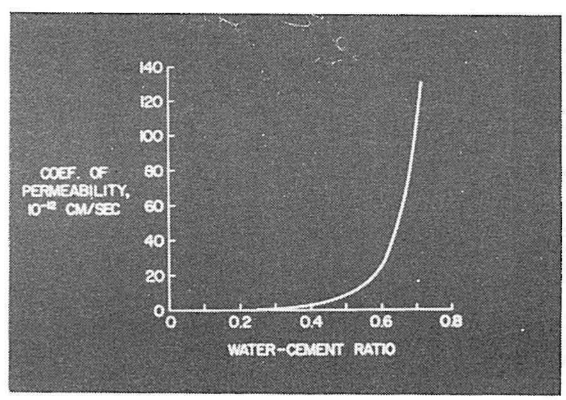
a. its void content increases.

b. it is less resistant to the passage of water.

c. it is less durable to aggressive fluids.







Suggested References

Chapter 1

1. Design and Control of Concrete Mixtures, 13th Edition, 1988.

2. Waddell, J.J., Concrete Construction Handbook, 2nd Edition, McGraw-Hill, 1974.

3. Neville, A., Properties of Concrete, 3rd Edition, Pitman Publishing, 1981.

4. U.S. Bureau of Reclamation, Concrete Manual, 8th Edition, U.S. Department of the Interior, 1975.

5. Troxell, G.E., Davis, H.E., and J.W. Kelly, Composition and Properties of Concrete, 2nd Edition, McGraw-Hill, 1968.

Chapter 2

The Role of Cement and Water in Concrete

Instructional Objectives:

1. Describe the fundamental role of portland cement in concrete.
2. Describe the composition and manufacture of portland cement.
3. Explain what happens when water and cement come in contact.
4. Explain the role of water and the origin of the microstructure and pore system in hardened cement paste.
5. Explain why water-cement ratio and degree of hydration control the behavior of hardened cement paste.

Desired Student Achievements:

1. Describe the raw ingredients and manufacturing process for portland cement.
2. Describe the differences among the five standard cement types and determine when the use of each type is appropriate.
3. Distinguish between hydration and drying.
4. Explain the impact of water-cement ratio on strength, porosity, permeability, and durability.
5. Explain why proper curing is essential, and how the continued hydration of cement influences behavior.

Chapter 2

The Role of Cement and Water in Concrete

1. Introduction

1.1 The Difference Between Concrete and Cement

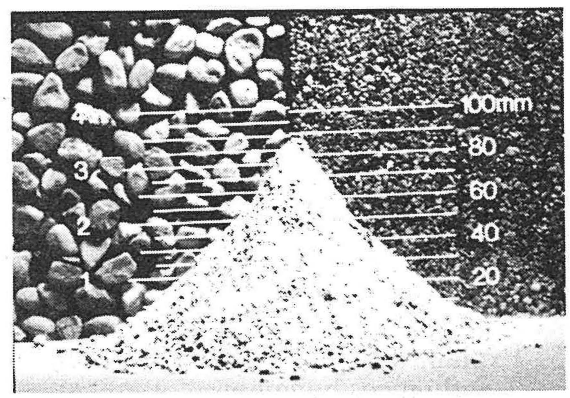
Concrete is a composite material composed of

a. ____________________

b. ____________________

c. ____________________

d. ____________________



Cement is the glue, adhesive, or binder that holds the **concrete** together.

Refer to the composite materials matrix on page 2-3.

1.2 Definitions

Paste is cement and water.

Mortar is paste and fine aggregate.

Concrete is mortar and coarse aggregate.

Composite Construction Materials Matrix

Coarse Aggregate	Fine Aggregate	Paste (Binder)	Material
	Materials		
Natural Gravel	Natural Sand	Lime	
Crushed Rock	Fine Crushed Rock	Gypsum (Plaster)	
Natural Lt. Wt. Agg	Manufact'd Lt. Wt. Fines	Hydraulic Lime	
Manufact'd Lt. Wt. Agg	Natural Lt. Wt. Fines	Burnt Hydraulic Lime	
Iron Ore	Ilmonite	Portland Cement	
Steel Punchings	Asbestos	Alumina Cement	
Marble Chips	Cellulose Fibers	Oil Well Cement	
Waste Materials	Flyash	Polymer Latex	
Hazardous Waste	Microsilica	Epoxy	
Recycled Pavement	Styrofoam Beads	Asphaltic Cement	
Wood Chips	Vermiculite	Natural Clays	
	Examples		
Natural Gravel	Natural Sand	-0-	Granular Soil
-0-	Silt	Clay	Cohesive Soil
-0-	Silt	Clay, Lime, Flyash	Stabilized Soil
-0-	Fine Masonry Sand	Lime	Lime Mortar
-0-	Fine Masonry Sand	Gypsum	Gypsum Mortar
-0-	Fine Masonry Sand	Portland Cement & Lime	Masonry Mortar
-0-	Coarse Concrete Sand	Portland Cement	Concrete Mortar
Natural Gravel	Coarse Concrete Sand	Portland Cement	Concrete (PCC)
Crushed Rock	Coarse Concrete Sand	Portland Cement	Concrete (PCC)
Natural Lt. Wt. Agg	Coarse Concrete Sand	Portland Cement	Lt. Wt. Concrete
Natural Lt. Wt. Agg	Manufact'd Lt. Wt. Fines	Portland Cement	Lt. Wt. Concrete
Manufactured Lt. Wt. Agg	Coarse Concrete Sand	Portland Cement	Lt. Wt. Concrete
Manufactured Lt. Wt. Agg	Manufact'd Lt. Wt. Fines	Portland Cement	Lt. Wt. Concrete
Natural Gravel	Coarse Concrete Sand	Asphaltic Cement	Asphaltic Cement Conc.
Crushed Rock	Coarse Concrete Sand	Asphaltic Cement	Asphaltic Cement Conc.
Iron Ore	Ilmonite	Portland Cement	Heavyweight Conc.
Natural Gravel	Coarse Concrete Sand	Epoxy	Epoxy Concrete
Walnuts	Marshmallows	Sugar & Cocoa	Rocky Road Fudge

1.3 Concrete Properties that Depend on Cement Properties

1.3.1 Fresh Concrete

Water demand

Workability

Slump

Rate of slump loss

Setting time

1.3.2 Transition from fresh to hardened concrete

Rate of strength gain

Rate of heat development

1.3.3 Hardened Concrete

Strength (compression, tension, shear)

Modulus of elasticity

Properties pertaining to durability:

a. frost resistance

b. sulfate resistance

c. chloride resistance

d. alkali-aggregate reaction

e. porosity

f. permeability

There are good, practical reasons, therefore, for knowing more about portland cement!!!

2. Portland Cement

2.1 Summary

Portland cement is manufactured from common earth materials by means of a readily understandable process.

Water added to portland cement causes the formation of microcrystals known as the "cement gel."

- These crystals contain water as a primary constituent.

- The crystals have both positive and negative charges on their surfaces.

- The crystals bond to one another by electrical attraction. The electrical charge is carried from crystal to crystal by **water molecules.**

- Water is therefore required both to form the crystals **and** to bind them together.

Dry portland cement powder is "instant glue" (just add water). The strength of the crystal-to-crystal bonds is responsible for the strength of the hardened cement, and for the strength of the hardened concrete.

2.2 Cement Composition

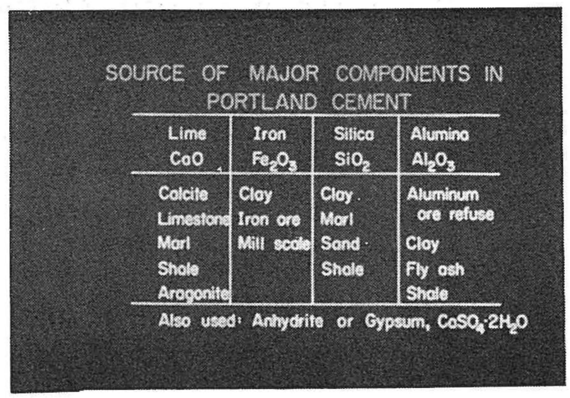
2.2.1 Key active ingredients

a. **lime** (CaO) = calcium oxide

b. **silica** (SiO_2) = silicon dioxide

Sources of lime include limestone, chalk, and shells.

Sources of silica include clay, shale, slate, volcanic ash, and flyash.



SOURCE OF MAJOR COMPONENTS IN PORTLAND CEMENT

Lime CaO	Iron Fe_2O_3	Silica SiO_2	Alumina Al_2O_3
Calcite Limestone Marl Shale Aragonite	Clay Iron ore Mill scale	Clay Marl Sand Shale	Aluminum ore refuse Clay Fly ash Shale

Also used: Anhydrite or Gypsum, $CaSO_4 \cdot 2H_2O$

2.2.2 Nomenclature used in the cement industry

C = calcium oxide (lime)

S = silicon dioxide (silica)

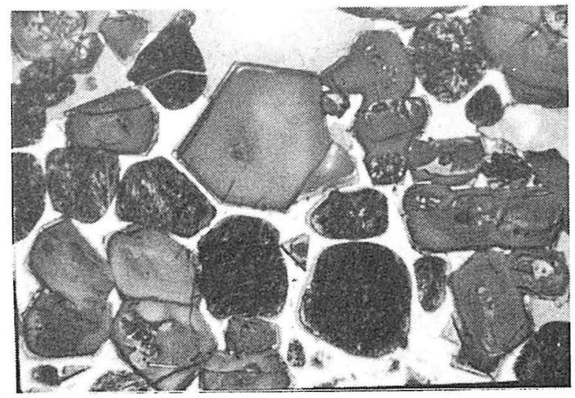
A = aluminum oxide

F = iron oxide

H = hydrated form (combined with water)

Note: "C" is <u>not</u> carbon, and "S" is <u>not</u> sulfur

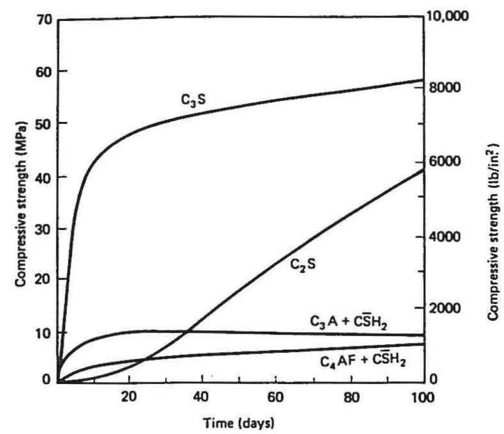
Cement is lime and silica combined into a product called calcium silicate. The lime and silica can combine in 2 different ways:



a. C_2S

b. C_3S

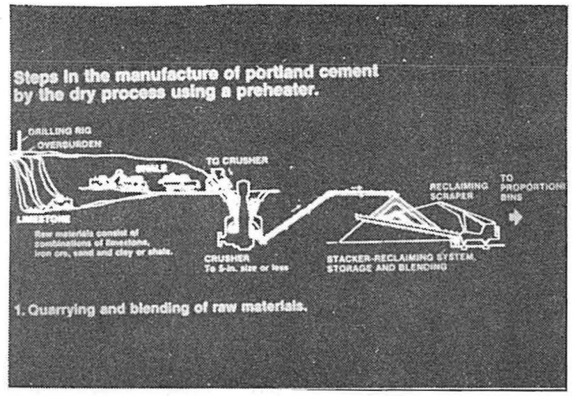
The advantage of C_2S is slow, long term continued strength gain. The advantage of C_3S is more rapid early strength gain, making C_3S preferable for most modern construction.



Water added to calcium silicate forms microcrystals of **calcium silicate hydrates**, or "CSH."

2.3 Cement Manufacture

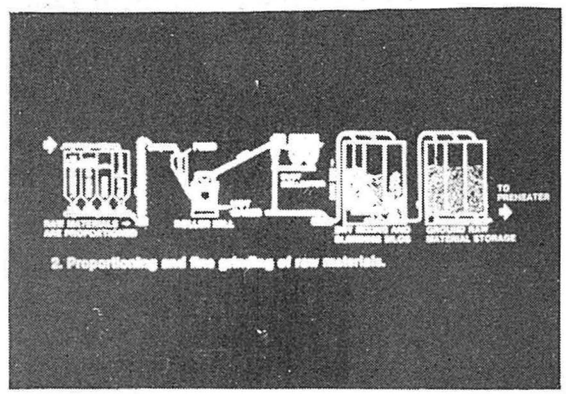
2.3.1 Process of combining lime and silica



a. Obtain raw ingredients

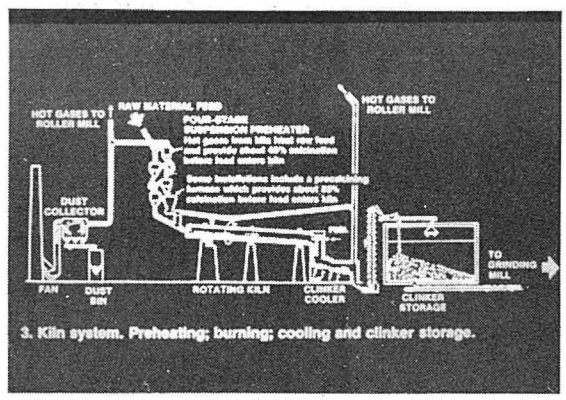
b. Crush

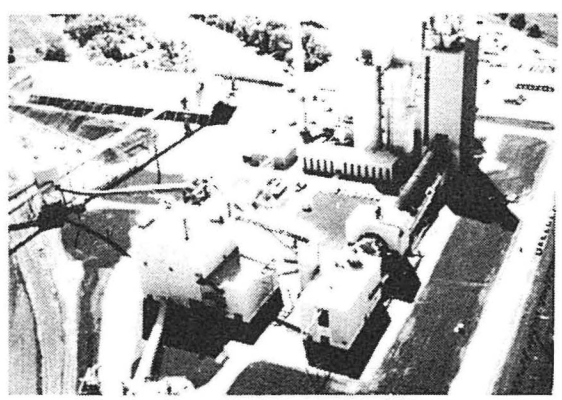
c. Blend



d. Heat in a rotary kiln

- approximately 2300°F to make C_2S
- approximately 3500°F to make C_3S





2.3.2 "Fluxing agents"

Aluminum oxide
Al_2O_3 = "A"

Iron oxide
Fe_2O_3 = "F"

Fluxing agents allow the manufacture of C_3S at a **lower** temperature, which reduces the cost of manufacture.

When fluxing agents are blended with lime and silica, C_3S can be produced at approximately 2500°F.

The fluxing agents **are not** catalysts; they **combine** with the lime:

$C + A \rightarrow C_3A$

$C + A + F \rightarrow C_4AF$

2.3.3 Final products

$C + S \rightarrow C_3S$ (tricalcium silicate)

$C + S \rightarrow C_2S$ (dicalcium silicate)

$C + A \rightarrow C_3A$ (tricalcium aluminate)

$C + A + F \rightarrow C_4AF$ (tetracalcium aluminoferrite)

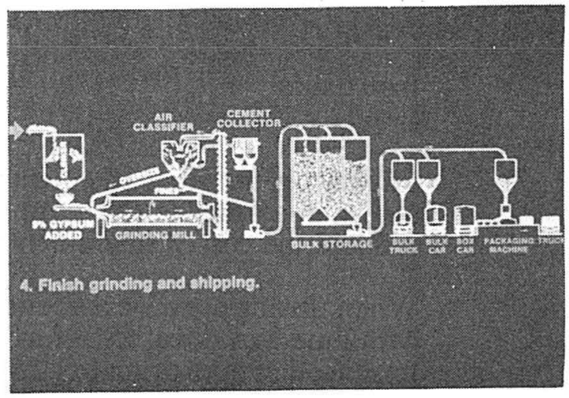
We only wanted C_2S and C_3S, but we have to live with C_3A and C_4AF as well!

2.3.4 "Clinkers"

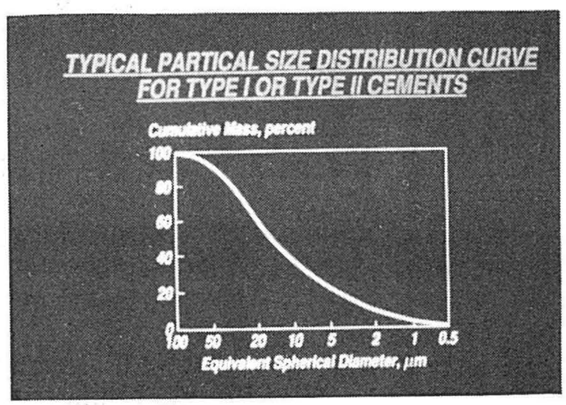
Hot "clinkers" come out of the rotary kiln:

- 1/8" to 1" diameter in size.
- Mixed chemical composition.

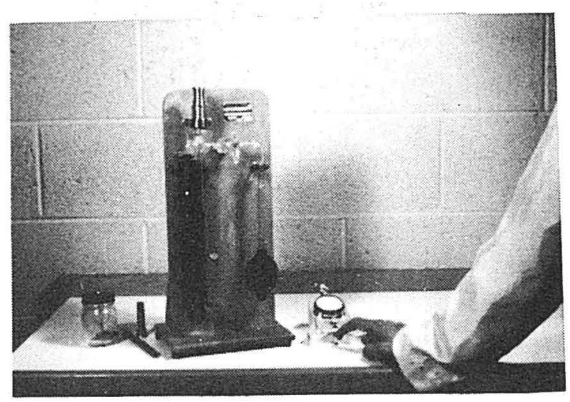
Clinkers are ground to < 90 microns to form cement grains of same compositional mix:



- Cement grains are small enough to pass through a sieve that holds water
- Cement grains have a surface area of 225 m^2/kg (which equals approximately 100,000 square feet per 94 lb. sack)



The fineness of ground cement may be measured by the Blaine air permeability test (AASHTO T-153, ASTM C-204)



2.3.5 Summary of Manufacture

Input

Lime (CaO)	63%
Silica (SiO_2)	21%
Alumina (Al_2O_3)	6%
Iron (Fe_2O_3)	3%
Impurities	7%

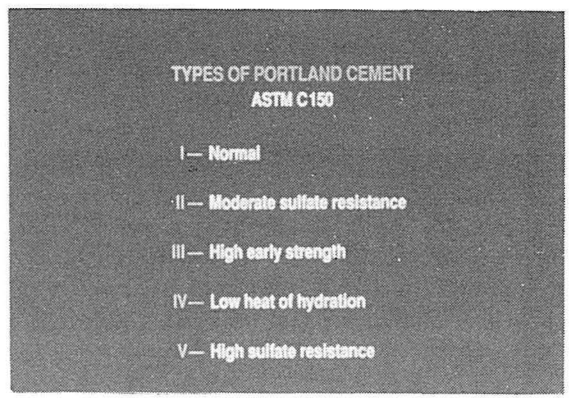
Heat to 2300 - 2500°F....

Output (average Type I cement)

C_3S	49%
C_2S	25%
C_3A	12%
C_4AF	8%
Impurities	6%

2.4 Cement Types

2.4.1 ASTM Standard Cement Types



Type I
Normal

Type II
Moderate heat, moderate sulfate resistance

Type III
High early strength

Type IV
Low heat

Type V
Sulfate resistant

All common portland cements are composed of the same 4 primary ingredients (minerals): C_3S, C_2S, C_3A, and C_4AF.

Cement performances depend on the behavior of each mineral and their interaction.

Standard cement types (ASTM C-150 Types I-V) simply mix the minerals in different proportions, with variations in fineness.

CEMENT COMPOUNDS AND FINENESS

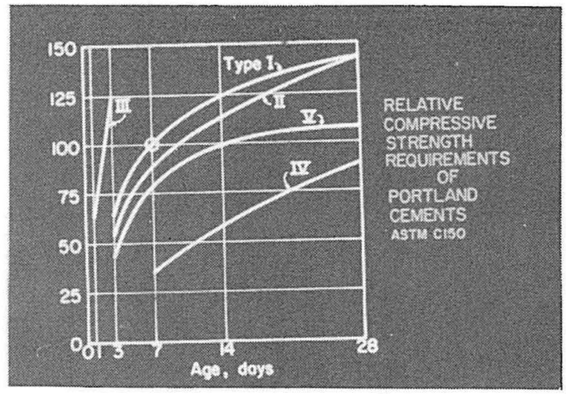
Type	C_3S	C_2S	C_3A	C_4AF	Blaine fineness, m^2/kg
I	55	19	10	7	370
II	51	24	6	11	370
III	56	19	10	7	540
IV	28	49	4	12	380
V	38	43	4	9	380
White	33	46	14	2	490

2.4.2 Average Composition of Standard Cements (percent)

Component	Type I	Type II	Type III	Type IV	Type V
C_3S	49	46	56	30	43
C_2S	25	29	15	46	36
C_3A	12	6	12	5	4
C_4AF	8	12	8	13	12
Gypsum	2.9	2.8	3.9	2.9	2.7
Free CaO	0.8	0.6	1.3	0.3	0.4

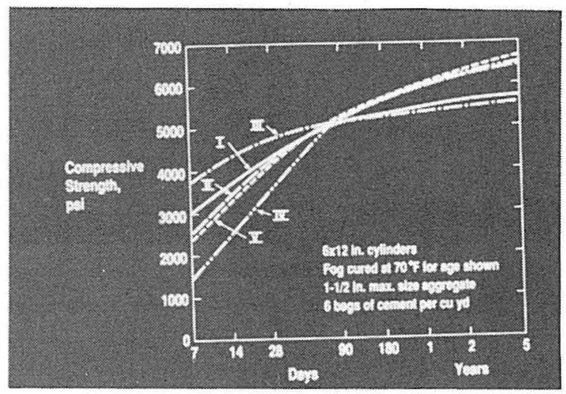
2.4.3 Reasons for Varying Cement Types

Rate of strength gain

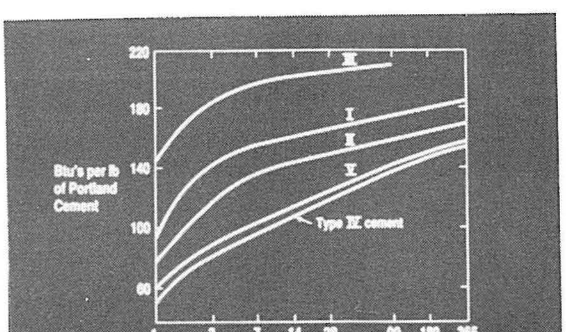


a. Varying composition (adding more C_3S) increases early strength gain

b. Increasing cement fineness, by using Type III ("high-early strength") cement causes faster strength gain (Type III cement is ground finer and thus gains strength faster).



Heat of hydration



a. The formation and binding of crystals gives off heat (exothermic reaction):

C_3S	216 BTU/lb
C_2S	112 BTU/lb
C_3A	373 BTU/lb
C_4AF	180 BTU/lb

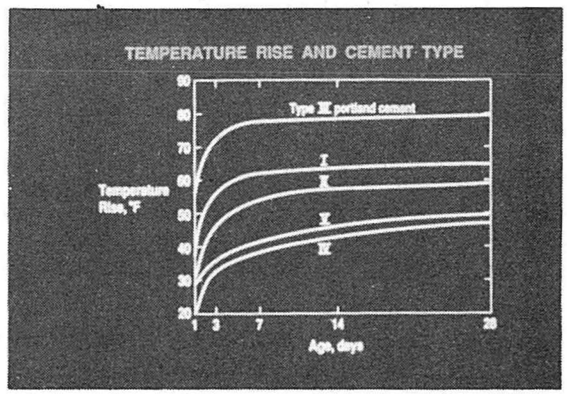
The heat produced is on the order of 20,000 BTU per sack of cement, and 120,000 BTU per cubic yard of concrete.

This can translate to a 11-14°F temperature rise **per sack** of cement.

b. When concrete heats up it may or may not cause problems.

c. When concrete cools at the surface, it definitely causes trouble: cracking.

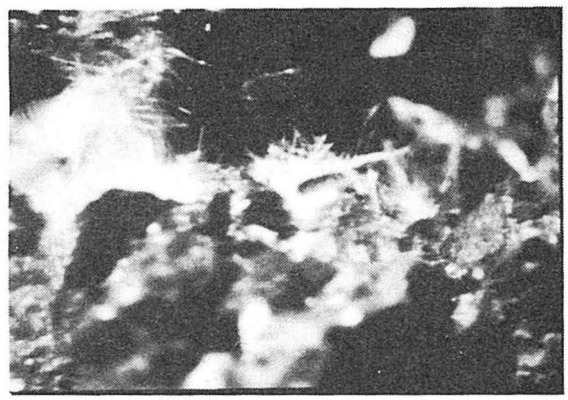
d. "Cooler" cements (Types II and IV) reduce temperature problems in massive placements.



Sulfate resistance

a. Sulfates are present in soil, wastewater, acid rain, smokestacks.

b. Sulfates react with C_3A to disintegrate concrete.



c. Use cement with a low C_3A content (Types II and V) when a sulfate environment is expected.

CEMENTS FOR SULFATE EXPOSURES

Sulfate exposure	SO_4 in soil, %	SO_4 in water, ppm	Cement type
Negligible	0.00–0.10	0–150	—
Moderate*	0.10–0.20	150–1500	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)
Severe	0.20–2.00	1500–10,000	V
Very severe	Over 2.00	Over 10,000	V plus pozzolan**

* Seawater
** Pozzolan that improves sulfate resistance with Type V cement

Gypsum

a. C_3A reacts so fast it can cause concrete to set in 30 to 45 minutes. This is called **flash set.**

b. Gypsum ($CASO_4$) is added to cement to prevent flash set

c. Gypsum coats the C_3A portions of the cement grains and retards the C_3A reaction

d. Gypsum itself can sometimes set when it has been converted to "Plaster of Paris." This is known as **false set.**

2.4.4 Comparison of Type I cement to other types

I to II

a. II is "cooler" -- less C_3S, C_3A.

b. II is more sulfate resistant.

c. II contains more C_4AF (to balance reduction in C_3A).

I to III

a. III has faster strength gain, but slightly lower ultimate f'_c.

b. Set times are the same.

c. III has more C_3S (more CaO is used in manufacture).

d. III is ground finer and consequently has faster strength gain.

e. III requires more gypsum to compensate for increased surface area of finer cement.

I to IV

IV is much cooler because it contains less C_3S and C_3A.

I to V

a. V has high sulfate resistance.

b. V has very low C_3A content.

c. V has less C_3S because of low C_3A (less flux).

2.4.5 Variability of Cements

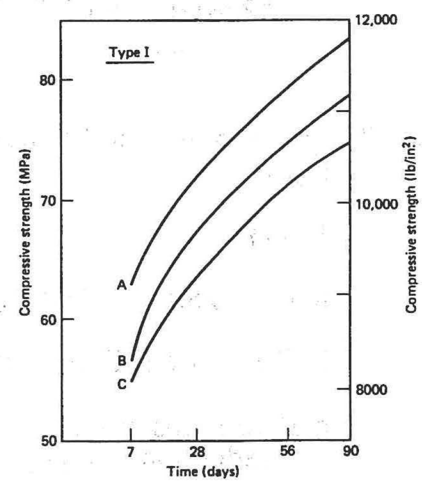
Variations in the following concrete properties may result from variations in cement properties:

a. strength

b. water demand

c. shrinkage

d. heat generation



3. Water-cement Interaction

3.1 Hydration

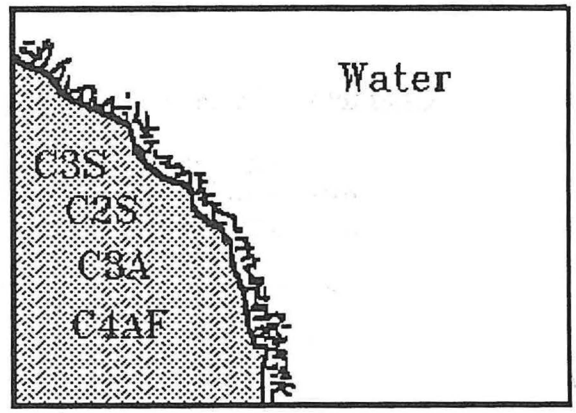
Hydration is the chemical reaction in which water combines with cement to form microcrystals of calcium silicate hydrate (CSH).

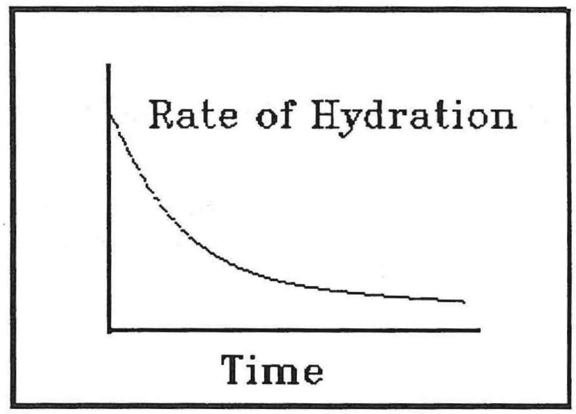
a. C_2S and C_3S combine with water to make CSH.

b. C_3A and C_4AF combine with water to form other hydrate crystals.

The water is consumed in the reaction: hydration is **not** "drying out."

Hydration occurs at the surface of the cement grain. As the surface becomes covered with microcrystals, less water can reach the unreacted surface.





3.2 Development of Microstructure

Microstructure is the structure of the microcrystals (gel), cement grains, and spaces in-between.

3.2.1. Development of solid structure (gel)

Microcrystals can assume the following schematic forms:

a. rod

b. plate

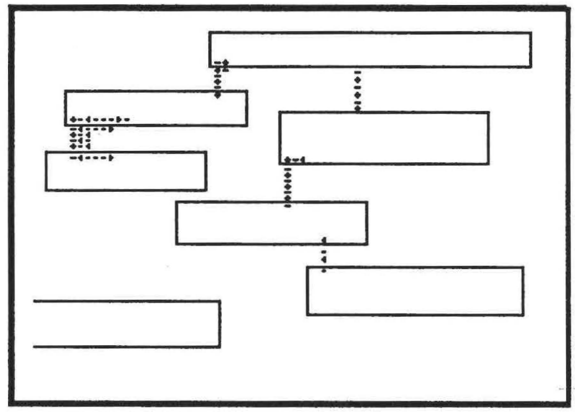
c. crumpled sheet

Characteristics of crystal bonding:

a. Microcrystals are characterized by positive and negative electrical charges on their surfaces.

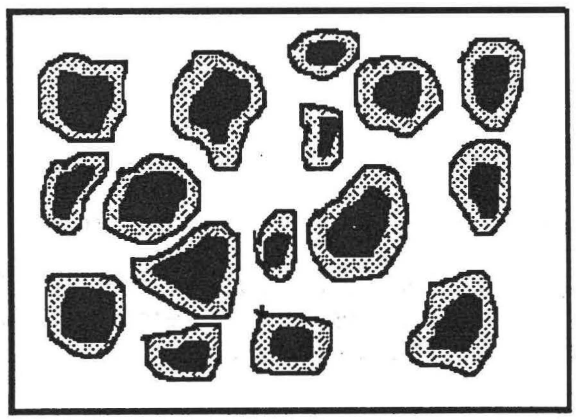
b. Some microcrystals bond by direct charge attraction from one crystal to another.

c. The primary bond is through transfer of electric charge attraction from one crystal to another by means of polarized water molecules.



3.2.3 Development of void spaces between solid particles

Cement grains get smaller as the hydration reaction proceeds at their surfaces.



The volume of gel (hydration products) produced is less than the combined volume of cement and water (cement paste) required to form the gel. Voids therefore develop as the cement hydrates.

Space originally occupied by water in the cement paste contributes to porosity.

Example -- Calculation of Porosity

Before hydration:

100 lb portland cement (SG 3.15)	--> vol =	.51 cf
42 lb water (SG 1.00)	--> vol =	.67 cf
142 lb cement paste	--> vol =	1.18 cf

After hydration:

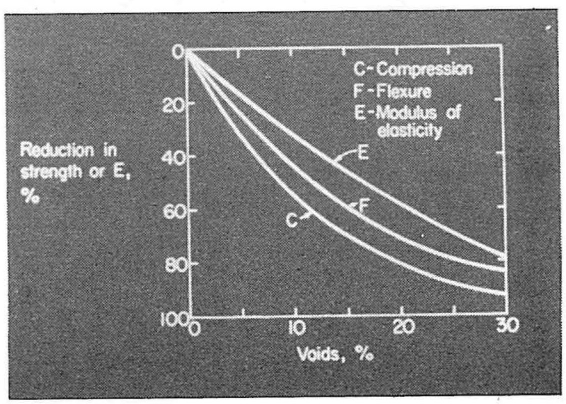
142 lb hydrated cement (SG 2.17)	--> vol =	1.05 cf
void space	--> vol =	.13 cf
hydrated cement paste	--> vol =	1.18 cf

Porosity = .13/1.18 = 11%

3.2.4 Consequences of internal voids

Internal voids **decrease** strength and durability.

Internal voids **increase** porosity and permeability.



3.3 Factors Affecting Hydration

3.3.1 Water (moisture)

Water is required to make the crystals **and** to bond the crystals together.

The entire hydration reaction can only occur in "water-filled" space.

Loss of moisture decreases hydration.

a. **Self-desiccation** is loss of moisture due to consumption during hydration that causes further hydration to cease.

b. When the relative humidity inside the concrete at the location of the cement grain drops below approximately 75%, **hydration ceases.**

3.3.2 Temperature

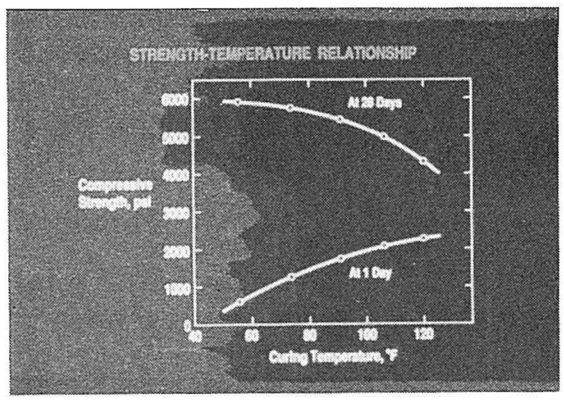
Consequences of **higher** temperature:

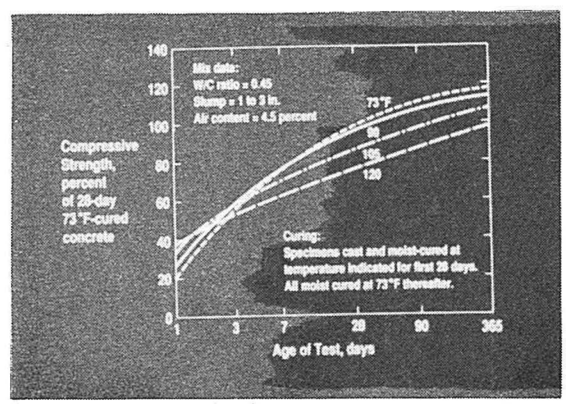
a. increased **rate** of hydration

b. rapid early strength gain

c. lower long-term strength

Rapid hydration leads to non-uniform gel with poorer structure.





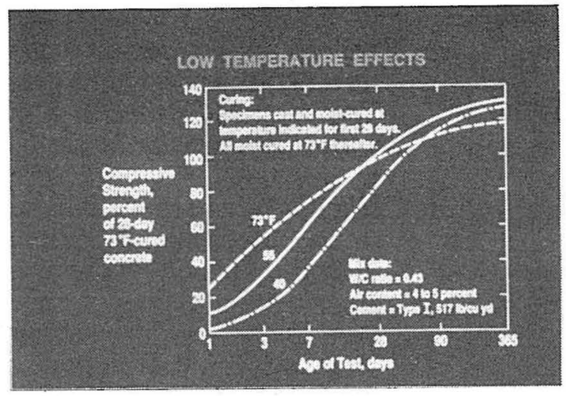
Consequences of **lower** temperature:

a. decreased **rate** of hydration

b. slow early strength gain

c. higher long-term strength

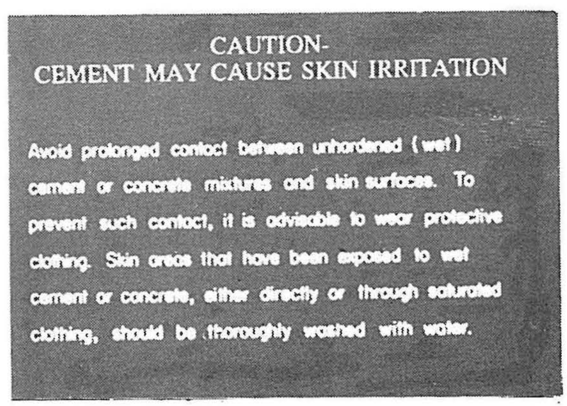
Slow hydration leads to a more uniform gel with denser structure.



See further discussion in Chapter 4, Fresh Concrete and Construction Procedures.

3.4 Setting and Hardening

These processes begin immediately after water and portland cement come in contact.

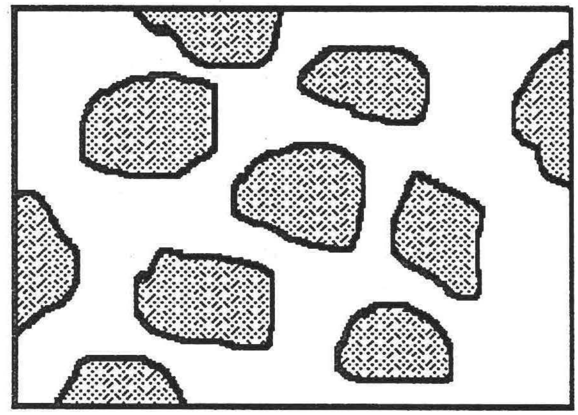


3.4.1 Setting

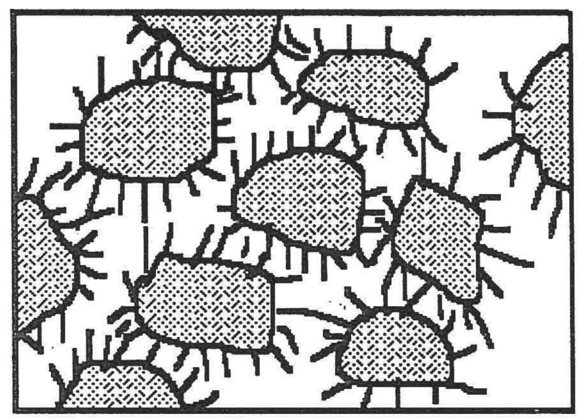
a. Mix water becomes highly alkaline in less than 10 minutes.

b. The hydration reaction begins at the surfaces of cement grains. The crystals formed by C_3A and water develop the fastest.

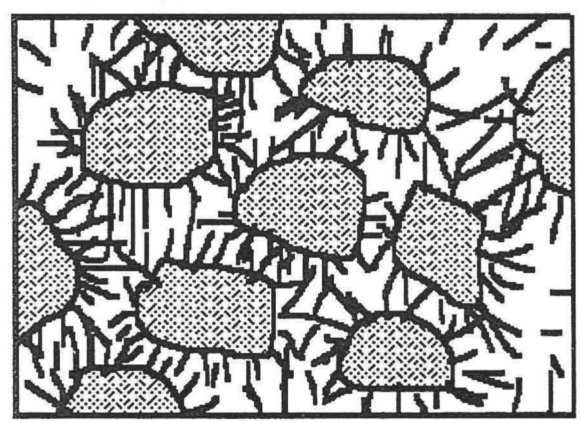
c. Cement grains are initially able to move independently, but as hydration products grow, weak interlocking begins. The concrete is in a "thixotropic" state: vibration or agitation can break the weak interlock.



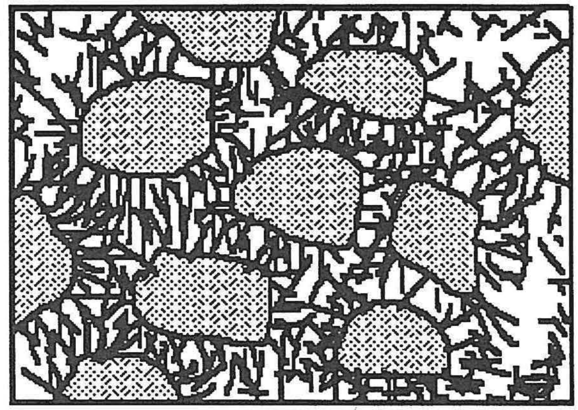
d. **Initial set** is reached when the weak skeleton begins to hold grains in place.



e. **Final set** is reached when the skeleton becomes rigid and grains can no longer move. When final set is reached, large spaces remain between cement grains.



3.4.2 Hardening



During **hardening**, the spaces between cement grains are slowly filled in by growth of hydration products.

Strength and durability develop at this stage.

3.5 Factors Affecting the Development of Strength and Durability

3.5.1 Initial spacing between cement grains

Initial spacing depends on water-cement ratio and compaction.

3.5.2 Degree to which the water between grains is replaced by hydration products

Degree of hydration depends on presence of sufficient moisture and maintenance of appropriate temperature.

Curing is the process of providing sufficient moisture and temperature for hydration to continue.

4. Importance Of Water-Cement Ratio

4.1 Definitions

The **water-cement ratio** is the weight of water divided by weight of cement.

The **cement volume fraction** is the fraction of total paste volume occupied by cement particles (equals volume of cement divided by total volume of paste).

Example -- Calculation of Cement Volume Fraction

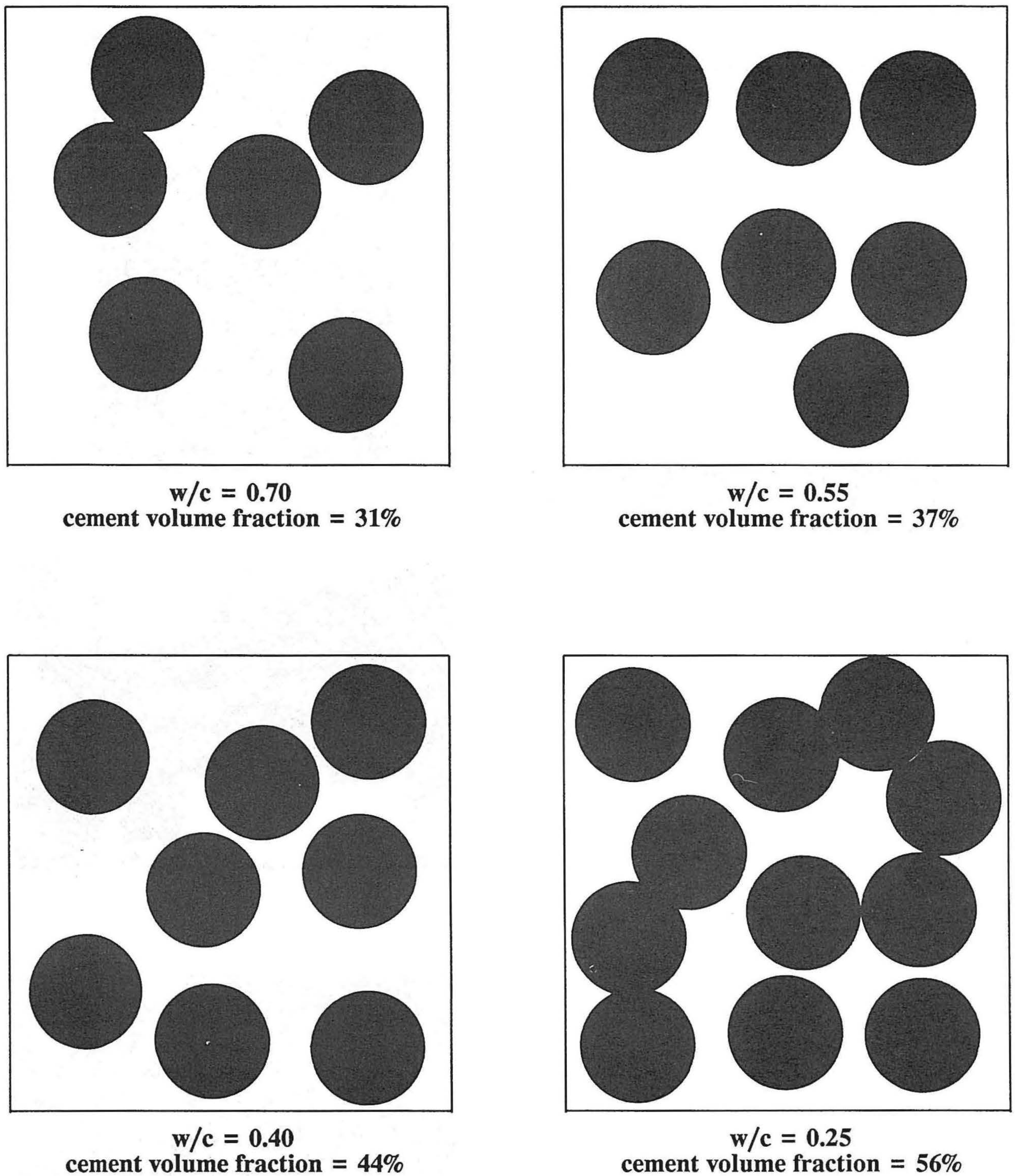
Water-cement ratio = 0.45

45 lb water	(SG 1.00)	--> vol =	.72 cf
100 lb portland cement (SG 3.15)		--> vol =	.51 cf
145 lb cement paste		--> vol =	1.23 cf

Cement volume fraction = .51 cf / 1.23 cf = 41 %

Relationship between w/c and cement volume fraction

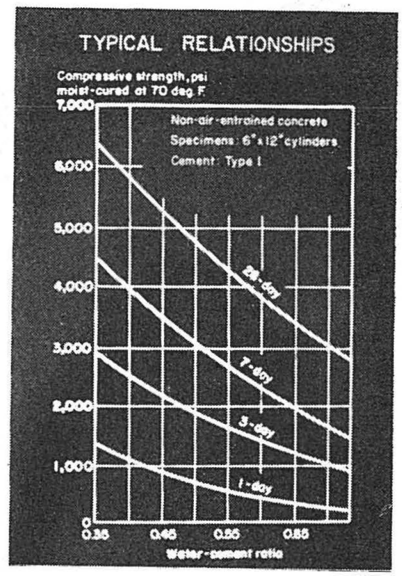
w/c ratio	Cement volume fraction
.40	44 %
.45	41 %
.50	39 %
.55	37 %
.60	35 %
.65	33 %
.70	31 %
.75	30 %



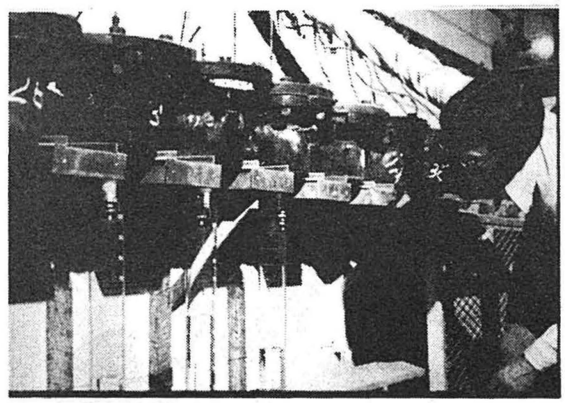
Schematic diagrams of the solids content (by volume) of non-air-entrained water and cement pastes with the water/cement ratios shown

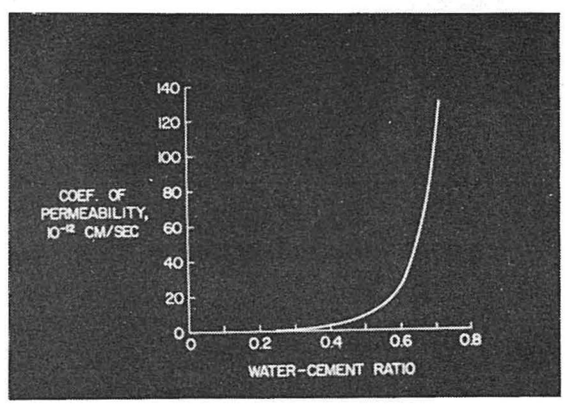
4.2 Effect of W/C on Strength and Durability

Compressive strength increases with decreasing w/c ratio.



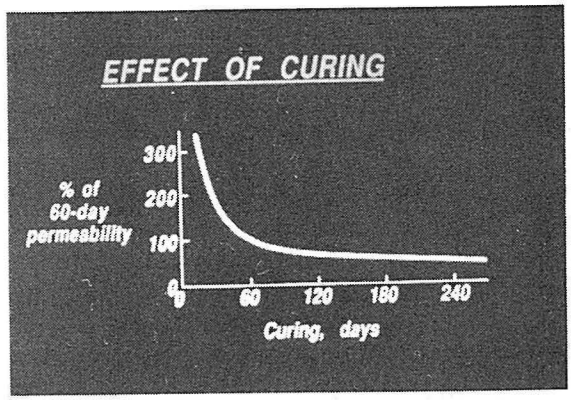
Porosity and **permeability** (which are measures of durability) increase with increasing w/c ratio.

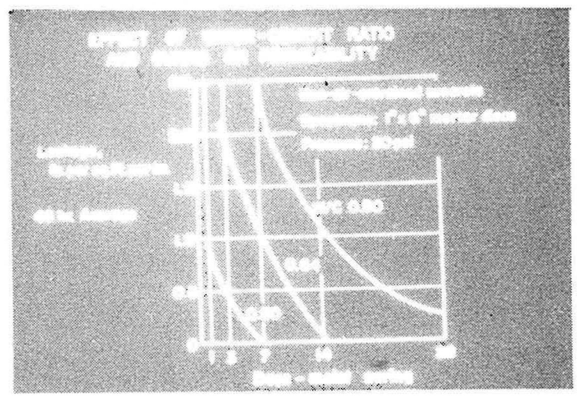




4.3 Relationship Between W/C and Curing in Development of Quality Concrete

The w/c ratio and curing work hand-in-hand to determine the final quality of concrete.





The combined effects of w/c ratio and curing were observed in an experiment by Powers, et al.

w/c ratio	required curing time
.40	3 days
.45	7 days
.50	14 days
.60	6 mos
.70	1 year
>.70	impossible

Suggested References

Chapter 2

1. Lea, F.M., The Chemistry of Cement and Concrete. Chemical Publishing Co., 1971.
2. Czernin, W., Cement Chemistry and Physics for Civil Engineers. Bauverlag Publishers, 1980.
3. ACI Committee 225, Guide to the Selection and Use of Hydraulic Cements. American Concrete Institute, 1986.
4. Design and Control of Concrete Mixtures, 13th Edition. Portland Cement Association, 1988.
5. Mehta, P.K., Concrete Structure, Properties, and Materials. Prentice-Hall, 1986.

Chapter 3

Admixtures

Instructional Objectives:

1. Introduce the basic types of admixtures:

   Water-reducing agents
   High-range water-reducing agents (superplasticizers)
   Accelerators
   Retarders
   Mineral admixtures, slags, and pozzolans
   Corrosion inhibitors

2. Discuss generic problems and concerns with the use of admixtures.
3. Explain the fundamental chemical/physical mechanisms through which each admixture works.
4. Discuss benefits and liabilities associated with each type of admixture.
5. Introduce standard industry specifications for admixtures.

Desired Student Achievements:

1. Recognize situations in which each type of admixture would be advantageous.
2. Understand the influence that each admixture type has on cement and concrete behavior in the fresh and hardened state.
3. Identify quality control concerns associated with each admixture type.
4. Understand typical dosage rates and methods of batching for each admixture type.
5. Describe the basic mechanism through which each admixture works.

Chapter 3

Admixtures

1. Introduction

1.1 Definitions

An **admixture** is a material other than water, aggregate, and cement, added immediately before, during or after mixing.

An **addition** is a material added to dry cement by the cement manufacturer.

1.2 Types of Admixtures

a. Air entraining (discussed in Chapter 6)

b. Water reducing

c. Set retarding

d. Set accelerating

e. Mineral (pozzolans)

f. Corrosion inhibitors (discussed in Chapter 8)

g. Combinations

1.3 Reasons for Use

a. To enhance concrete properties

b. To modify fresh concrete behavior

c. To compensate for cement characteristics

d. To save money

1.4 Applicable AASHTO/ASTM Standards

Cement
AASHTO M-85
ASTM C-150

Chemical Admixtures
AASHTO M-194
ASTM C-494

Air Entrainment
AASHTO M-154
ASTM C-260

Flyash
AASHTO M-295
ASTM C-618

Granulated Slag
AASHTO M-302
ASTM C-989

Microsilica/Silica Fume
(Draft standards in progress)

1.5 Factors affecting admixture behavior

Admixture behavior is **very** sensitive to **many** variables.

1.5.1 Cement Characteristics

a. Type

b. Chemistry

c. Fineness

d. Impurities

1.5.2 Aggregate Characteristics

a. Type

b. Chemistry

c. Gradation

Table 2.11 Cement type and source can influence the volume of air obtained in both plain and air-entrained mixes

Cement code	Air entrained (%)			
	No addition	Admixture		
		1	2	3
A	3.1	5.2	5.3	3.6
B	1.2	5.3	4.4	3.2
C	1.2	5.4	5.5	3.0
D	1.1	5.1	5.4	2.0
E	1.4	3.9	3.5	2.8
F	2.3	6.2	5.4	4.5
G	2.4	7.9	6.3	4.3
H	1.0	5.4	4.5	3.6
I	1.3	6.2	5.2	3.0
J	1.8	7.8	8.1	4.6
K	1.0	6.9	5.9	3.6
L	1.7	7.2	5.8	4.3

Table 2.12 The amount of air-entraining agent required to obtain 4% air is increased for higher surface area cements

Cement	Specific surface area	Quantity of admixture required (ml/0.0368 m^3 batch) for 4% air
A	2750	6.5
B	3750	10.0
C	4750	14.0

1.5.3 Temperature

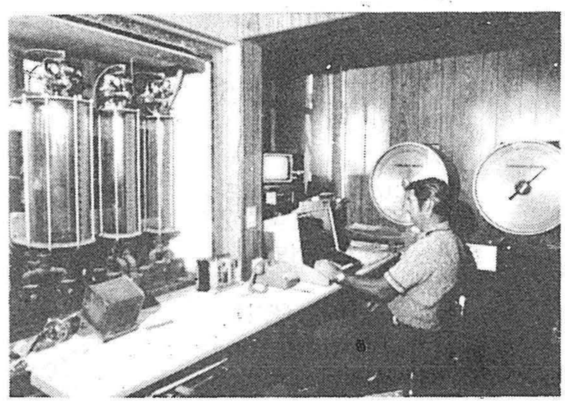
1.5.4 Mix characteristics

a. Proportions

b. Water-cement ratio

c. Slump

1.5.5 Mixing Procedure



a. Equipment

b. How admixture added

c. When admixture added

d. Concentration of admixture

e. Presence of other admixtures

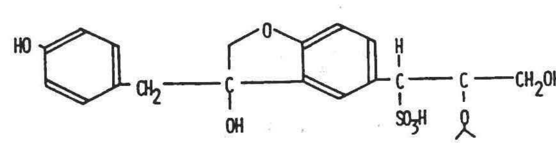
Many of these factors change during a project, or even during a single day's work.

You must test the admixture in the mix that you intend to use -- in large batches, in correct equipment, and under anticipated site conditions.

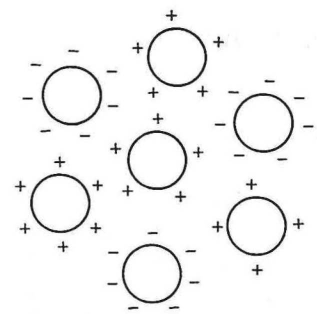
2. Water Reducing Agents (WRA)

2.1 Description

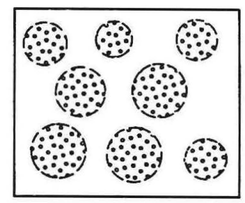
Organic salts, acids, surfactants

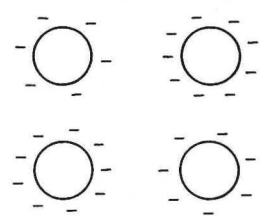


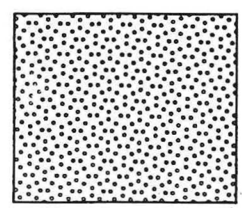
Polar end adsorbs to cement particles.



Negatively charged end causes mutual repulsion of cement particles.







Can reduce required water by up to 10% at constant slump

2.2 Reasons for Use

2.2.1 Saving money

For a given w/c ratio, using a WRA reduces the amounts of water and cement required to maintain a given level of workability, thereby lowering the cost of materials.

2.2.2 Increasing strength and/or durability

For a given amount of cement, using a WRA allows a lower w/c ratio to be used without sacrificing workability. A lower w/c ratio means greater strength and durability.

2.2.3 Increasing slump

For a given w/c ratio, using a WRA increases the slump of concrete.

2.3 Mix Design Considerations

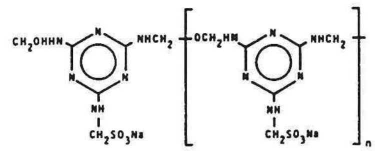
The dosage for 10% water reduction is approximately 3 to 6 ounces per sack of cement.

If you use a water reducer and you reduce the water and cement volume, replace it with fine and coarse aggregate in the same proportions as in the initial mix.

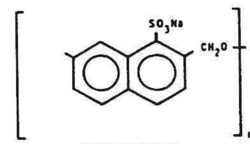
2.4 High Range Water Reducing Admixtures (HRWRA, superplasticizers)

2.4.1 Characteristics

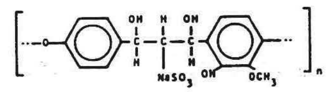
Long chain organic polymer molecules.



SODIUM SALT OF
SULFONATED MELAMINE FORMALDEHYDE
(a)



SODIUM SALT OF
SULFONATED NAPTHALENE FORMALDEHYDE
(b)



SODIUM LIGNOSULFONATE

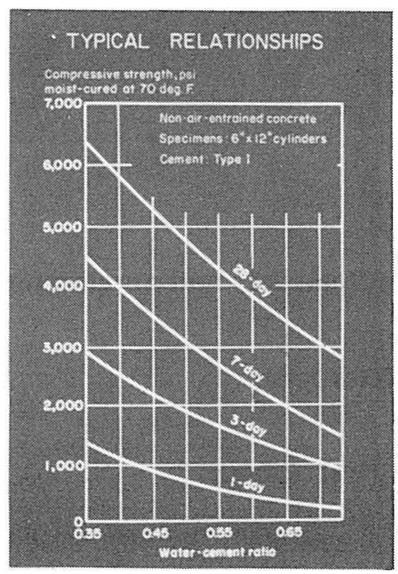
HRWRA's function like WRA, but are more effective. They can reduce the amount of water by 30% at a constant slump.

The dosage for 30% water reduction is approximately 12 ounces per sack of cement (less than 1% by weight of cement).

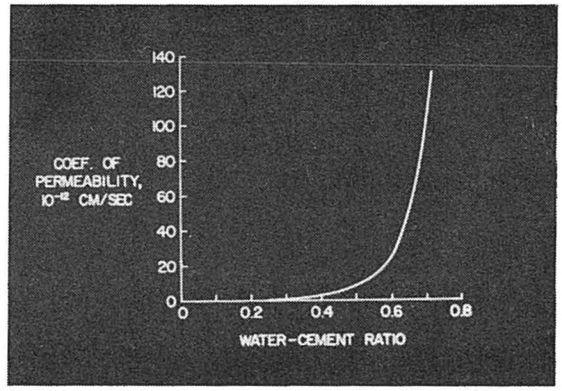
2.4.2 Reasons for Use

a. To save cement cost

b. To get a low w/c ratio (thus very high strength).

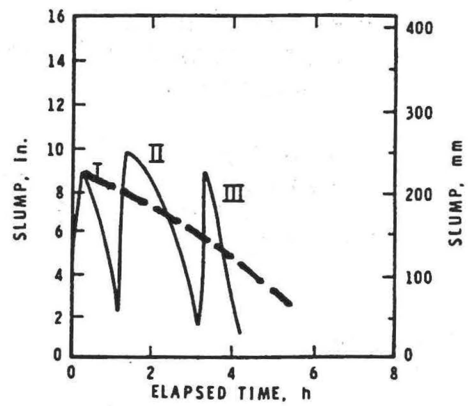


c. To get a low w/c ratio, thus low permeability.



d. To obtain very high slump ("flowing concrete").

2.4.3 Distinction between types



AASHTO/ASTM Type F -- HRWRA only

AASHTO/ASTM Type G -- HRWRA and retarder

3. Set Retarders and Accelerators

3.1 Retarders

3.1.1 Description

Organic molecules (may be sugars).

Very similar to WRA (often combined).

Block C_3S and C_3A hydration.

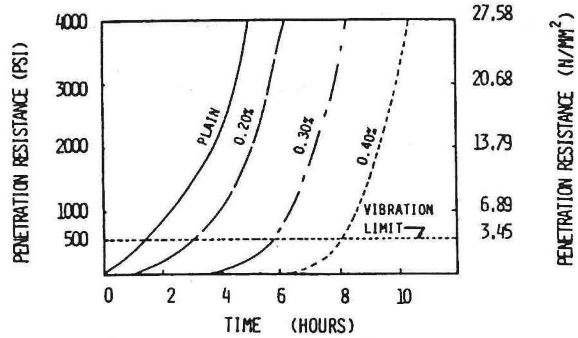
3.1.2 Action

Can delay set by 1 to 3.5 hours.

Extend thixotropic phase.

May accelerate rate of slump loss.

Increase length of time that cement grains remain in colloidal suspension.



3.1.3. Uses

Hot weather work

Difficult placements

Expected delays

3.2 Accelerators

3.2.1 Description

Accelerators are usually based on calcium chloride ($CaCl_2$) in various forms. Some non-chloride accelerators are now available in response to corrosion problems.

They have complex, controversial chemistry and physics.

3.2.2 Function/use

Accelerate setting.

Some evidence of increase in rate of strength gain.

Generally used in cold weather to allow early slab finishing and avoid OT expense.

Dosage 1 to 2% by weight of cement.

3.2.3 Problems Associated with Use

a. Reduced sulfate resistance

b. Increased alkali-aggregate reaction

c. Corrosion

d. Increased shrinkage

There is no question that $CaCl_2$ effectively accelerates set very economically. With respect to other effects, however, its use is controversial.

4. Mineral Admixtures (Pozzolans)

4.1 Introduction

4.1.1 Pozzolans

Pozzolans are siliceous or siliceous/aluminous materials which have little or no cement value alone.

When finely divided, pozzolans will react with lime and water **at ordinary temperature** to form a product similar to that produced by cement.

4.1.2 The Pozzolanic Reaction

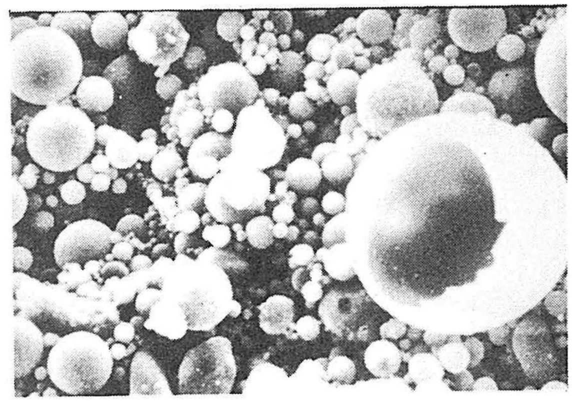
Reactive silica + lime + water --> CSH

The reaction will only occur if the silica is reactive (i.e. , non-crystalline (glassy) and very finely divided (high surface area)).

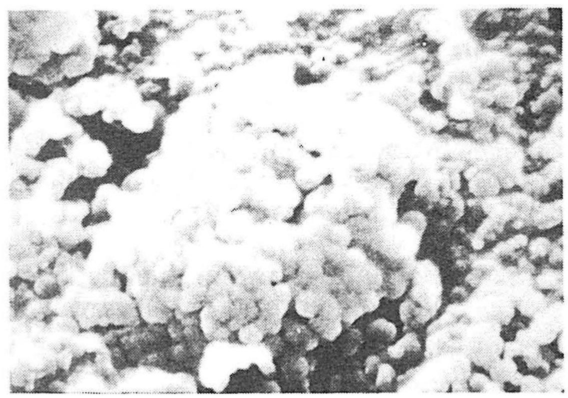
4.1.3 Sources of reactive silica

Volcanic ash

Flyash
(coal ash, Pulverized Fuel Ash (PFA))
Finely divided residue from the combustion of coal.



Microsilica
(silica fume, condensed silica fume, volatilized silica)
A product of SiO vapors formed in electric arc furnaces used to convert quartz (SiO_2) to silicon.



Blast Furnace Slag
Non-metallic silicates and aluminum silicates of calcium, developed in a molten condition with iron in a blast furnace.

In the molten state slag is **very** similar to magma in the earth's interior -- hot, fluid, molten silicates. This explains similarity to pozzolans.

Granulated slag
A glassy granulated material formed by immersing hot slag in cold water.

In practice, all of the above are sometimes referred to as pozzolans, particularly flyash. **All** of the materials react according to the "pozzolanic reaction."

Each source varies in purity, influence of impurities, uniformity, particle size and shape, and gradation.

4.1.4 Lime sources

a. CaO in cement

b. $Ca(OH)_2$ produced by cement hydration

c. Added lime (in the case of lime-flyash stabilized soils)

4.1.5 Terminology

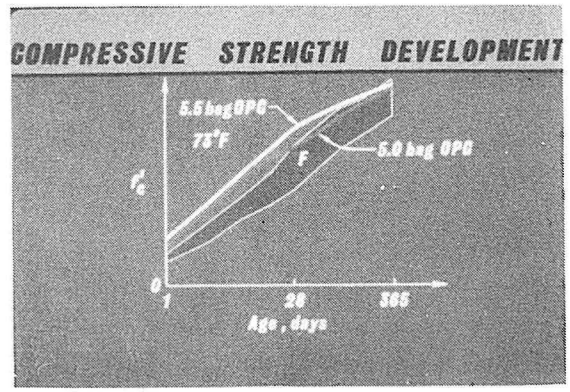
Blended cement
Cement to which reactive silica is added during **cement** production.

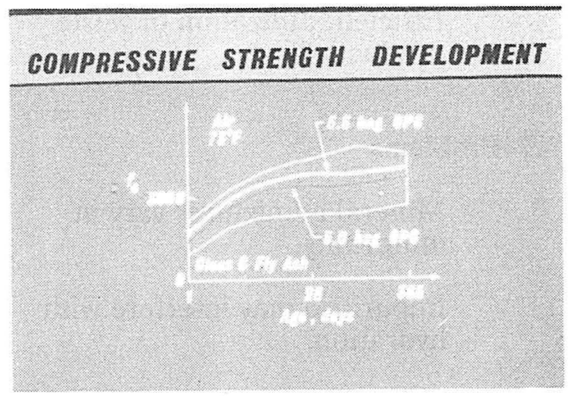
Mineral admixture
Reactive silica or flyash added during **concrete** production.

Portland-pozzolan blended cement
Pozzolan mixed or interground with portland cement.

4.1.6 Characteristics of concrete made with mineral admixtures

May affect rate of strength gain.





May affect water requirement for a given slump.

Lower heat of hydration (replaces C_3S with C_2S).

Behaves like Type II or Type IV portland cement.

Increased long-term strength (at expense of early strength).

Reduced permeability.

CHLORIDE PENETRABILITY

	Sample Depth	
Mix	½-1 in.	1-1½ in.
OPC	0.30	0.07
C	0.08-0.31	0-0.07
F	0-0.12	0-0.12

May influence susceptibility to sulfate attack and AAR.

Efficient utilization of waste products.

4.1.7 Problems

Mineral admixtures vary in uniformity.

Impurities may interfere with hydration.

Impurities may interfere with other admixtures (e.g., carbon content interfering with action of air entraining agent).

Close QC/QA is required.

Not all mineral admixtures are available in all areas.

Selection and approval of materials should be made with care.

4.2 Flyash

4.2.1 General

Characteristics depend on **coal source** and burning characteristics:

a. Temperature

b. Duration

c. Physical plant

d. Coal grinding

Carbon contents of various types of coal:

Vegetation type	carbon content
Wood	49%
Peat	60%
Lignite	70%
Subbituminous	75%
Bituminous	85%
Anthracite	94%
Graphite	100%

Non-carbon percentages are impurities in the coal industry, but represent the material present in the ash when the coal burns away.

Flyash consists of spherical, glassy particles which average 15 to 20 microns in size.

Composition of most flyash:

Silica (SiO_2)	40-90%
Alumina (Al_2O_3)	20-60%
Iron oxide (Fe_2O_3)	5-25%
Lime (CaO)	1-15%

The minerals in flyash are similar to those found in cement, and represent the minerals present in the original vegetation.

The silica in flyash is only partially reactive (only 60 to 85 percent is non-crystalline).

The carbon in flyash is generally present in particles larger than 45 microns.

4.2.2 Specifications

Admixture
AASHTO M-295
ASTM C-618

Testing
ASTM C-311

Blended cements
AASHTO M-240
ASTM C-595

4.2.3 Low-calcium flyash (Type F)

Produced from burning bituminous or anthracite coal.

Rich in silicate minerals, low in calcium minerals.

Minimum content of (SiO_2 + Al_2O_3 + Fe_2O_3) is 70%.

Because the carbon content of the coal is high, the carbon content of the ash can be significant (6% limit, 12% optional).

Pozzolanic, with very little cementing action alone (very similar to natural pozzolans).

Natural pozzolans with 70% (SiO_2 + Al_2O_3 + Fe_2O_3) are classified as Type N.

4.2.4 High-calcium flyash (Type C)

Produced by burning subbituminous or lignite coal.

15 to 35 percent CaO.

50% or more (SiO_2 + Al_2O_3 + Fe_2O_3).

Not strictly a pozzolan, since it has a cementing ability on its own (due to CaO and SiO_2 content).

4.2.5 Advantages of flyash

Lower heat.

Increased resistance to chemical attack and seawater.

Dilution of portland cement produces lower alkali content and lower C_3A content.

Reduced shrinkage and creep.

Increased long-term strength.

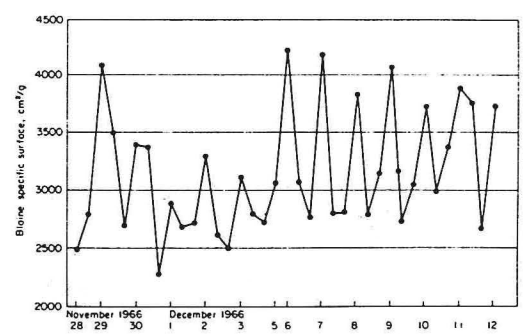
Decreased permeability.

4.2.6 Disadvantages

Quality control/quality assurance.

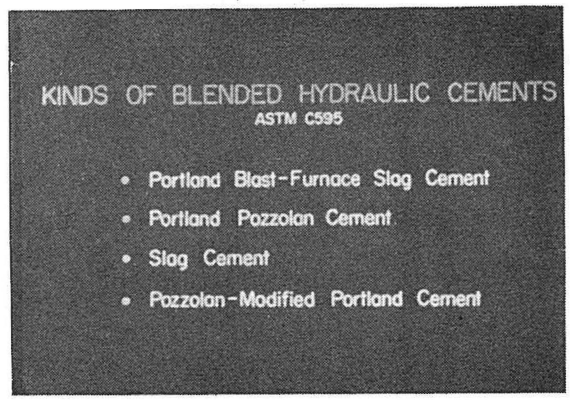
Uniformity of source and processes may vary.

Potential deleterious effects of trace materials on admixtures and cement chemistry.



1 g/cm³ = 1 Mg/m³

4.2.7 Blended Cements with Flyash and Pozzolans



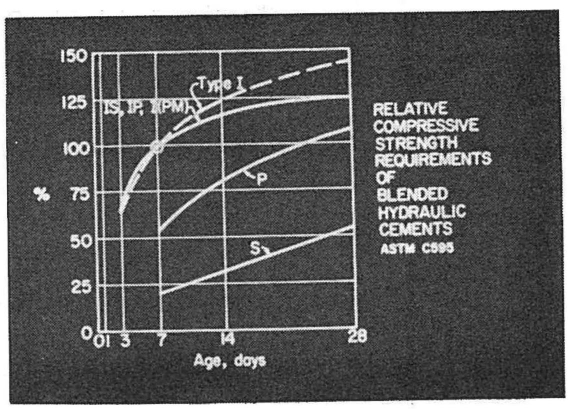
Portland-pozzolan cement
Type IP {MS,A,MH}
Type P {MS,A,LH}

MS = moderate sulfate A = air entraining MH = moderate heat LH = low heat

a. 15-40% pozzolan.

b. Type IP is for general construction.

c. Type P is for use where high strength at early age not required.



Pozzolan modified cement
Type I(PM) {MS,A,MH}

a. for general construction.

b. less than 15% pozzolan.

Portland blast furnace slag - pozzolan cement
Blend of portland cement and slag blended with a pozzolan.

4.3 Blast Furnace Slag

4.3.1 General

Nonmetallic silicates and aluminosilicates of calcium.

In a blast furnace, limestone unites with impurities in coke and iron.

Molten mass floats on top of iron.

Slag is composed of metal oxides.

NOTE: open-hearth slag is not *to be used in concrete*.

4.3.2 Air-cooled slag

Result of slow cooling of slag.

Dense, crystalline -- artificial igneous rock.

Can be used as aggregate (stronger than many natural aggregates).

Good sulfate resistance.

Good corrosion protection.

Can contribute to volume expansion.

4.3.3 Foamed slag

Very rapid cooling by water jets causes the formation of CO and H_2 gases, which expand slag to form porous, lightweight aggregate.

4.3.4 Granulated slag

Formed when slag is cooled by immersion in water.

Consists of glassy, non-crystalline reactive silica.

Ground to about 80% passing No. 325 sieve (a little coarser than Type I cement).

There can be enough CaO present for slag to have cementing ability on its own.

Can be used as a mineral admixture (AASHTO M-302, ASTM C-989).

4.3.5 Blended Cements with blast-furnace slags

Slag cement
Type S

a. use in combination with Portland cement or lime

b. greater than 70% slag

Portland-blast furnace slag cement
Type IS {MS,A,MH}

a. used for general construction

b. 25 to 70% slag

Slag-modified Portland cement
Type I(SM) {MS,A,MH}

a. used for general construction

b. less than 25% slag

High early strength blended cement

4.3.6 Advantages & Disadvantages

Same as for flyash (see Sections 4.2.4 and 4.2.5 above).

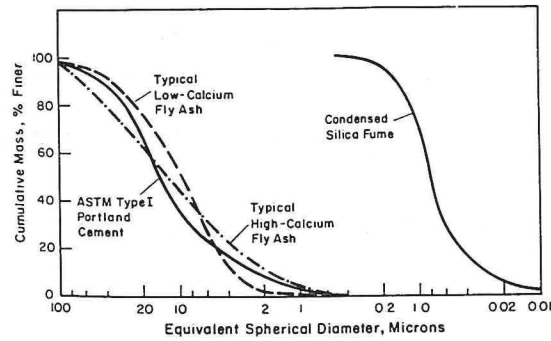
4.4 Microsilica

4.4.1 General

Beneficial for strength and durability because of

a. Pozzolanic reaction

b. Fine particle size (.1 to .01 times the size of cement and flyash)



Reduces porosity and permeability; hydration products form in capillary pores and at paste-aggregate interface.

Improves paste-aggregate bond strength.

Because the small particle size increases water demand; a water reducing agent is required.

4.4.2 High Strength mix design

a. Experimental mix

1000 lb Type I cement
200 lb microsilica
1682 lb 1/2" crushed stone
905 lb sand
266 lb water + HRWRA
22 w/(c+p)

f'_c = 16,170 psi

$f_{c(120 \text{ days})}$ = 18,020 psi

b. Low permeability mix

680 lb Type I cement
85 lb microsilica
1282 lb #1 crushed gravel
1435 lb sand
272 lb water*
6 % air

*subtract 85 lbs of water from microsilica slurry weight of 170 lbs.

Suggested References

Chapter 3

1. ACI Committee 212, Admixtures for Concrete and Guide for Use of Admixtures in Concrete. American Concrete Institute, 1987.

2. Fly Ash Facts for Highway Engineers (FHWA-DP-59-8). Federal Highway Administration, 1986.

3. Helmuth, R., Fly Ash in Cement and Concrete. Portland Cement Association, 1987.

4. Ramachandran, V.S., ed., Concrete Admixtures Handbook. Noyes Publishers, 1984.

5. Rixom, M.R., and N.D. Mailvaganam, Chemical Admixtures for Concrete (2nd Edition). SPON Publishers, London, 1986.

Chapter 4

Construction Processes and Fresh Concrete Behavior

Instructional Objectives:

1. Review general good practice for mixing, transporting, placing, consolidating, finishing, and curing fresh concrete.

2. Review general good practice for placing concrete in hot and cold weather.

3. Describe standard tests for fresh concrete, their significance, and use:

   Air Content
   Slump
   Unit Weight and Yield
   Sampling locations and procedures

Desired Student Achievements:

1. Recognize recommended vs. non-recommended practices in handling fresh concrete, and explain the reasoning behind your choices.

2. Explain the use and limitations of the slump test.

3. Describe the limitations of the standard tests for air content.

4. Explain why proper sampling techniques are critical, and explain the impact of the selection of location from which the sample is taken.

5. Explain appropriate field techniques for consolidation of concrete, curing, and hot and cold weather protection, and explain the reasons behind such procedures.

Chapter 4

Construction Processes and Fresh Concrete Behavior

1. Introduction

1.1 Topics to be covered

Properties of fresh concrete.

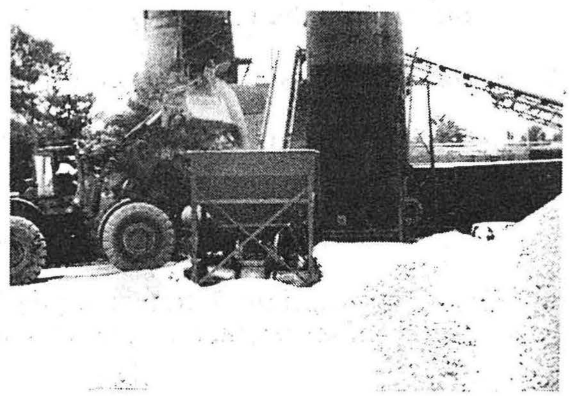
Behavior of fresh concrete.

Development of appropriate properties of hardened concrete.

Beneficial construction practices.

1.2 Overview

The manufacturing process of portland cement concrete begins with the selection and processing of raw materials, and ends with appropriate concrete batching, transport, placement, consolidation, finishing, and curing.



On-site steps in the concrete-making process have a major impact on the final properties of the hardened concrete.

Concrete placed and cured under field conditions can have dramatically different properties than the same concrete placed and cured under laboratory conditions.

2. Methods of Concrete Mixing and Transport

2.1 Description of Methods

Central mix
All components, including water, are added and mixed at the plant.

Truck (transit) mix
All components are added at the plant; mixing is done en route to jobsite.

Job mix
Dry components are added at plant; water is added at the site.

NOTE: A combination of transit mix and job mix is often used, where less than the full amount of water is added at the plant, and the balance is added at the site.

2.2 Comparison of Methods

2.2.1 Central mix

Employs large mixers which are located in the plant itself.

Provides the most uniform concrete if the haul time from the plant to the site is short.

Requires most expensive plant, but cheaper trucks can be used.

If the rate of slump loss is high, water will probably be added at the site.

2.2.2 Truck (transit) mix

Can provide good concrete if enough mixing time is allowed and if truck is in good condition.

Will give non-uniform results if mix times and truck conditions vary from truck to truck.

Requires less expensive plant, but more expensive trucks.

2.2.3 Job mix

The only answer for very long hauls or jobs in remote areas.

Must be prepared for the long delay on site to add water and thoroughly mix it.

Trucks need high-capacity water tanks.

2.3 Standards

2.3.1 National Ready-Mixed Concrete Association (NRMCA)

Concrete Plant Standards

Plant Certification Checklist

2.3.2 Truck Mixer Manufacturer's Bureau

Truck Mixer Standards

2.3.3 AASHTO M-157, ASTM C-94

(Note: these specs are not identical)

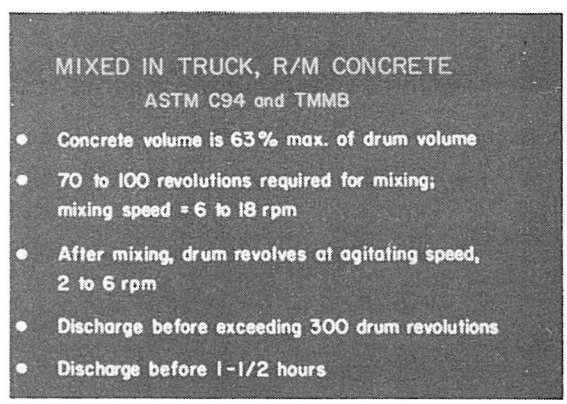
Standard Specification for Ready-Mixed Concrete

a. Mixing required: 70-100 revolutions.

b. Reject after 300 revolutions or 90 minutes.

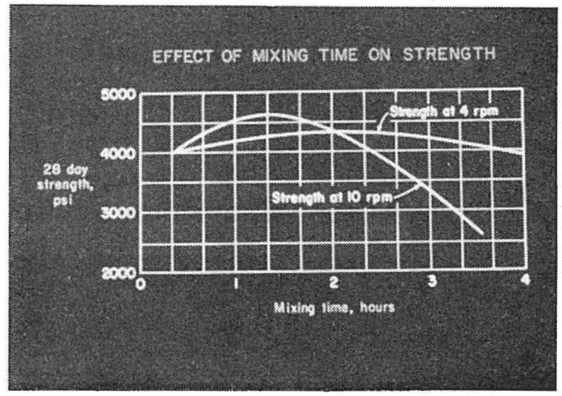
c. Temperature requirement.

d. Testing requirement.



Practicing engineers should know both M-157 and C-94

NOTE: Concrete properties can vary with mixing time, drum rpm, type of mixer, etc.



3. General Fresh Concrete Properties

3.1 Introduction

Fresh concrete is an intermediate, temporary, **transitional** stage.

The properties of fresh concrete are a principal concern to contractors and field personnel.

Typical concerns:

a. Time available for placing and finishing.

b. formwork pressure

c. flowing concrete

d. removal of forms and shores

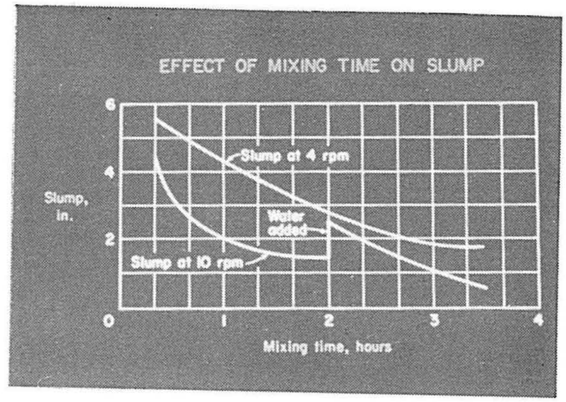
e. slip forming operations

Fresh concrete has traditionally (and unfortunately) been of less concern to designers, specification writers, and researchers. Far less research has been performed on fresh concrete than on hardened concrete.

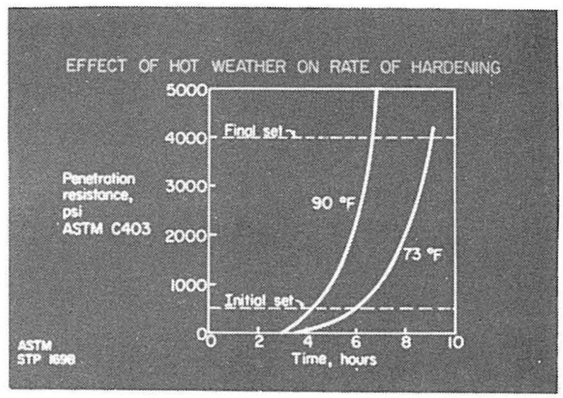
Fresh concrete is a "moving target."

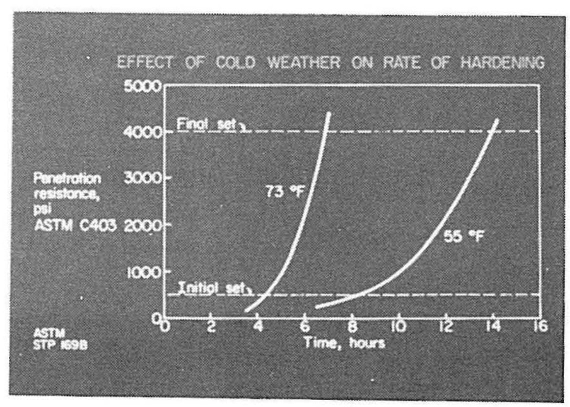
3.2 Properties that Change with Time

Rate of slump loss

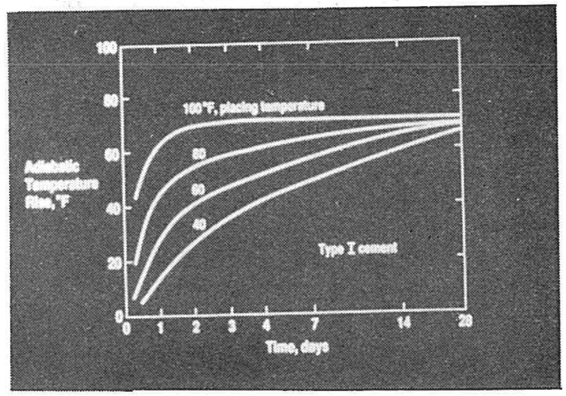


Rate of setting

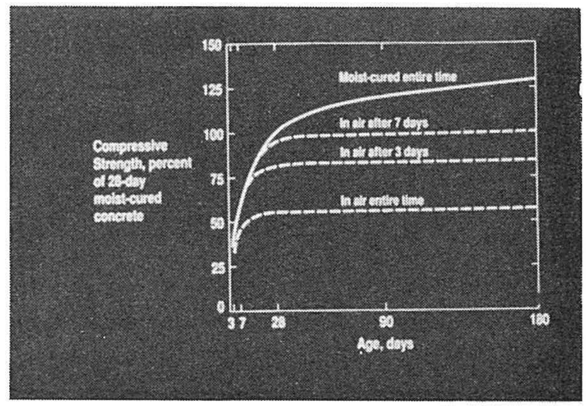




Rate of heat evolution



Rate of strength gain



3.3 Factors that Affect Properties of Fresh Concrete

Time

Environment

Construction

a. equipment

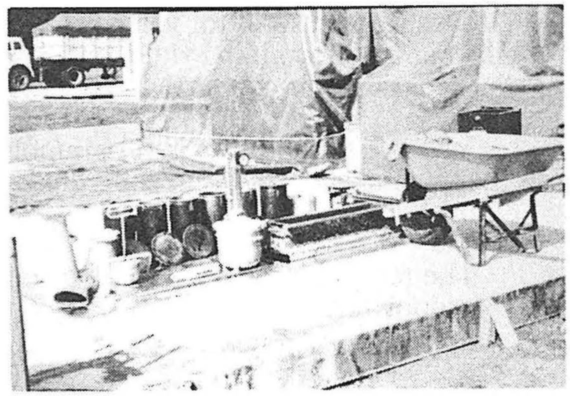
b. methods

Materials

4. Tests on Fresh Concrete

4.1 Sampling

AASHTO T-141
ASTM C-172



The sample should be representative of the concrete used in the project.

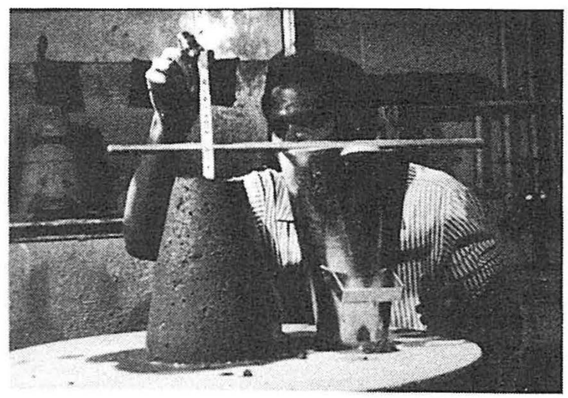
The timing of sampling is important.

Take a composite sample from the middle of the batch.

Be alert for water addition.

4.2 Slump

AASHTO T-119
ASTM C-143



The slump test is most useful as a measure of consistency (i.e., "uniformity").

High slump indicates a risk of segregation.

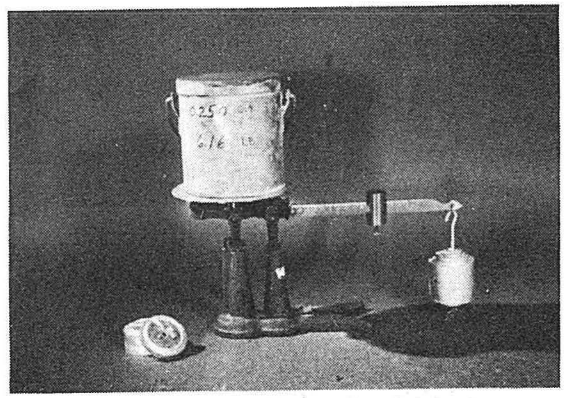
The relationship of slump to strength and durability is unclear.

Timing is important -- all concrete eventually has zero slump.

The rate of slump loss increases with temperature and some admixtures.

4.3 Unit Weight, Yield, Air Content

AASHTO T-121
ASTM C-138



This test is useful for verifying batch weight, determining yield, and measuring air content.

Yield determination is very important to the contractor and the concrete producer.

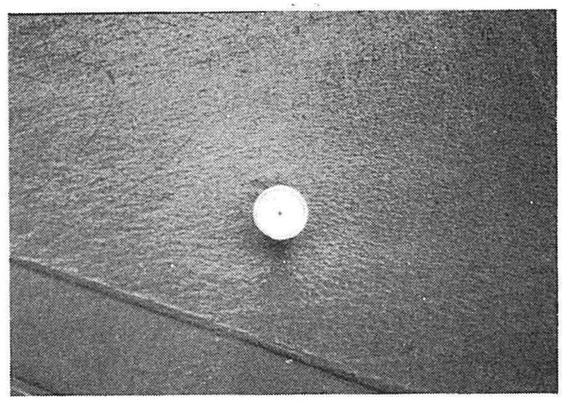
The test requires knowledge of mix proportions.

4.4. Air Content

This test is discussed in Chapter 6.

4.5 Temperature

ASTM C-1064



It may be important to know if concrete is too hot or too cold at the time of placement.

AASHTO M-157 and ASTM C-94 set minimum and maximum temperature requirements for ready-mixed concrete.

See the discussion of temperature in the section on Hot/Cold Weather Concrete, Section 4.6.5.

5. Typical Problems/concerns with Fresh Concrete

5.1 Problems at the Batch Plant

Insuring that materials used in mix are the same as approved materials.

Proper proportioning.

Proper operation of equipment.

5.2 Problems in the Field

5.2.1 Changing the mix ingredients or proportions in the field

Addition/reduction in effective water content.

Changes in air void system.

Changes in paste, aggregate, air bubble distribution due to handling.

5.2.2 Failure to consolidate concrete

Poor overall compaction leading to lower density, increased porosity, increased permeability.

Poor bond to rebar.

Poor consolidation in corners, around inserts.

5.2.3 Jobsite and environmental damage

Shock, vibration, impact.

Water on surface.

Cracking due to rapid drying.

Rapid freezing.

5.2.4 Failure to achieve properties predicted in the laboratory

Field processes and conditions can lead to deviations from expected properties.

a. improper moisture control

b. improper temperature control

c. both

6. Proper Care and Handling of Fresh Concrete

6.1 Preservation of Mix Composition and Uniformity

6.1.1 Control water addition

Know water content as delivered.

Determine allowable water addition on the basis of w/c ratio.

Add a **measured** quantity of water.

Mix thoroughly.

6.1.2 Be aware of the impact of mixing and placing on air void system

Measure air content in the field:

a. Measure at various times.

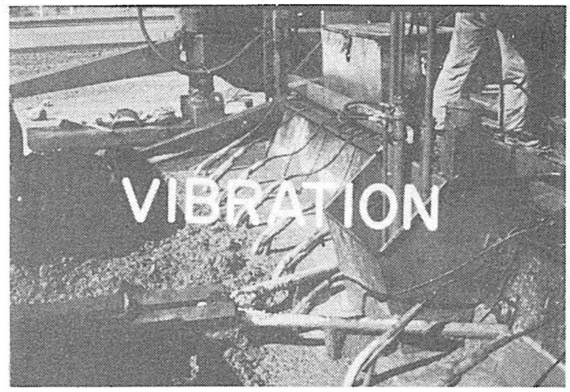
b. Measure at various locations.

c. Perform microscopical analysis on hardened concrete.

6.1.3 Avoid segregation

6.2 Proper Consolidation

See PCA <u>Design and Control...</u>, Chapter 9.



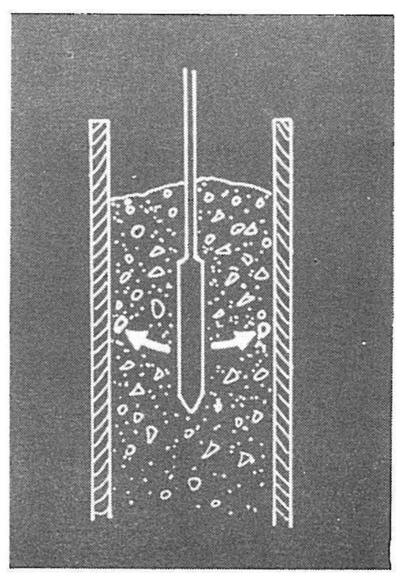
6.2.1 General

Vibration temporarily liquefies concrete by forcing pressurized water between aggregate particles.

Methods of vibration:

a. Internal (immersion).

b. External (e.g., attach to forms).



NOTE: The following discussion is limited to internal vibration.

The effect of the vibrator is restricted to a small "radius of action" around the point of insertion:

distance from center of 2" vibrator	amplitude of vibration
1	100%
2	63%
4	34%
6	22%
8	15%
10	11%
12	8%
14	6%

Time is required for the limited effect of the vibrator to be felt by concrete.

Typical field use of the vibrator is usually inadequate, especially in horizontal members like bridge decks.

Specialized equipment and construction processes may have unique requirements for vibration.

6.2.2 Guidelines for good practice

a. Consolidate in layers of 12 to 18 inch maximum depth.

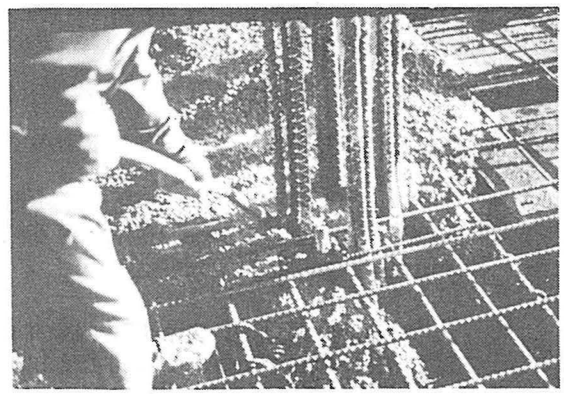
b. Insert vibrator at equally spaced intervals of 1.5 times the radius of action.

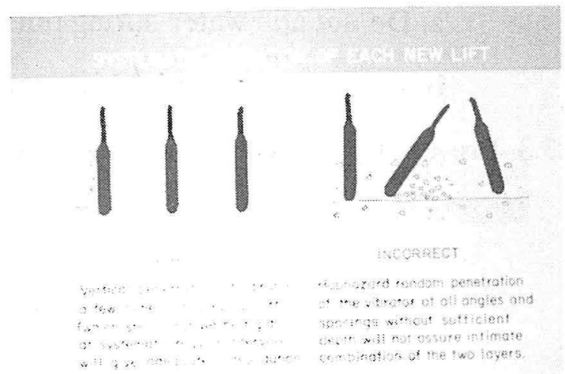
c. Hold the vibrator in place for 5 to 15 seconds.

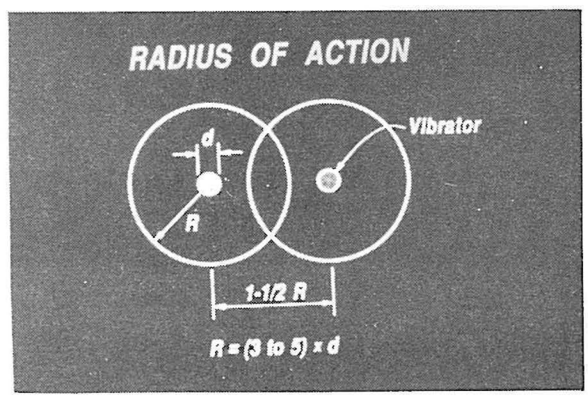
d. Remove the vibrator slowly (3" per second).

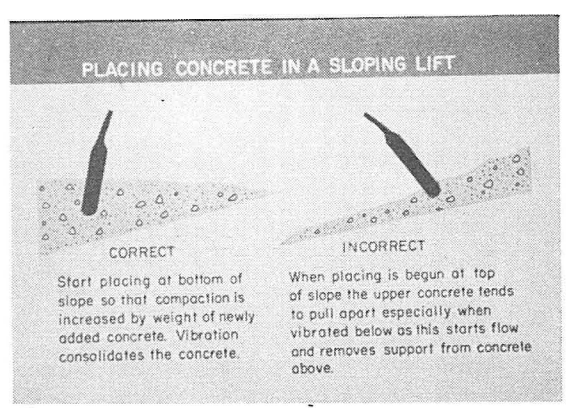
e. Match vibrator to the mix and the member.

See Report of ACI Committee 309... for details.









6.3 Prevention of damage to fresh or recently cast concrete

6.3.1 Prevent nearby shock or vibration

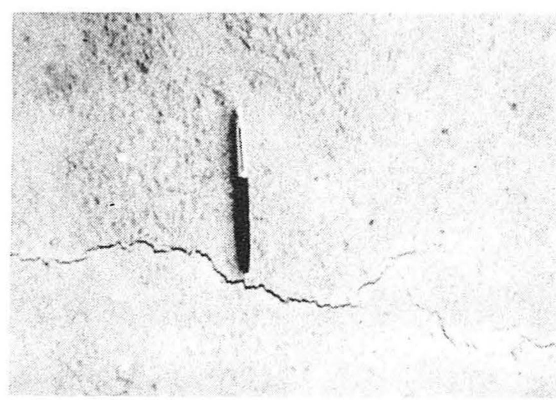
6.3.2 Prevent ponding of excess water on the surface prior to setting

The presence of excess water on the surface prior to setting increases the w/c ratio at the surface.

a. Do **not** add water during finishing.

b. Avoid placement in driving rain.

6.3.3 Prevent plastic shrinkage cracking



To reduce the opportunity for cracking due to rapid surface drying (i.e., "plastic shrinkage cracking"):

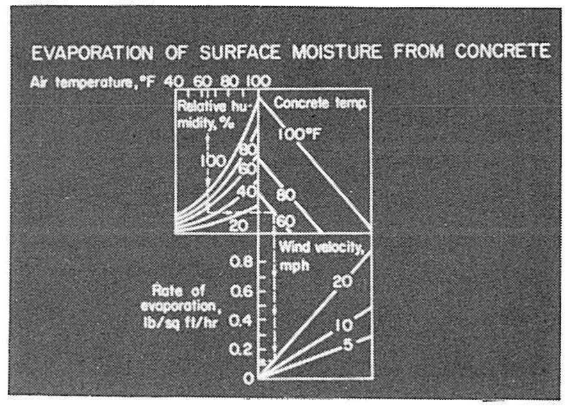
a. Avoid placement when weather promotes rapid evaporation:

- warm, clear, bright sun, breezy, low humidity
- cold, clear, bright sun, breeze, low humidity

The natural evaporation can be greater in winter than in summer.

b. Reduce the evaporation rate when possible:

- erect sun screens and wind breaks.
- wait for more favorable conditions.



c. Reduce the temperature of the concrete.

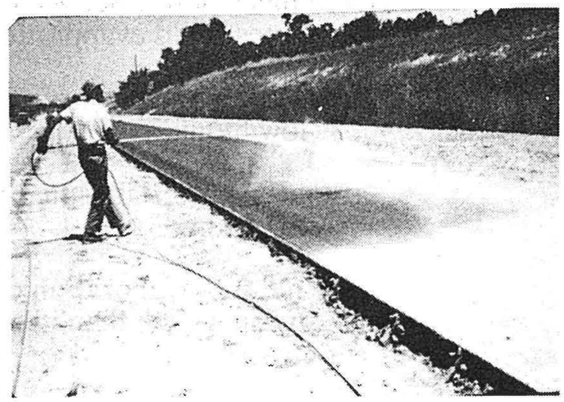
d. Revise the mix design (mixes vary in their tolerance to rapid drying and cracking).

e. Revise the finishing procedure:

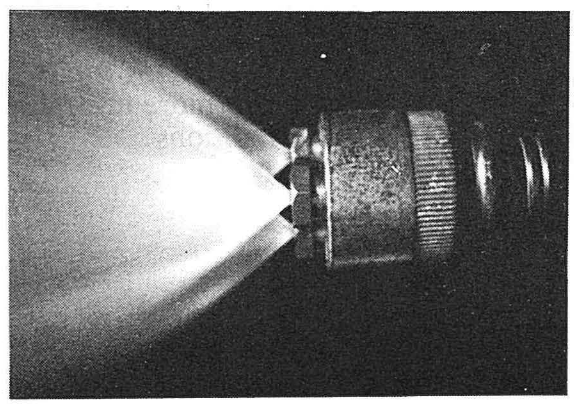
Use a slower contact speed to reduce friction (friction drag between the finishing tool and the concrete contributes to surface stresses).

f. Rapidly apply curing procedures.

- curing should be initiated ASAP following application of surface texture.

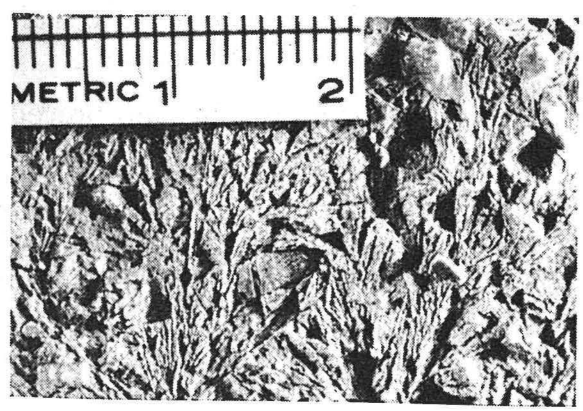


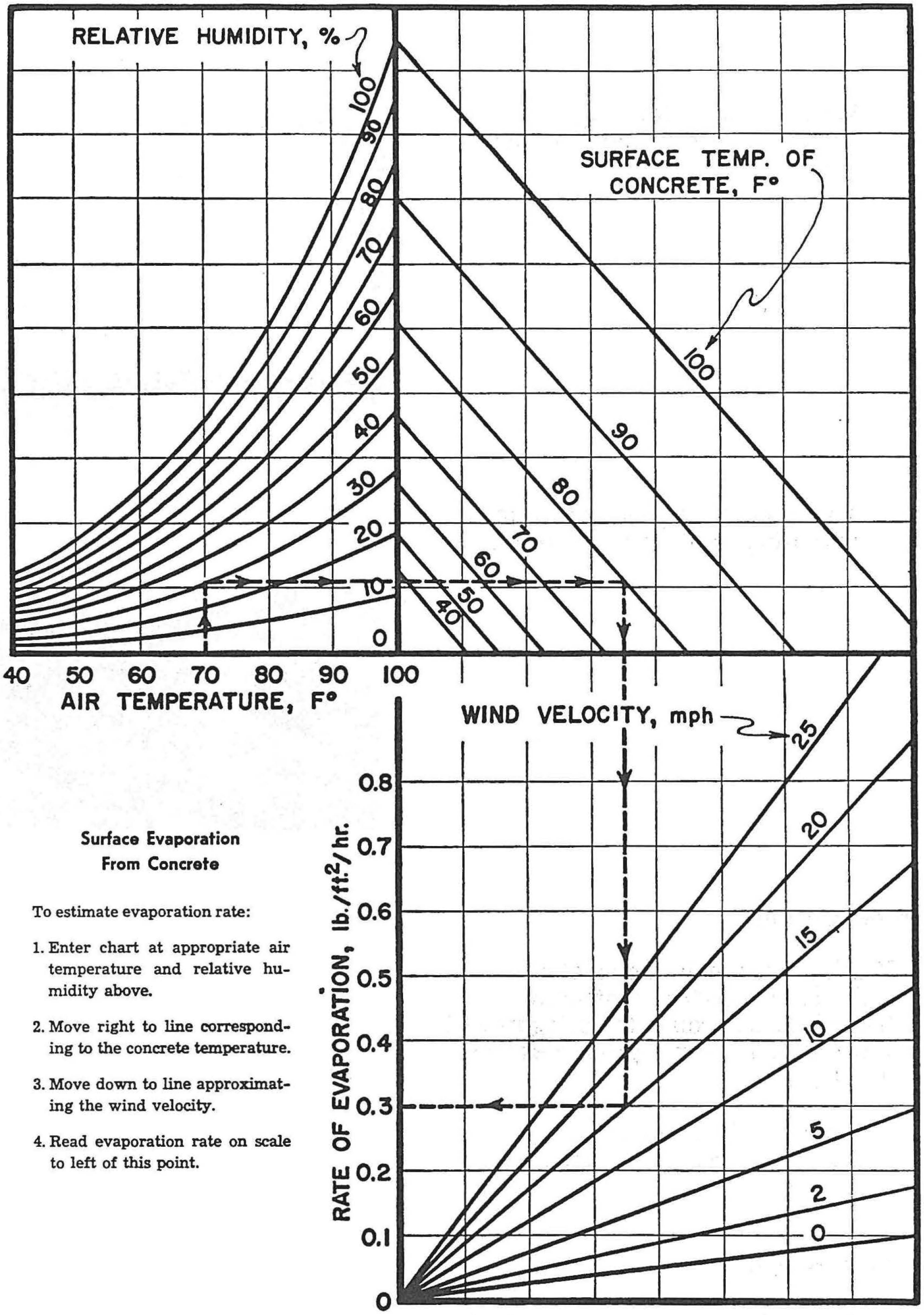
- don't wait until entire placement is finished.
- use fog spray.



6.3.4 Prevent rapid freezing

Even air-entrained concrete can be damaged by freezing prior to the development of an in-situ compressive strength of 500 to 1000 psi.





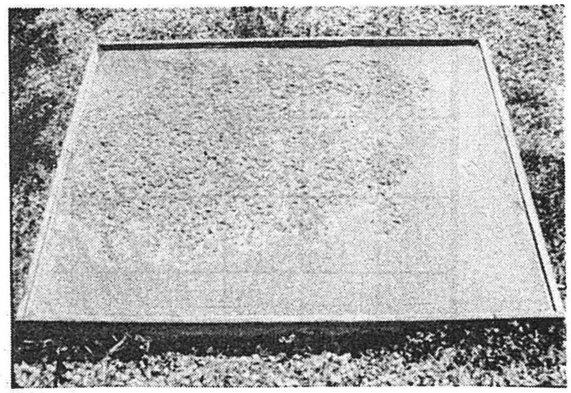
Surface Evaporation From Concrete

To estimate evaporation rate:

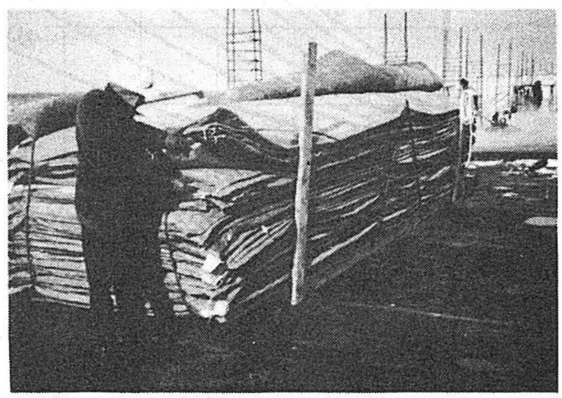
1. Enter chart at appropriate air temperature and relative humidity above.
2. Move right to line corresponding to the concrete temperature.
3. Move down to line approximating the wind velocity.
4. Read evaporation rate on scale to left of this point.

Nomograph for calculating evaporation from free-water surfaces, intended for estimating evaporation from the surface of freshly cast concrete

Water curing in freezing temperatures can lead to surface scaling.



To protect freshly cast concrete, use insulating blankets, straw, or plastic.



6.4 Proper Curing

"Curing is the maintaining of a satisfactory **moisture content and temperature** in concrete during its early stages so that desired properties may develop."

(Source: ACI Committee 308, Standard Practice for Curing Concrete)

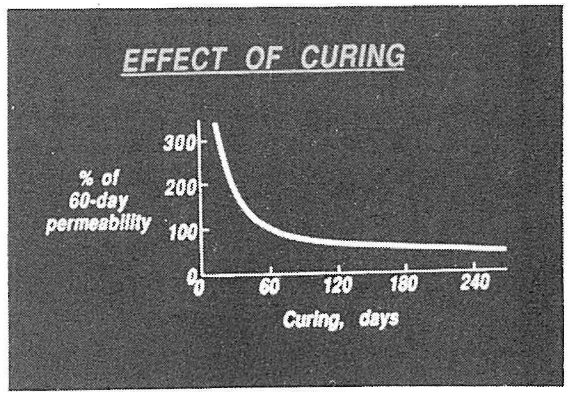
6.4.1 Moisture control

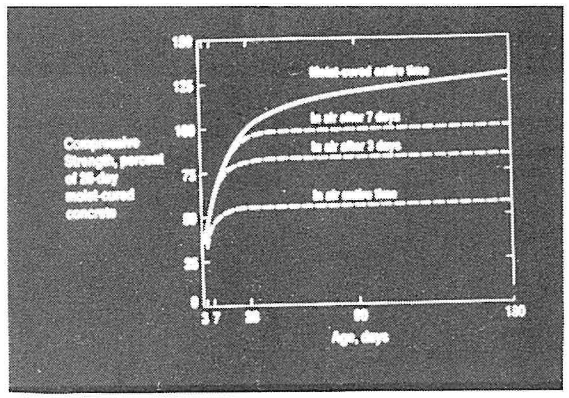
Portland cement grains continue to hydrate only when in contact with water.

Hydration ceases when the relative humidity inside the concrete falls below approximately 75%.

Proper curing measures will maintain sufficient moisture to sustain hydration.

Both strength and permeability are significantly influenced by curing.





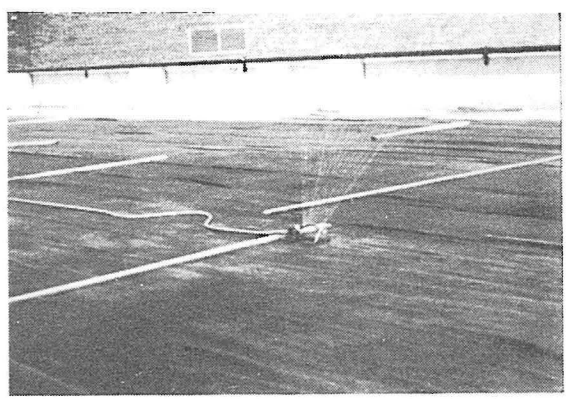
6.4.2 Wet curing

External application of water by

a. ponding

b. using sprinkler or soaker hoses

c. using paper, burlap, or burlene



Wet curing prevents evaporation and provides additional water to the cement.

6.4.3 Curing by moisture retention

No external application of water is used. Moisture is retained by

a. using curing compounds or membranes.

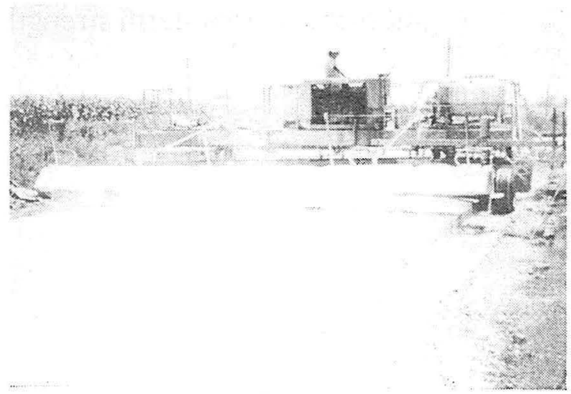
b. using paper or plastic coverings.

This method also retards evaporation, but does not supply additional water to the cement.

6.4.4 Time of application

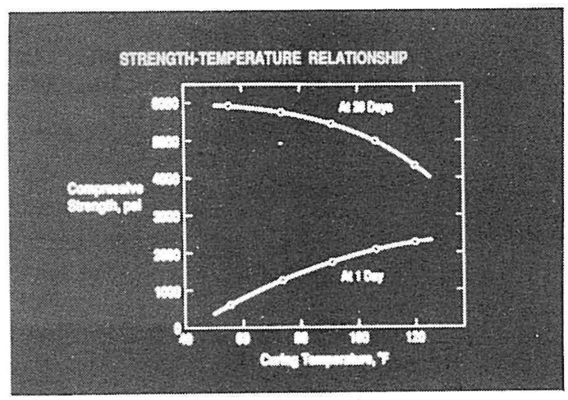
Apply cure immediately after finishing operations -- don't wait until placement is complete.

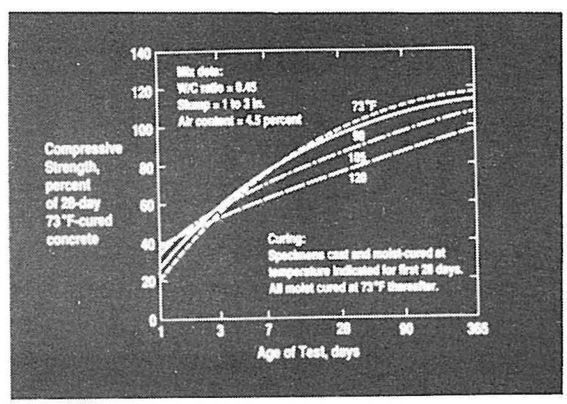
A spray-on cure followed by wet curing or moisture retention is beneficial when it is practical to do so.



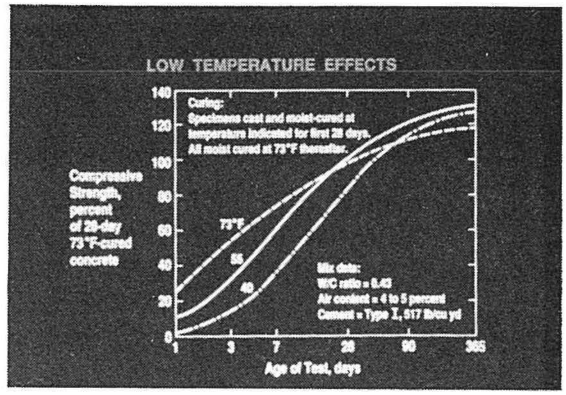
6.4.5 Temperature control

Higher temperatures increase the rate of early strength development.

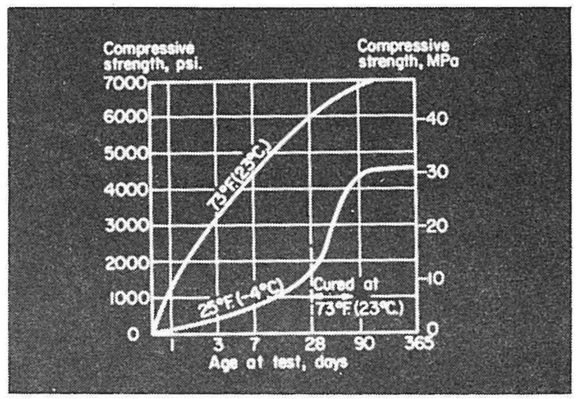




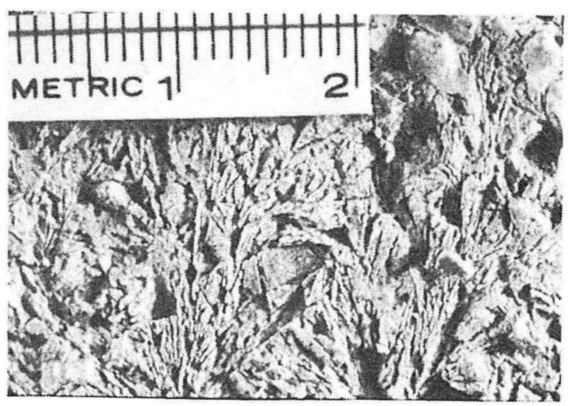
Lower temperatures decrease the rate of early strength development, but increase long-term strength.



Very low temperatures will make early strength gain impractically slow, **and** reduce long term strength.



Early freezing, before compressive strength reaches 500 to 1000 psi, can damage even air-entrained concrete.



The need for temperature control depends on the desired performance of the concrete.

Maintain high temperatures

- for early shoring and falsework removal.

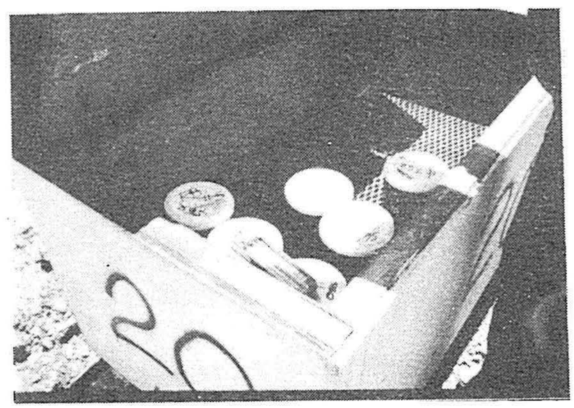
- if high early strength is required.

Cooling may be required

- for development of long-term strength.

- to limit maximum temperature or maximum temperature differential.

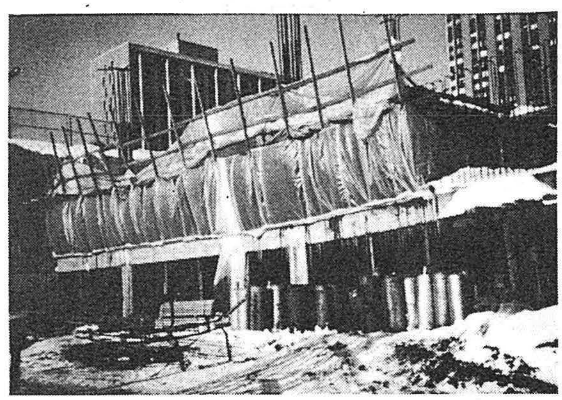
Temperature control is required for the structure and the test specimen.



Methods of maintaining warm concrete:

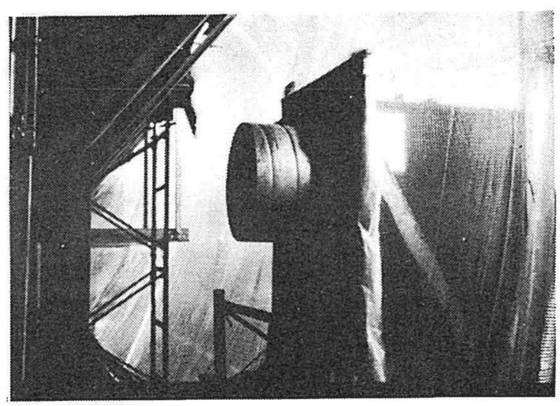
a. Insulation

- blankets
- plastic sheets and straw
- insulating boards (styrofoam, etc)
- insulated forms
- tents, shelters



b. Application of heat to concrete after placement

- use electric, gas, or oil heaters
- vent combustion heaters to avoid CO_2 damage



c. Heating the concrete mix

- heated aggregate
- heated mix water
- preheat trucks

Methods of cooling concrete

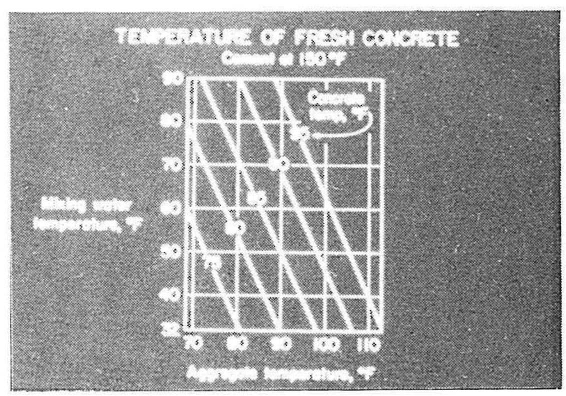
To cool concrete, cool the mix:

a. Revise the mix design.

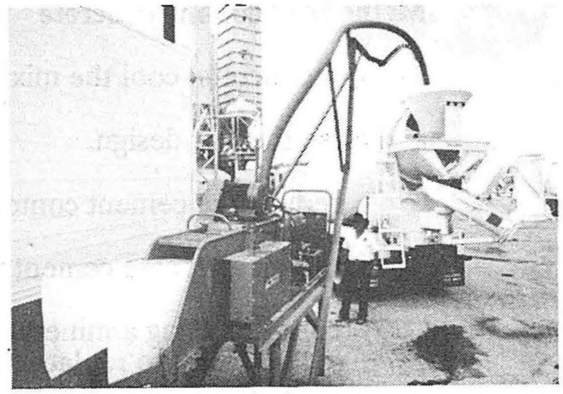
- reduce the cement content
- use an alternate cement type
- consider using a mineral admixture to replace some of the cement

b. Cool the aggregates.

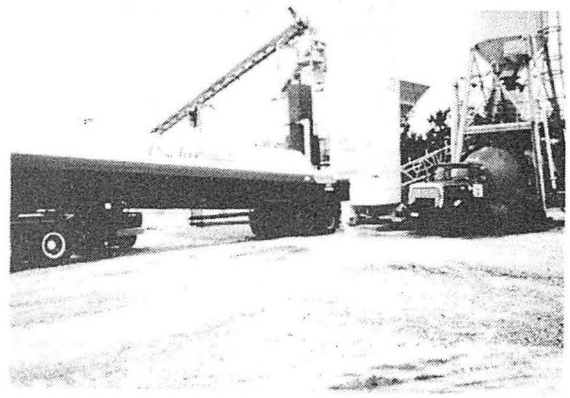
c. Cool the mix water.

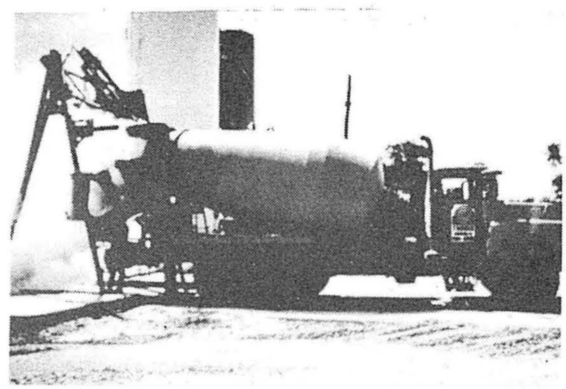


d. Replace water with ice.



e. Inject liquid nitrogen.





Suggested References

Chapter 4

1. ACI Committee 304, Guide for Measuring, Mixing, Transporting, and Placing Concrete, American Concrete Institute, 1986.

2. ACI Committee 309, Standard Practice for Consolidation of Concrete, American Concrete Institute, 1987.

3. ACI Committee 308, Standard Practice for Curing Concrete, American Concrete Institute, 1986.

4. ACI Committee 305, Hot Weather Concreting, American Concrete Institute, 1982.

5. ACI Committee 306, Standard Specification for Cold Weather Concreting, American Concrete Institute, 1987.

Chapter 5

Properties and Behavior of Hardened Concrete: Strength, Cracking, Shrinkage, Elasticity, and Creep

Instructional Objectives:

1. Describe the origin of strength in PCC:

   Aggregate Strength
   Paste Strength
   Bond Strength

2. Describe the fundamental failure mechanism of concrete in compression -- microcracking through macrocracking, accompanied by expansion. Transfer these concepts to cracking and failure in flexure and direct tension.

3. Describe applications of these principles in both standard testing and in structural behavior.

4. Discuss the deformation of hardened concrete, to include shrinkage effects, elastic deformation, and time-dependent (creep) deformation.

Desired Student Achievements:

1. Understand the mutual dependency of paste, aggregate, and bond strength, and the step-wise formation of microcracks leading to failure of concrete in compression, flexure, and direct tension.

2. Describe practical applications of the fundamentals of concrete cracking, including applications to materials testing and structural behavior.

3. Describe situations in which the elastic, shrinkage, and creep behavior of concrete is important.

Chapter 5

Properties and Behavior of Hardened Concrete

1. Introduction

1.1 Mechanical properties

Strength

a. Compressive

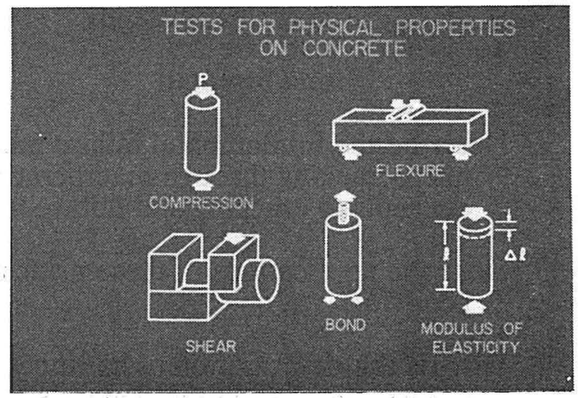
b. Flexural

c. Shear

d. Bond

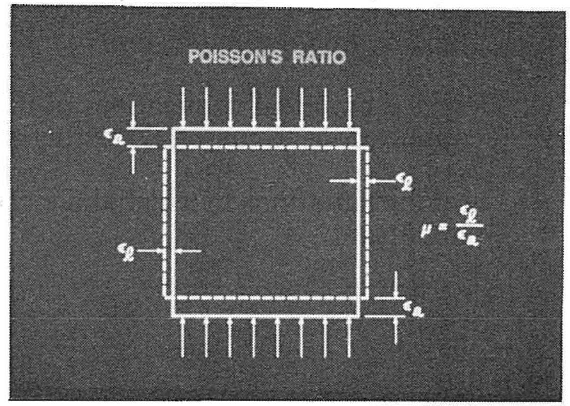
e. Direct tensile

f. Splitting tensile



Modulus of elasticity

Poisson's ratio



Coefficient of thermal expansion

COEFFICIENT OF EXPANSION OF CONCRETE

Aggregate type	Expansion, millionths per degree Fahrenheit
Quartz	6.6
Sandstone	6.5
Granite	5.3
Basalt	4.8
Limestone	3.8

Creep coefficient

Fracture toughness

Fatigue behavior

1.2 Other Physical Properties

Porosity

Pore size distribution

Permeability

Volume stability

Thermal conductivity

Electrical conductivity

Density

Chemical stability

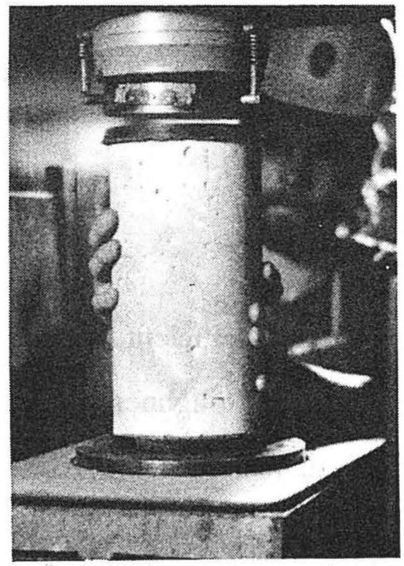
Frost resistance

1.3 Comments

Primary property of interest **may not** be compressive strength.

In some cases there may be a tendency in industry to assume that if compressive strength is satisfactory, all other properties must be satisfactory as well -- this is not true!

Durability-related properties will be introduced in subsequent sessions.

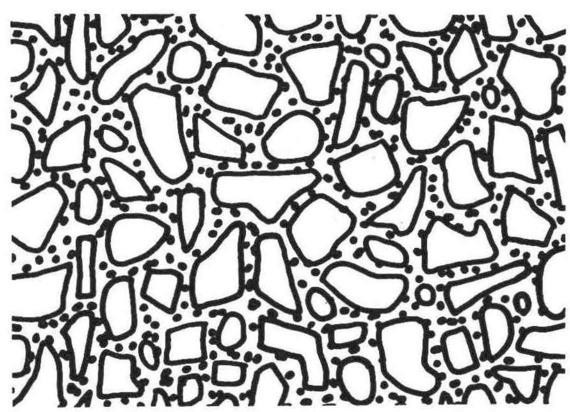


2. Origin and Development of "Strength" in Concrete

2.1 Concrete as a Two-Phase Material

Coarse aggregate

Mortar (everything else)



2.2 Factors influencing concrete strength

Strength of coarse aggregate

Strength of mortar

a. Strength of fine aggregate

b. Strength of hardened paste

c. Strength of bond between fine aggregate and paste

Strength of bond between aggregate and mortar

The test method and test conditions may significantly affect apparent strength.

2.3 Coarse Aggregate Strength

For most concrete, coarse aggregate strength is **not** the weak link that leads to failure.

Type	Compressive Strength
granite	26,200 psi
trap rock	47,000 psi
limestone	23,000 psi
sandstone	19,000 psi
marble	16,900 psi
quartzite	36,500 psi
Gneiss	21,300 psi
Schist	24,600 psi

For w/c < 0.40, aggregate strength may be similar to paste strength.

For w/c > 0.65, aggregate strength doesn't make much difference.

Direct, uniform compressive stress at failure for aggregates is many times greater than the compressive strength of normal concrete.

On the average, coarse aggregates experience higher stresses than the concrete.

Bond failures are common.

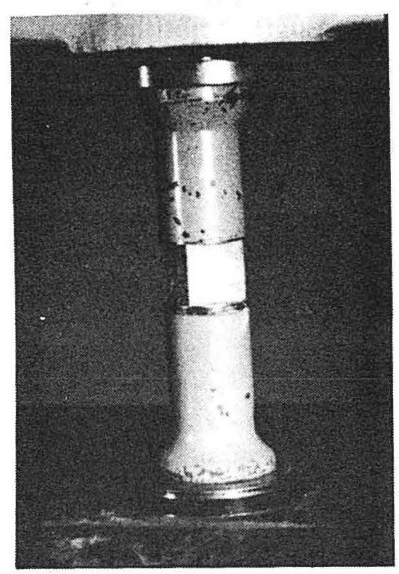
2.4 Mortar Strength

The strength of the mortar phase is intimately related to the strength of the portland cement itself.

Variations in **cement strength** will lead to variations in concrete strength.

Variations in the **rate** at which the cement gains strength will lead to variations in the rate at which the concrete gains strength.

Cement strength is tested in the form of mortar.

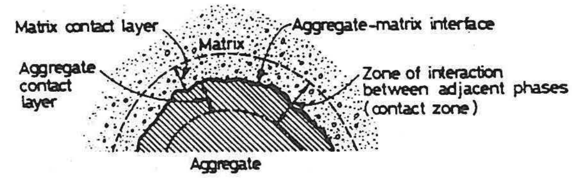


Addition of coarse aggregate may increase or decrease the strength of the concrete relative to the mortar depending on the proportions of each.

Decreasing the mortar strength (keeping coarse aggregate type and proportion constant) will decrease the concrete strength.

2.5 Mortar-aggregate bond strength

2.5.1 Physico-chemical interaction at mortar-aggregate interface



2.5.2 Bond components

a. Chemical bonding

b. Mechanical interlock

c. Adhesion and friction

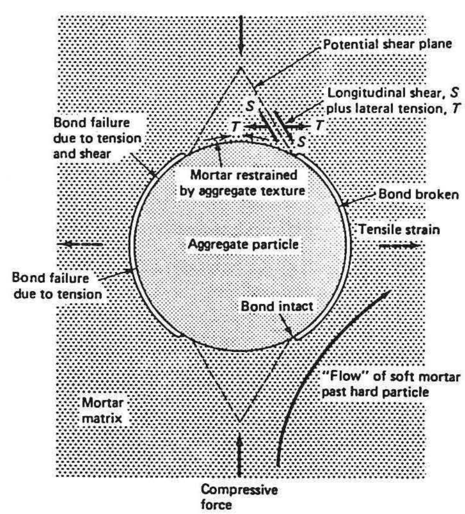
2.5.3 Factors affecting bond strength

a. Cement chemistry

b. Aggregate chemistry

c. Mortar strength (as influenced by w/c ratio, time, temperature, and moisture control)

- compression
- tension
- shear



d. Aggregate surface texture

- rough -- better interlock
- smooth -- better adhesion

Rough aggregate generally gives better bond, but requires more water for workability, so there is little net strength increase.

e. Cleanliness of aggregate particles

- crushed -- "rock flour"
- natural -- silt

The standard test for aggregate cleanliness is described in AASHTO T-176 and ASTM C-33.

3. Failure Mode of Concrete Through Microcracking

3.1 Microcracks

Microcracks are discrete cracks which generally range from microscopic to just visible with the unaided eye in size.

a. **Bond** microcracks form at aggregate mortar interface.

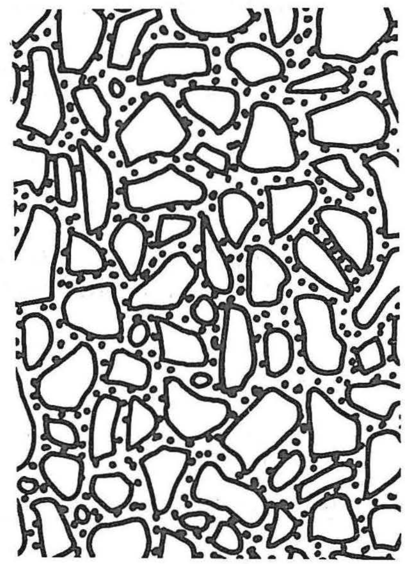
b. **Mortar** ("matrix") microcracks form within the mortar itself.

c. **Aggregate** microcracks form within the aggregate particles.

Microcracks ultimately coalesce to form readily visible "macro"-cracks.

3.2 Growth of Microcracks within a Concrete Specimen Experiencing Increasing Compressive Stress

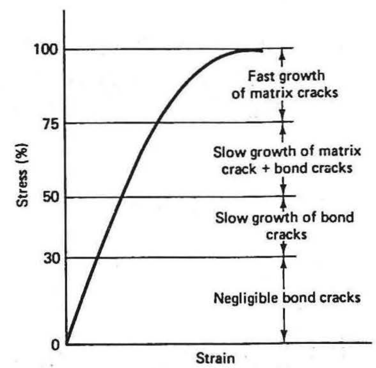
3.2.1 Microcrack behavior



a. Negligible cracking occurs up to about 30% of f'_c.

b. Bond cracks begin at 30% of f'_c.

c. Mortar (matrix) cracks begin at 50% of f'_c.



d. The "discontinuity point" is reached at 75% of f'_c.

- cracks develop rapidly and are unstable.
- mortar cracks begin to connect with each other and with bond cracks.

e. Load paths through the specimen begin to break down.

f. Concrete continues to carry its load as long as stress paths remain.

g. Stress levels increase in remaining paths until the concrete fails.

3.2.2 Microcrack characteristics and consequences

Bond cracks

a. Form early, at low stress levels.

b. Of marginal importance in compressive behavior.

c. Of **critical** importance in flexure and direct tension.

d. "Stable" cracks -- growth stops when stress increase stops.

Mortar cracks

a. Begin as stable cracks.

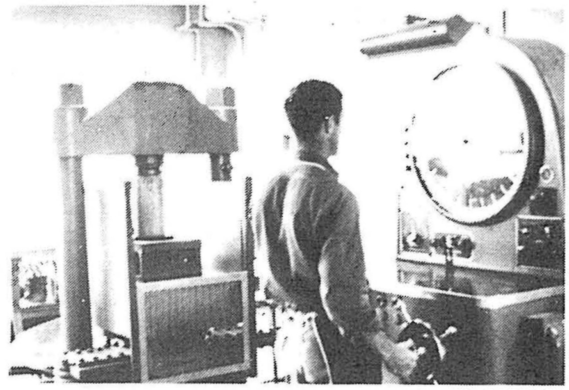
b. Become unstable near "discontinuity point." The volume of the concrete begins to **increase** at the discontinuity point.

c. Mortar cracks can be unstable and **continue** to grow after load stabilizes or is removed.

Sustained and cycled load

The long term ("sustained") load limit for concrete is the discontinuity point. The repeated load limit is **below** the discontinuity point.

Rate of loading



Since the growth of microcracks inside the specimen takes time, the **rate of loading** is critical in obtaining measurements of strength.

a. Rapid loading generally leads to higher strength values.

b. Slow loading generally leads to lower strength values.

Rates of loading for ASTM tests:

a. Compression cylinder test ASTM C-39 AASHTO T-22	20 - 50 psi/second
b. Flexural Beam test ASTM C-78, C-293 AASHTO T-97, T-177	125 - 175 psi/minute
c. Split cylinder test ASTM C-496 AASHTO T-198	100 - 200 psi/minute
d. Bond ASTM C-234 AASHTO T-159	< 5000 lb/min

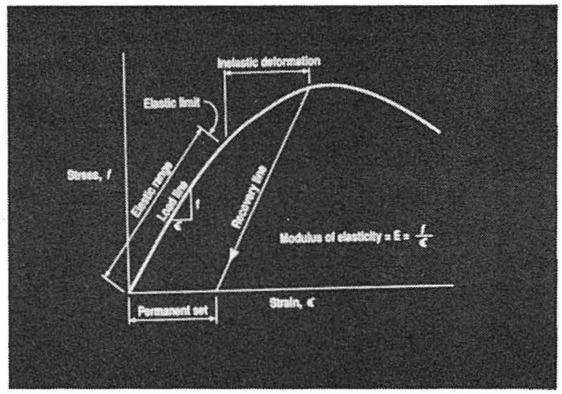
Failure

Failure is associated with coalescence of the microcracks and a volumetric expansion

Stress-strain curve

a. The steadily decreasing stiffness of concrete is due to the increase in microcracking.

b. The permanent set is due to microcracking.



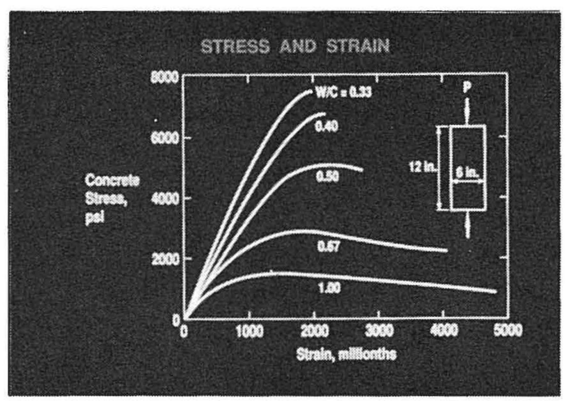
Altering behavior

a. Improvements in bond strength increase modulus of elasticity and flexural and direct tensile strength.

To improve bond strength,

- use cleaner aggregates
- use admixtures or other additives to improve bond
- change type of aggregate

b. Increases in overall strength are usually accompanied by increases in modulus of elasticity. ("stiffness").



4. Macro-Behavior

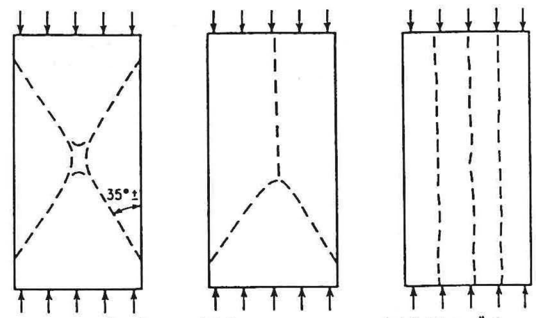
4.1 Compression Behavior

4.1.1 Behavior of a cylinder

By studying how and why a typical 6 x 12 cylinder breaks, we learn a great deal about the mechanical behavior of concrete

Cylinder failures can generally be characterized into 2 types (with various combinations):

a. Diagonal



(a) Shear or "cone" failure (b) Combination shear and splitting failure (c) Splitting or "columnar" failure

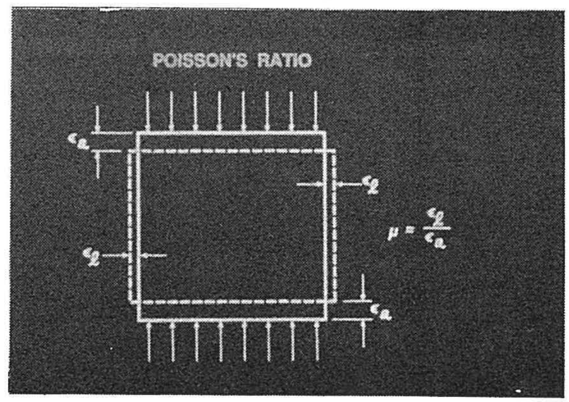
b. Columnar

The diagonal failure has often been explained as a "diagonal shear" failure based on principal shear stress. In fact, this type of failure is often called a "diagonal shear" pattern.

The vertical cracks can be formed intentionally by reducing the friction between the specimen and the test machine. Principal shear stresses remain the same, however.

Explanations for both failures:

a. Concrete failure in compression is accompanied by volume expansion.



b. Impact of end conditions and cylinder capping.

- friction between cylinder and test machine creates end restraint.
- end restraint prevents expansion at ends of cylinders.
- cylinders free to expand only at their centers.
- net result of end restraint is to "reinforce" the cylinder, with failure initiating at mid-height in a "cone" shape.

Care must therefore be taken to ensure that cylinder capping system provides sufficient restraint or compressive strength test values will be reduced (see AASHTO T-22).

Applications to Structural Behavior

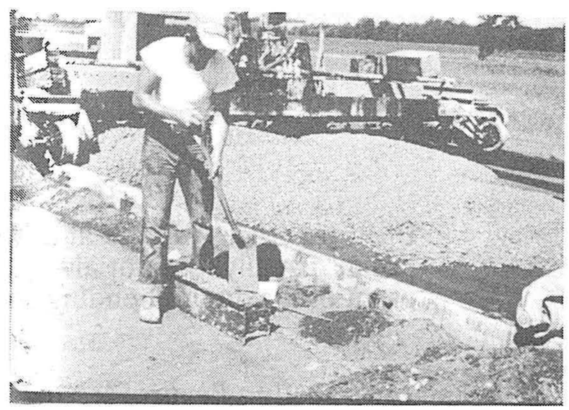
a. Failure of column in compression.

b. Reinforcement of a column in compression.

c. Reinforcement of a bearing pad to limit expansion

d. Implications for repair and strengthening of under-strength concrete.

4.2 Flexural (Tensile) Behavior and Testing

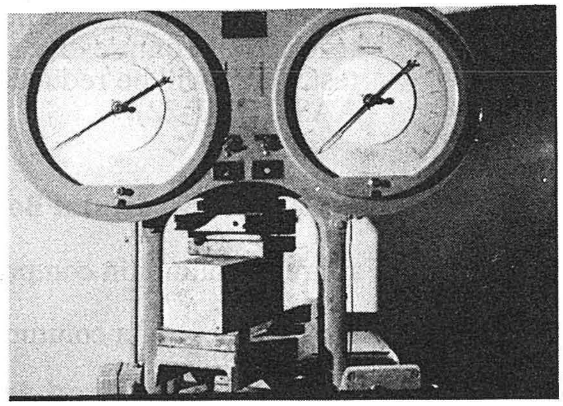


4.2.1 General

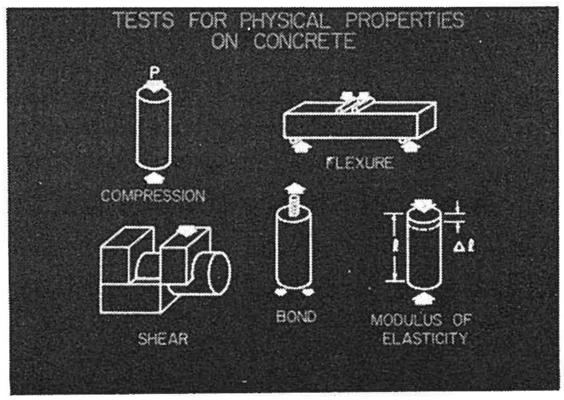
Bending induces both compressive and tensile stresses, but the tensile stresses usually govern cracking.

Tensile bond between mortar and aggregate is far more critical than in compression.

Flexural failure is associated with an expansion or "stretching" of the concrete, just as in the case of compression failure.



The numerical values for the flexural or tensile expansion of concrete at failure, also known as the "limiting tensile strain," are approximately equal to the values for expansion at failure in compression.



Flexural cracks initiate at a "weak point," usually, but not always, at the point of maximum bending stress.

4.2.2 Factors affecting flexural testing

a. Flexural tests are sensitive to "flaws" in a specimen:

- shrinkage cracks
- nicks, gouges, indentations, surface finish

b. Flexural tests are sensitive to pre-existing stresses:

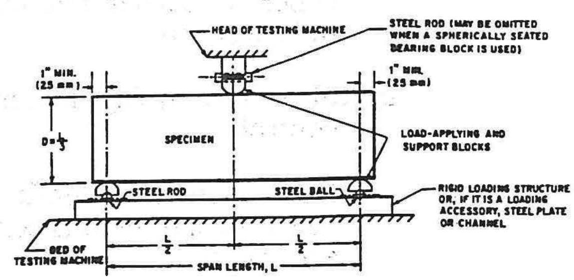
- thermal stresses
- shrinkage stresses

c. Temperature and moisture conditioning are critical in flexural testing.

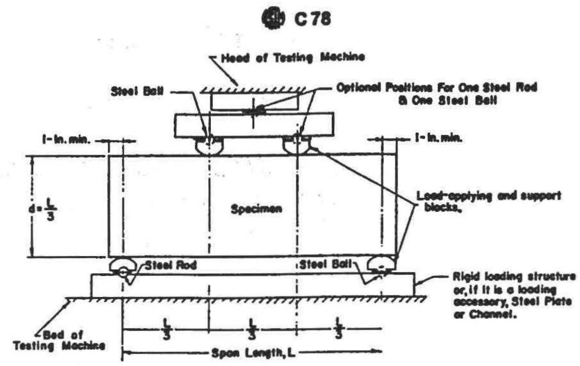
4.2.3. Differences between 3rd point and center point loading

Center point loading induces maximum tensile stress only at the midspan of the beam, which may or may not coincide with the point of minimum capacity.

C 293



Third point loading induces constant moment and zero shear stress over the central portion of beam. Failure is associated with the weakest point anywhere within this band. Test results in 3rd point loading are generally lower than with center point loading.



The reliability and precision of both methods can be increased measurably by conscientious attention to moisture and temperature requirements of the test method.

4.2.4 Applications to Structural Behavior

a. Flexural cracking in **reinforced** concrete members

Cracking is initiated when the concrete reaches a limiting failure strain.

b. Role of reinforcing steel in crack control

Reinforcing steel confines the concrete and inhibits concrete expansion.

c. Flexural cracking in **unreinforced** concrete members

Cracking is sudden with little warning, if any. Failure is sensitive to surface flaws.

5. Deformation of Concrete

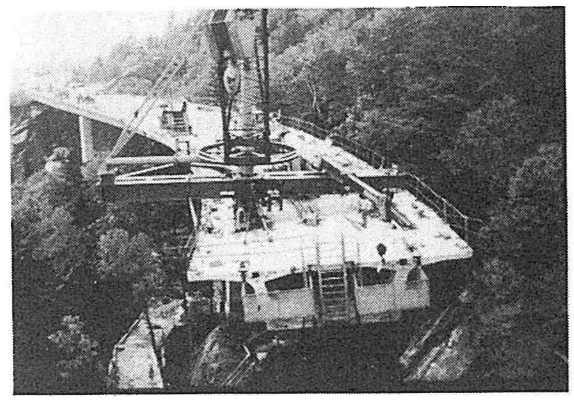
5.1 Examples of Problems Involving Deformation of Concrete

Shrinkage of pavements/Jointing

Deflection of bridge members

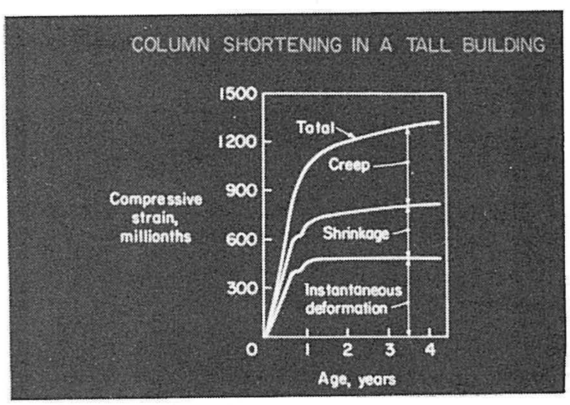
Cable-stayed bridges

Segmental bridges



5.2 Mechanisms

Final deformation is the result of a combination of individual mechanisms.



5.2.1 Instantaneous deformation

a. Concrete deformation due to deformation of supporting structure

- Formwork and shoring
- Steel girders
- Problems with skewed girders
- Settlement

b. Elastic deformation of the concrete due to self weight

c. Elastic deformation of the concrete due to construction load

5.2.2 Time-dependent deformation

a. Shrinkage

b. Elastic deformation due to time-dependent loads

c. Creep

- drying creep
- basic creep

5.2.3 Simplified basis for discussion

Shrinkage deformation is dependent on cement and concrete characteristics and on environment.

Elastic deformation is dependent on the level of applied stress and the modulus of elasticity of the concrete.

Creep deformation is dependent on cement and concrete characteristics, environment, and stress level.

5.3. Shrinkage Deformation

5.3.1 Introduction

Typical values for shrinkage strain:
200 - 1000 x 10^{-6} in/in.

Overall deformation =
shrinkage strain x length

Shrinkage stress (and cracking) develops in proportion to the degree to which the shrinkage deformations **are resisted.**

5.3.2 Factors which influence shrinkage

Material characteristics

Construction operations

Environmental conditions

Physical restraint to movement

5.3.3 Materials characteristics influencing shrinkage

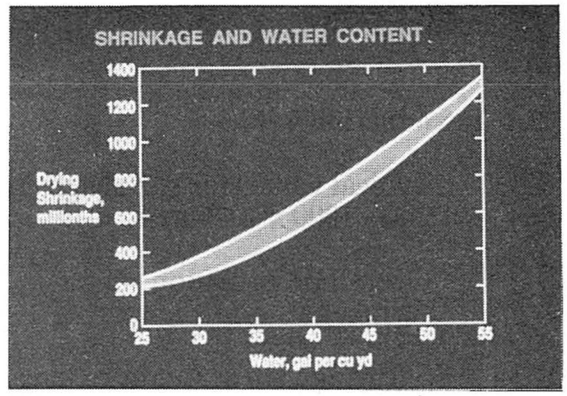
Aggregate type, quality, and cleanliness

Aggregate size

Aggregate proportions

Cement type

Total water content



CEMENT CONTENT AND DRYING SHRINKAGE*

Cement content, bags/cu yd	Water content, cu yd	Water-cement ratio	Shrinkage, %
5	0.20	0.72	0.03
6	0.21	0.62	0.03
7	0.21	0.54	0.03
8	0.21	0.46	0.03

*3x3x10-in. prisms cured wet 7 days, dried 14 days

Total paste content

Slump (???)

Admixtures

5.3.4 Construction operations influencing shrinkage

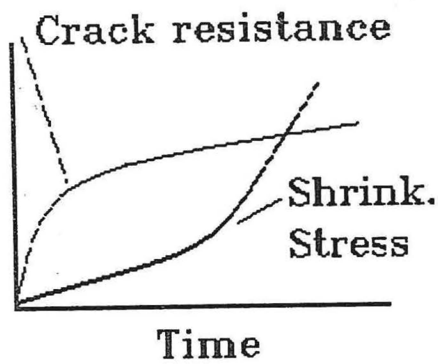
Mixing time

Concrete temperature

Water content altered for ease of placement

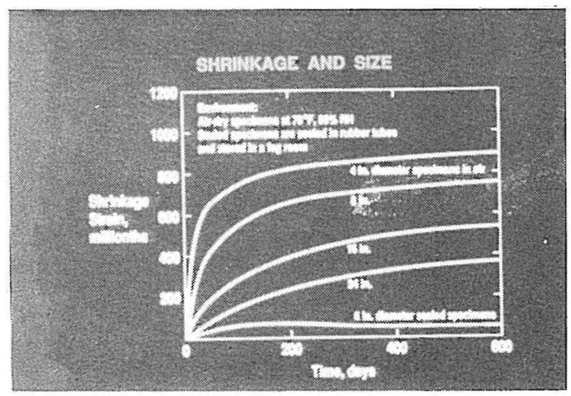
Method and duration of curing

Prevention of cracks is essentially a race to provide crack resistance prior to the development of shrinkage stresses.



5.3.5 Environmental conditions influencing shrinkage

Evaporative conditions (rate of drying and member geometry)



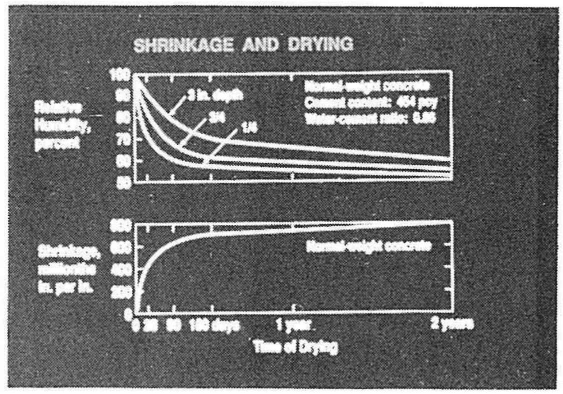
Temperature

5.3.6 Geometric interaction of effects

(Source: Tremper & Spellman, HRB 1963)

Factor	Shrinkage Increase
High temp. concrete	8%
High water content	10%
Small aggregate	25%
Overmixing	10%
High shrink cement	25%
Dirty aggregate	25%
High shrink agg.	50%
High shrink admix	30%
Combined effect	500%

5.3.7 Example of drying and shrinkage deformation as a function of time



5.4 Elastic Deformation

Elastic strain = stress divided by modulus of elasticity.

Elongation (or shortening) = strain x length

Examples:

Concrete with f'_c = 4000 psi

Modulus of elasticity (approximate) = 3600000 psi.

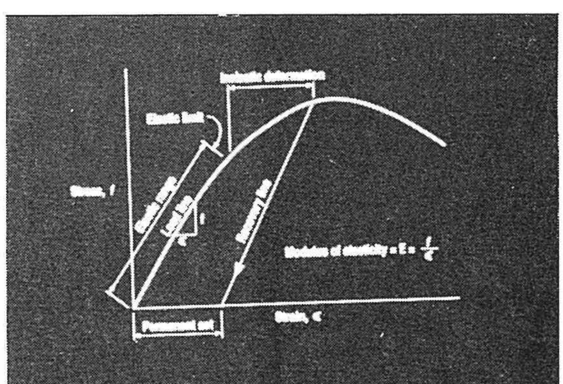
Applied compressive stress = 1000 psi

Compressive strain = 1000/3600000 = 0.028%

Shortening of a 20 foot long unreinforced column = 20 ft x 12 in x .028% = 0.06 in.

The slope or "steepness" of the stress-strain curve over the elastic range is a measure of the modulus of elasticity.

ASTM C-469 provides a method for measuring the modulus of elasticity (E_c) of concrete.



Linear materials have a fixed relationship between stress level and deformation.

Elastic materials return to their initial shape and position when the load is removed.

Linear-elastic is a simplifying assumption made for most engineering materials.

Concrete is only **approximately** linear, and only **approximately** elastic.

Factors which influence E_c include

a. aggregate E

b. mortar E

c. relative proportions

d. bond between mortar and aggregate

Factors which decrease bond strength, such as dusty aggregates, will significantly reduce the modulus of elasticity.

5.5 Creep Deformation

5.5.1 General

Similar to elastic deformation in dependence on stress level.

Continued, time-dependent deformation in response to applied stress:

a. Stress may be due to self-weight or superimposed load.

b. Stress level may change over time due to creep effects - "Stress Relaxation"

c. As a result of creep, concrete behaves over time as if it were less stiff.

d. The "**effective**" modulus of elasticity decreases with time.

5.5.2 Example of creep deformation over time

Definitions:

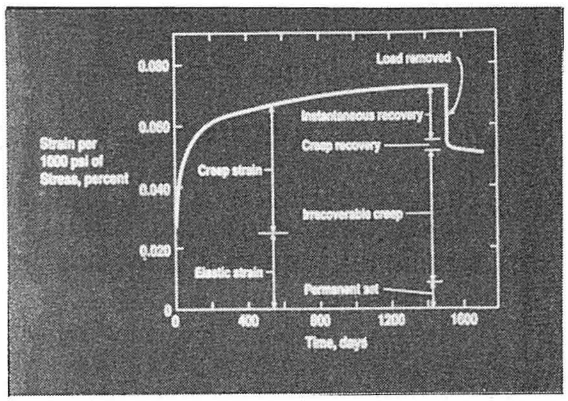
Creep strain is continued deformation with time under constant load.

Instantaneous recovery is elastic strain recovered when load is removed.

Creep recovery is creep strain recovered with time after load is removed.

Irrecoverable creep is creep strain which remains after load is removed.

Permanent set is inelastic strain which occurred at the time of loading and is not recoverable.

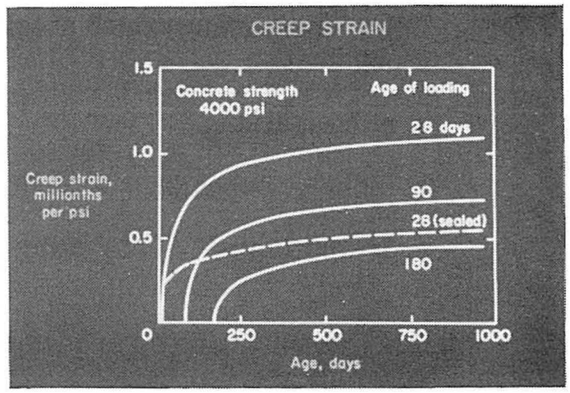


5.5.3 Types of creep

Creep can be separated into two types:

a. **Basic creep** is related solely to stress level and material characteristics (sealed conditions).

b. **Drying creep** is related to environmental conditions.



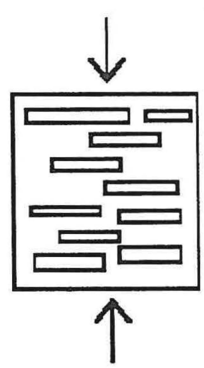
5.5.4 Mechanism

Creep is best understood by looking at the paste phase.

The porosity of paste phase permits redistribution of water under pressure.

Shock-absorber analogy

Loss of moisture to the outside accelerates process.



Other components which accelerate creep include

a. microcracking

b. inelastic behavior

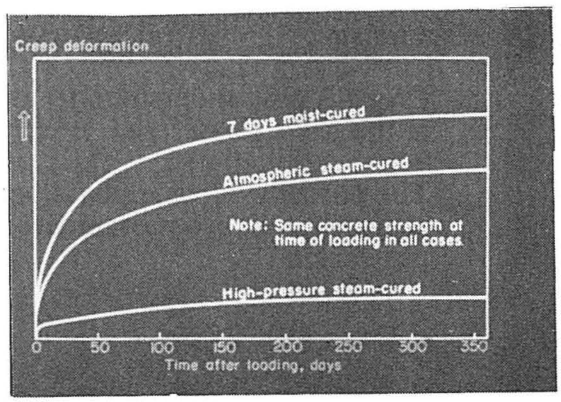
c. dissolution of CSH in paste

5.5.5 Factors influencing creep behavior of concrete

Paste content

Density of paste

Curing conditions



Aggregate characteristics

Temperature

Drying conditions

Stress levels

Concrete properties **at the time of loading**

5.5.6 Examples of typical creep characteristics

Specific creep = compressive strain / compressive stress

Specific creep values

f'_c (psi)	Specific creep (1/psi)
2000	1.4×10^{-6}
4000	0.8×10^{-6}
6000	0.6×10^{-6}
8000	0.4×10^{-6}

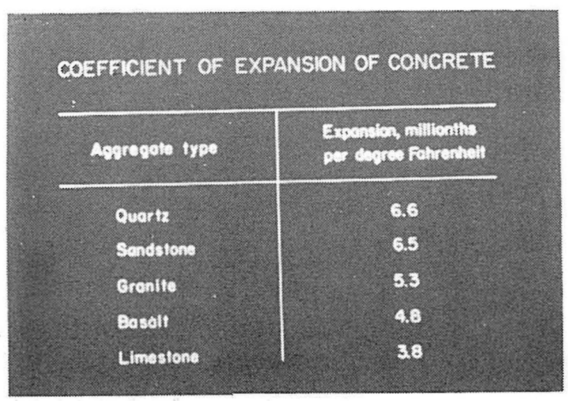
Estimated creep strain = specific creep value x compressive stress

6. Impact of Thermal Contraction and Moisture Gradients

6.1 Thermal Expansion and Contraction

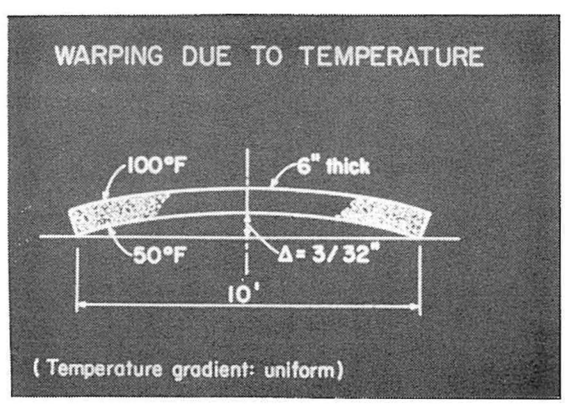
Concrete will change in dimension in response to changes in temperature

a. Coefficient of thermal expansion depends on coarse aggregate type and quantity


COEFFICIENT OF EXPANSION OF CONCRETE

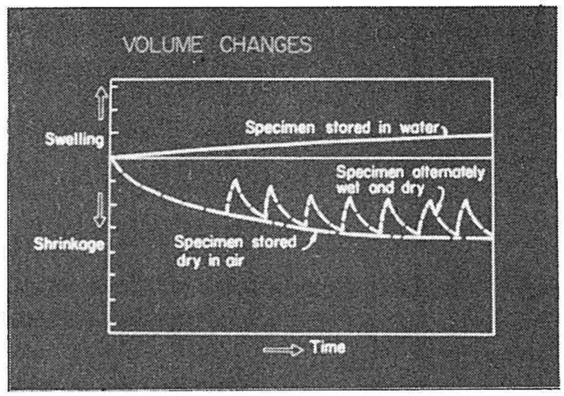
Aggregate type	Expansion, millionths per degree Fahrenheit
Quartz	6.6
Sandstone	6.5
Granite	5.3
Basalt	4.8
Limestone	3.8

b. Temperature gradients cause strain gradients which lead to curvature and warping.

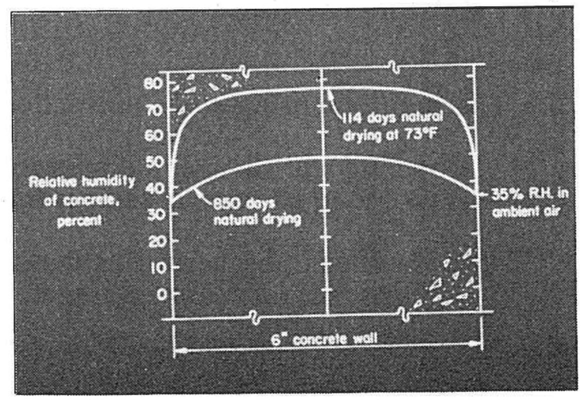


6.2 Moisture Gradients

Concrete will change dimension in response to changes in moisture content.



a. Moisture gradients develop due to non-uniform drying



b. Moisture gradients also cause strain gradients which result in curling, warping, and eventually cracking.

Suggested References

Chapter 5

1. Neville, A., Properties of Concrete, 3rd Edition. Pitman Publishing, 1981.
2. ACI Committee 224, Control of Cracking in Concrete Structures. American Concrete Institute, 1982.
3. Nilson, A.H., and G. Winter, Design of Concrete Structures, 10th Edition. McGraw-Hill Publishing Co., 1986.
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5. Mindess, S., and F. Young, Concrete. Prentice-Hall, 1981.

Chapter 6

Freeze-Thaw Durability

Instructional Objectives:

1. Describe the fundamental mechanisms of frost damage in concrete.

   Paste damage:

   Hydraulic pressure
   Ice accretion
   Osmotic Pressure

   Aggregate damage:

   unsoundness
   pop-outs
   D-cracking

2. Describe the selection of frost-resistant aggregates.
3. Describe the role of air voids in hardened cement paste.
4. Describe and explain the rationale for desirable air void system parameters.

(More on the evaluation of air void systems in laboratory sessions)

Desired Student Achievements:

1. Describe the mechanisms of frost damage in concrete.
2. Describe how to select frost-resistant aggregate.
3. Describe how entrained air provides for frost resistance.
4. Describe typical characteristics of an acceptable air void system.
5. Describe pitfalls in assessing frost resistance in fresh and hardened concrete.

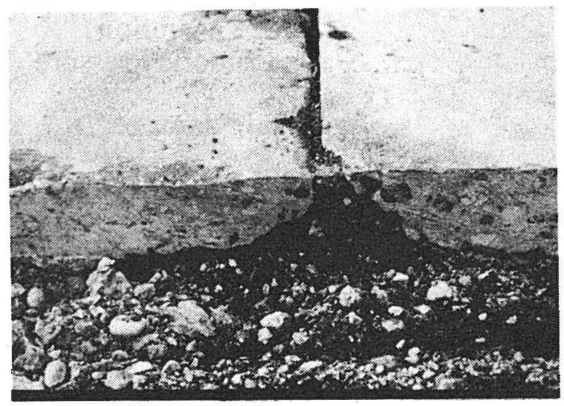
Chapter 6

Freeze-thaw Durability

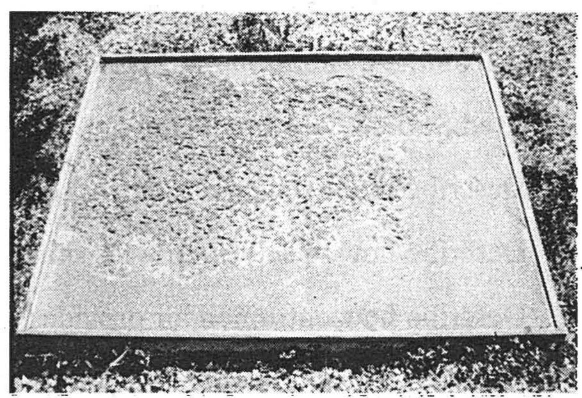
1. Examples of Frost Damage

Frost damage occurs when frost-susceptible paste, frost-susceptible aggregate, or both are present.

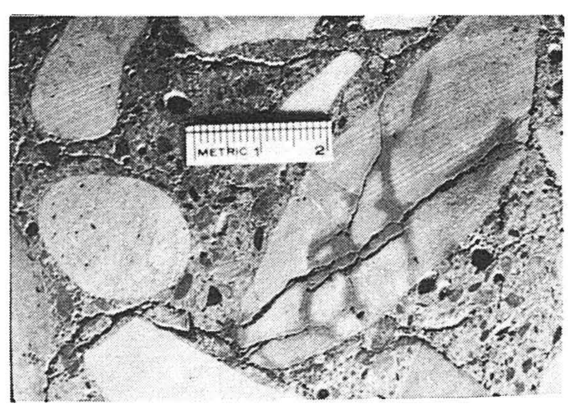
- Frost damaged paste



- Scaling



- Aggregate cracking



∘ D-cracking

2. Frost Damage in Concrete

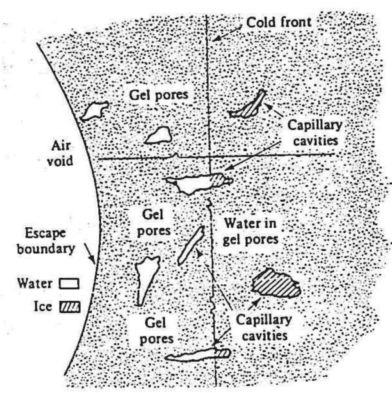
2.1 Frost Damage in Hardened Cement Paste

2.1.1 Review of Cement Paste Microstructure

a. Gel pores

Gel pores are interstitial voids **within** the CSH gel.

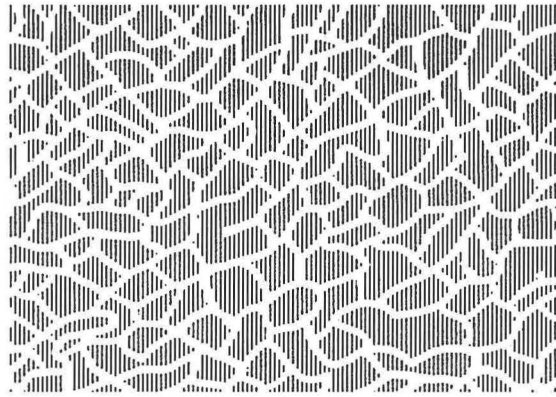
Gel pores comprise approximately 27% of the gel volume.



b. Capillaries

Capillaries are spaces (voids) in the **paste** volume which contained water in excess of that required for hydration.

The volume of capillaries increases with increasing w/c ratio.



2.1.2 Mechanisms of Frost Damage

a. Critical saturation

When ice freezes, its volume increases by about 9%.

If a closed vessel containing water is more than 91.7% full, freezing (and the subsequent expansion of the water) will cause stress in the vessel.

b. Hydraulic pressure

Stress develops due to unfrozen water moving through pores during freezing.

Factors that increase hydraulic pressure include

- longer flow path
- higher rate of freezing
- lower permeability
- higher concentration of salts in pore solution

Damage increases as the number of freeze-thaw cycles increases.

c. Osmotic pressure/ice accretion

Water moves from the gel to the capillaries in order to satisfy thermodynamic equilibrium and to equalize alkali concentrations.

If air voids are not present, the capillaries fill with water and ice. Pressure builds up and damages the paste.

If air voids are present, water will flow from the gel and the capillaries into the air voids, where it has room to freeze without damaging the paste.

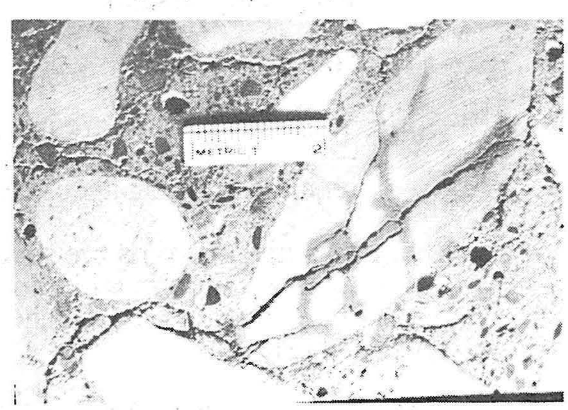
Osmotic pressure may be a major factor in "salt scaling."

2.2 Frost Damage in Aggregates

Frost damage in aggregates depends on porosity, absorption, permeability, and pore structure.

The critical saturation and hydraulic pressure concepts apply to aggregate.

Coarse aggregates with high porosity and medium-sized pores are often most susceptible.

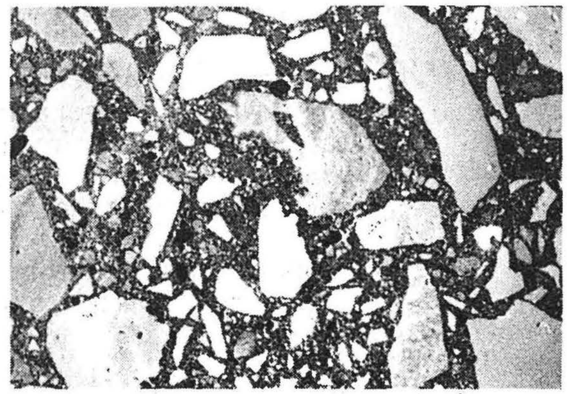


3. Characteristics of Frost Resistant Concrete

3.1 Air Entrainment and the Air Void System

3.1.1 Air voids

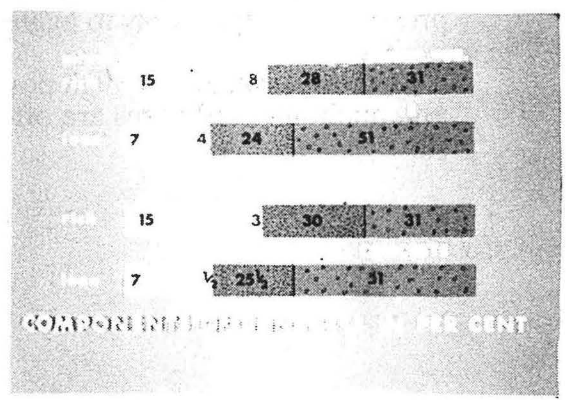
Air voids are on the order of 100 times larger than capillaries.



Entrapped air voids

a. Entrapped air voids are unintentional; they occur in **all** concrete.

b. Entrapped air voids are large (greater than 1000 microns) and irregularly shaped



Entrained air voids

a. Entrained air voids are intentional -- their formation requires use of an air entraining agent (AEA).

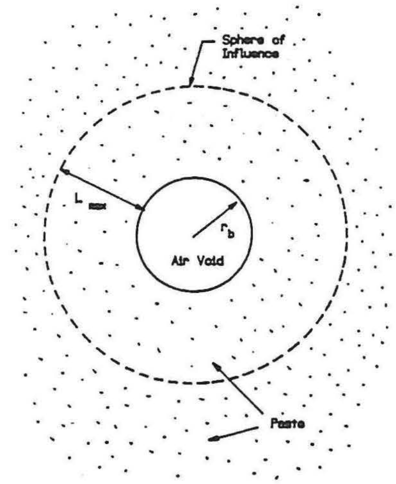
b. Entrained air voids are small (10 to 1000 microns, with most less than 100 microns) and nearly spherical.

Role of air voids in frost resistance

a. Air voids act as "relief sites" for hydraulic pressure

More air voids mean a shorter average flow path to relief sites.

b. "Protected paste" concept



Each air void protects a spherical shell of paste surrounding it.

For a given air content, a larger number of small voids protects more paste.

3.1.2 Air entraining agents (AEA)

Terminology

In a concrete mix, an air entraining agent is considered an **admixture.**

In dry cement, an air entraining agent is an **addition.**

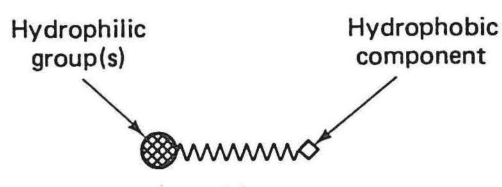
In AASHTO M-85 and ASTM C-150, air-entraining cements are classified as Types IA, IIA, IIIA, IVA and VA.

Air entraining admixtures are preferred over air-entraining cements because they allow better control of the final product.

Description

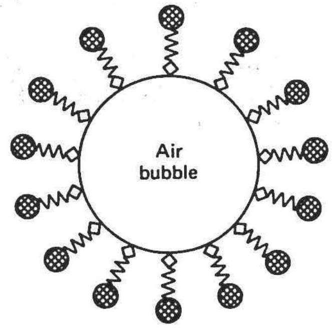
Air entraining agents are surface active agents ("surfactants"). Examples of surfactants are salts, detergents, and resins.

Air entraining agents have a polar end (hydrophilic) and a non-polar end (hydrophobic).



Action

a. Micelle formation: polar ends in water, non-polar ends away from water.



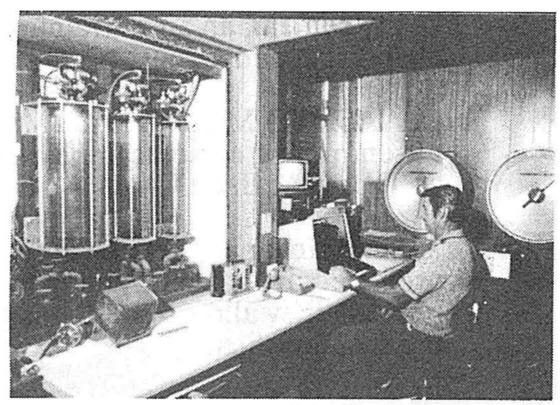
b. Reduced surface tension at air-water interface.

c. Foaming action.

d. Formation of billions of bubbles on the order of .002" in diameter.

Typical quantities

Usual batching proportions are on the order of .01% to .05% AEA by weight of cement.

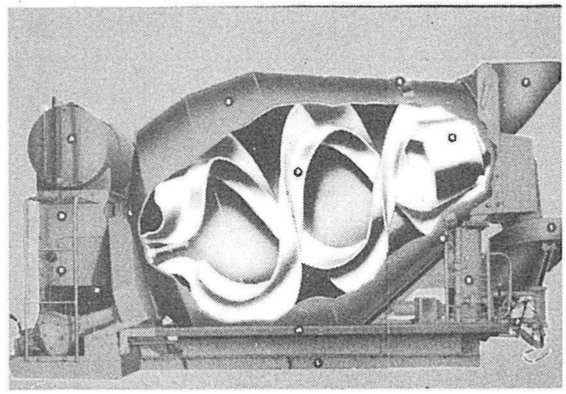


For average air entrainment of 3 to 5 percent, a typical dosage is about 1/4 ounce of AEA per sack of cement.

For such small quantities, measurements must be very accurate.

3.1.3 Formation of the air void system

Air is incorporated into all concrete (air-entrained or not) during mixing.



An AEA helps to **create** and **stabilize** a system of many small bubbles by

a. reducing surface tension, which allows very small bubbles to form.

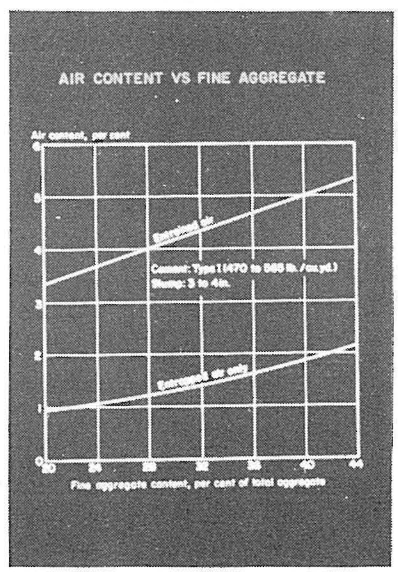
b. preventing coalescence.

c. preventing loss due to buoyant rise by anchoring bubbles to sand particles.

3.1.4 Factors affecting air entrainment

Materials/batching

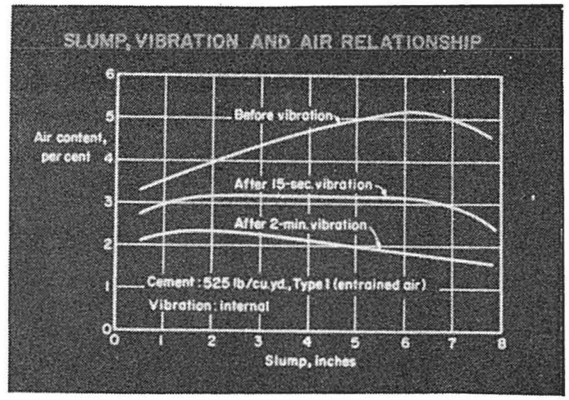
a. Amount of sand passing #30 to #50 sieve



b. Fine/coarse aggregate ratio

c. Cement, flyash, or other <#200 fines

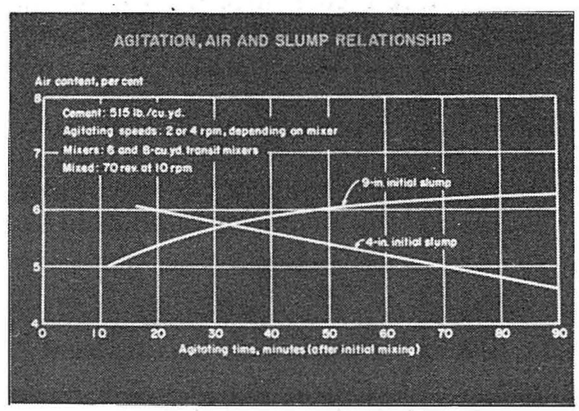
d. Slump



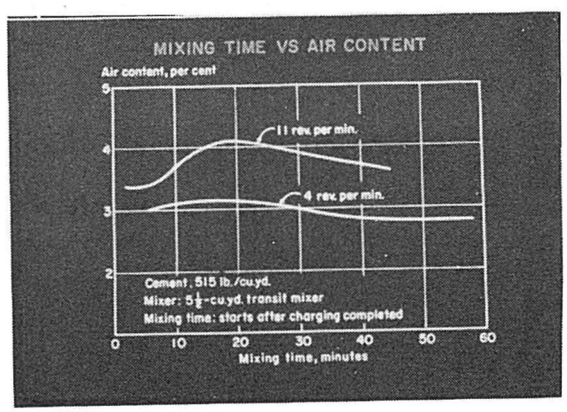
e. Quantity and type of AEA

Mixing and transporting

a. Agitation during mixing



b. Mixing time



c. Sharpness of mixer blades

d. Haul time

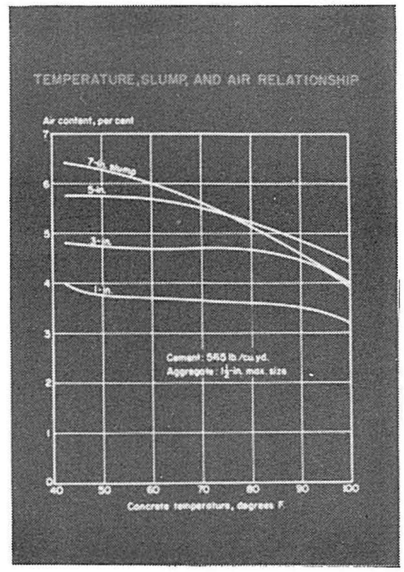
Placing

a. Pumping

b. Finishing

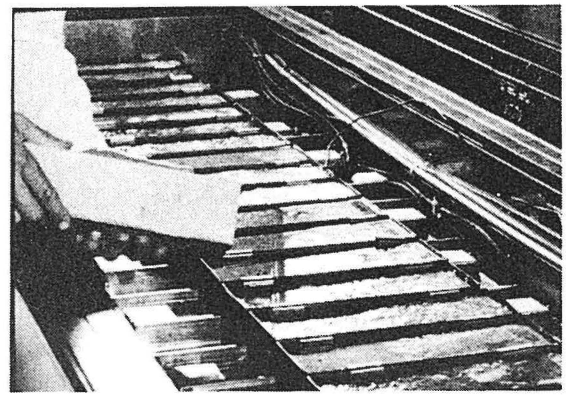
c. Consolidation

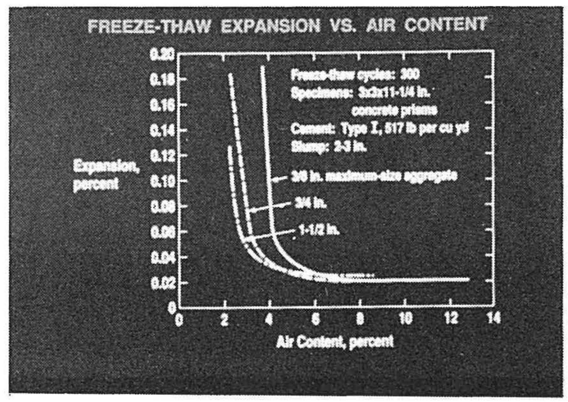
d. Temperature

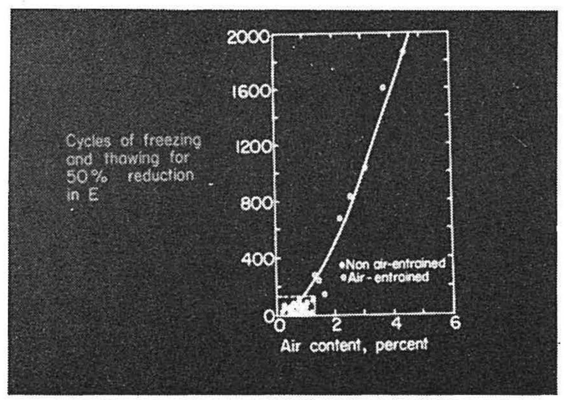


3.1.5 Effects of air entrainment

Increased freeze-thaw durability.





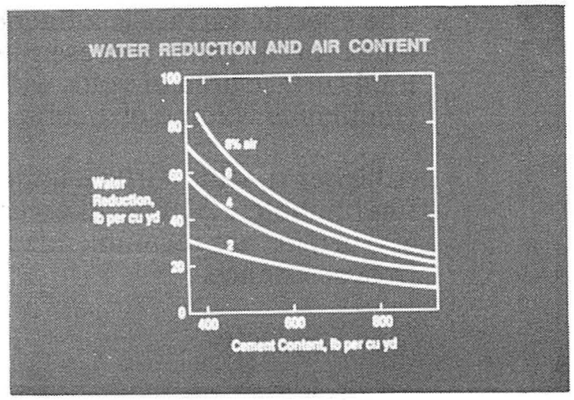


Increased sulfate resistance.

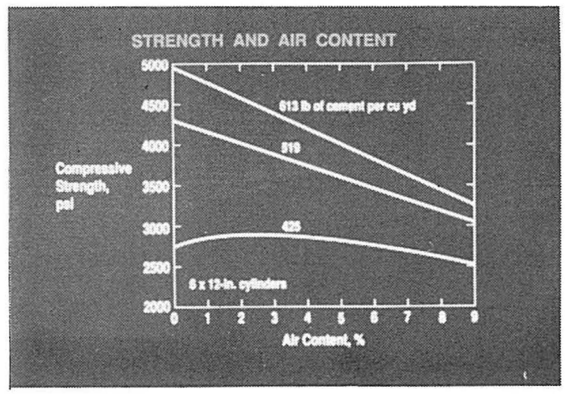
Increased workability (fresh).

Reduced strength.

a. Since AEA's increase workability, the water requirement can be reduced. If you take advantage of this, you can offset the strength loss due to reduced density.



b. If you do not reduce the amount of water, addition of entrained air will reduce strength.



3.1.6 Characteristics of an adequate air void system

Number of air voids (bubbles)

In frost-resistant concrete, there are approximately 10 billion bubbles per cubic yard of concrete, occupying 4 to 9 percent of the concrete volume.

Size of air voids and "specific surface"

The average air void size is approximately .002" in diameter.

Smaller bubbles are more effective in preventing frost damage. They also have a less adverse impact on strength.

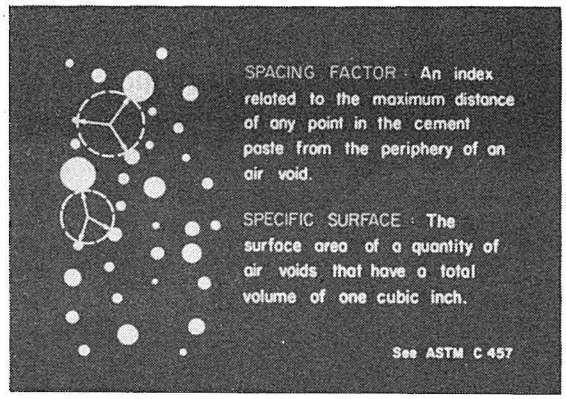
The **specific surface** is a fineness index for air voids, representing the total surface area of voids with a cumulative volume of 1 cubic inch.

A higher specific surface indicates finer bubbles. Values in excess of 600 in^2/in^3 are recommended for frost resistance.

"Spacing factor"

The spacing factor is a relative measure of the distance water has to travel to reach an air void.

A spacing factor of .008 inches or less is recommended for frost resistance.



3.1.7 Measuring the air void system

Air void system parameters

The following "parameters" are used to describe air void systems:

Air content
The volume of air (in percent) per unit volume of concrete.

Voids per inch
The number of voids intercepted per inch of traverse line in a linear traverse.

Mean chord length
The average length of chords intercepted in a linear traverse.

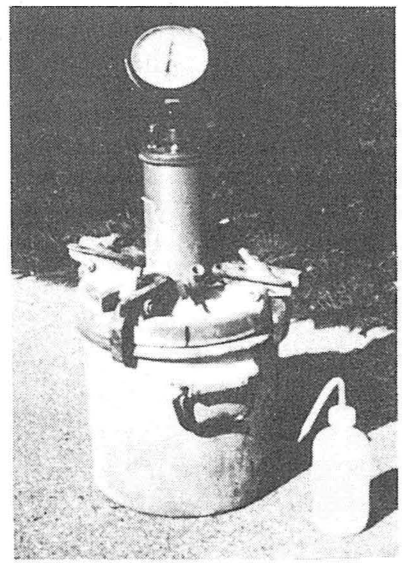
Specific surface
The total surface area of air voids divided by the total volume of air.

Spacing factor
A derived index related to the maximum distance of any point in the paste to the edge of an air void.

Measurement in fresh concrete

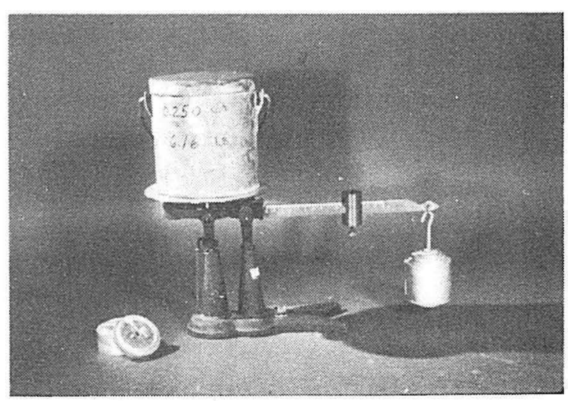
(NOTE: These tests give air content only!)

Pressure method
AASHTO T-152
ASTM C-231



Volumetric method "roll-o-meter"
AASHTO T-196
ASTM C-173

Unit weight (gravimetric) method
AASHTO T-121
ASTM C-138



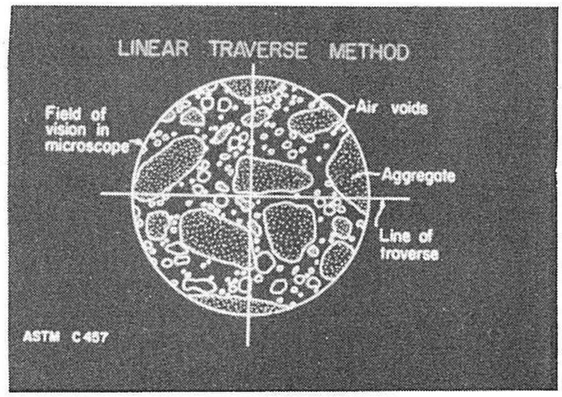
Measurement in hardened concrete

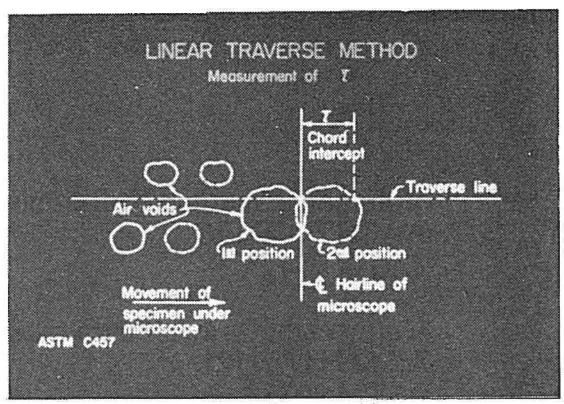
a. Microscopical analysis (ASTM C-457)

The samples used are polished plane sections of concrete.

Two methods are described in ASTM C-457:

The **linear traverse** measures the number and lengths of **chords** intercepted by a series of lines crossing the plane surface.





The **modified point count** counts the number of points on a rectangular grid which fall on each constituent (i.e., paste, aggregate, air) and the number of voids crossed while moving from point to point.

b. High-pressure air meter

3.2 Frost Resistant Aggregate

3.2.1 Factors influencing aggregate frost resistance

Type of aggregate

Aggregate porosity and permeability

Aggregate size effects

3.2.2 D-cracking

D-cracking is caused by freezing of coarse aggregate with a poor pore system near the bottom of a slab where moisture content remains high. Cracks propagate upwards to the surface.

The following tests have been used to detect vulnerable aggregate:

a. AASHTO T-161

Freezing and thawing with 90-day moist cure

b. Iowa Pore Index test

c. Mercury porosimetry determination of pores in the 0.04 to 0.2 micron radius range.

Field service record can be helpful. Some aggregates which cause D-cracking can be used if crushed to a smaller size.

3.2.3 Tests for frost resistance of aggregates

Freeze-thaw tests (see Section 3.3)

Soundness tests (see Section 3.3)

Refer to ASTM paper by Vogler and Grove (Reference 4)

3.2.4 Research in progress

Influence of aggregate chemistry

Influence of pavement geometry

Influence of de-icing salts

3.3 Tests for Frost Resistance of Concrete

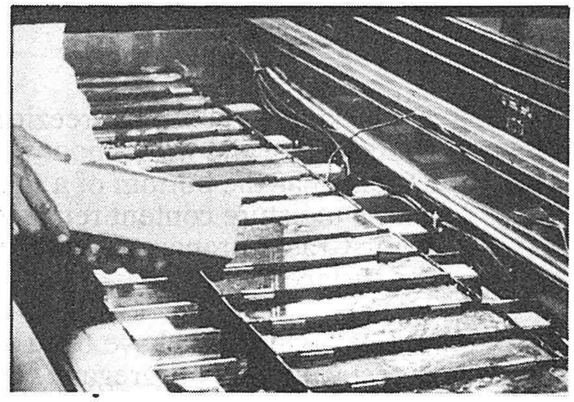
Resistance of Concrete to Rapid Freezing and Thawing
AASHTO T-161
ASTM C-666

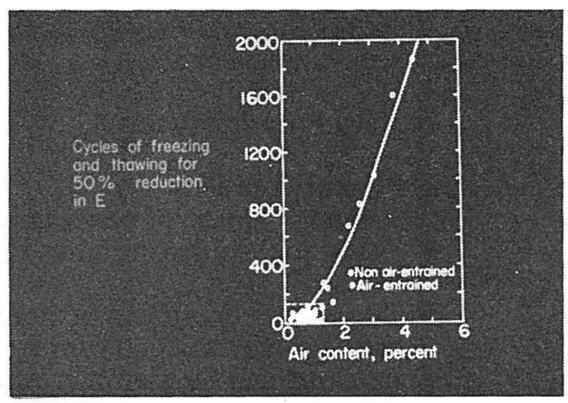
Procedure A: freezing and thawing in water.

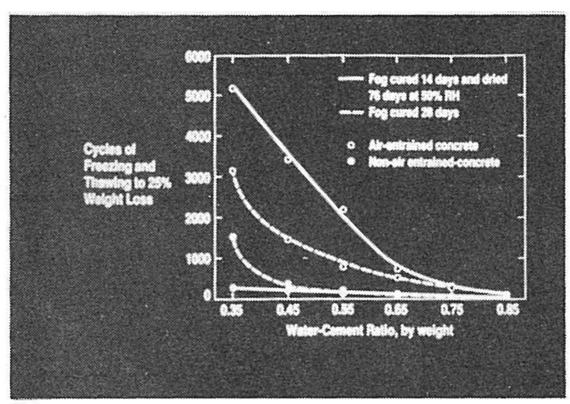
Procedure B: freezing in air, thawing in water.

Both procedures require 300 cycles from 0 to 40 F, at a rate of 2-5 hours per cycle.

Damage is measured by decrease in dynamic modulus, weight loss, and length change.





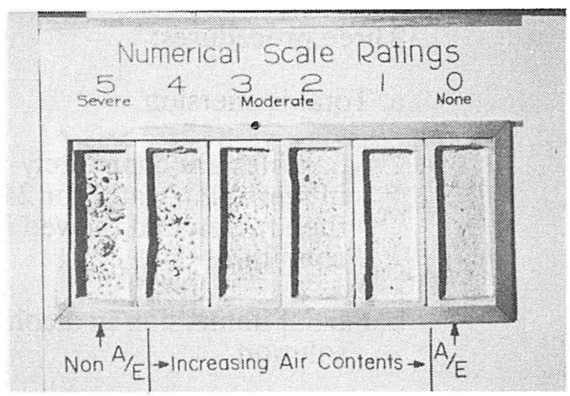


If an adequate air void system is present, excessive damage may indicate frost-susceptible aggregates.

Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
ASTM C-672

Surface is covered with solution of calcium chloride and subjected to cycles of freezing for 16-18 hours and thawing for 6-8 hours.

Visual examination is performed after every five cycles and specimens are rated (0 = no scaling; 5 = severe scaling)



Critical Dilation of Concrete Specimens Subjected to Freezing
ASTM C-671

This procedure evaluates the length change of concrete specimens with decreasing temperature, as distinct from thermal contraction.

Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
AASHTO T-104
ASTM C-88

This procedure calls for repeated immersion of aggregate in saturated solutions of sodium or magnesium sulfate.

The pressure in aggregate pores from salt crystal growth simulates the pressure from ice crystal growth during freezing.

The results of this test are not always consistent with actual freeze-thaw behavior.

Soundness of Aggregates by Freezing and Thawing
AASHTO T-103

Three procedures:

a. Total immersion

Samples are completely immersed in water for 24 hours, then frozen and thawed in this condition.

b. Partial immersion in alcohol-water solution

Samples are saturated under pressure and frozen in 1/4" deep solution.

c. Partial immersion in water

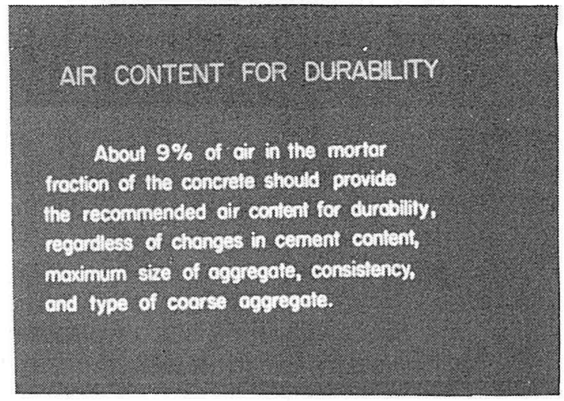
Samples are saturated under pressure and frozen in 1/4" deep water.

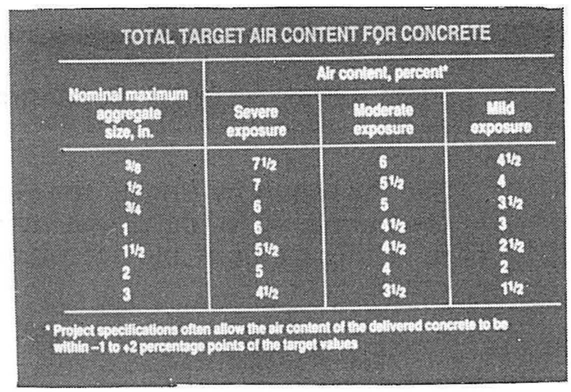
After required number of cycles, samples are sieved to determine loss.

4. Specifications

4.1 Specifying frost-resistant concrete

Total vs. entrained air



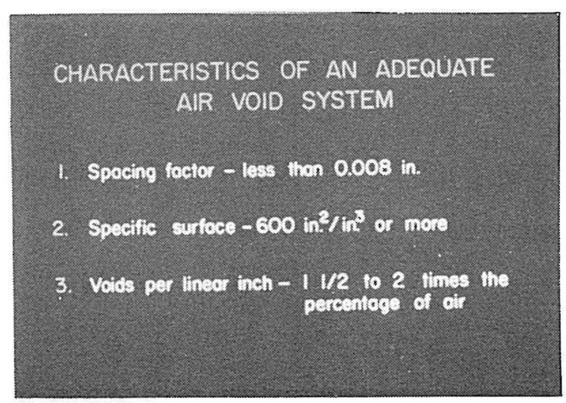


TOTAL TARGET AIR CONTENT FOR CONCRETE

Nominal maximum aggregate size, in.	Air content, percent*		
	Severe exposure	Moderate exposure	Mild exposure
3/8	7 1/2	6	4 1/2
1/2	7	5 1/2	4
3/4	6	5	3 1/2
1	6	4 1/2	3
1 1/2	5 1/2	4 1/2	2 1/2
2	5	4	2
3	4 1/2	3 1/2	1 1/2

* Project specifications often allow the air content of the delivered concrete to be within –1 to +2 percentage points of the target values

Air void system parameters



Tolerances

Field data: air content of central mix concrete by pressure meter.

Average = 5.5%

0.8% standard deviation

99% confidence interval is 3.4% to 7.6%.

Sampling

Since handling can modify air void system, location of sampling can be important.

4.2 Specifying frost-resistant aggregate

Field service record is the most reliable data.

See the report by Vogler and Grove (Reference 4) for details on variations in testing methods and acceptance criteria.

Suggested References

Chapter 6

1. Whiting, D. and D. Stark, Control of Air Content in Concrete. NCHRP Report 258, 1983.

2. Cordon, W.A., Freezing and Thawing of Concrete, Mechanisms and Control. Monograph No. 3, American Concrete Institute, 1966.

3. Powers, T.C., "The Air Requirement of Frost Resistant Concrete." HRB Proceedings, Volume 29, 1949, pp. 184-211.

4. Vogler, R.H., and G.H. Grove, "Freeze-Thaw Testing of Coarse Aggregate in Concrete: Procedures Used by Michigan Department of Transportation and Other Agencies." Cement, Concrete, and Aggregates, American Society for Testing and Materials, Summer, 1989.

5. ACI Committee 201, Guide to Durable Concrete. American Concrete Institute, 1982.

Chapter 7

Other Durability Problems

Instructional Objectives:

1. Introduce the most common forms of concrete deterioration:

    Alkali-aggregate reaction
    Sulfate Attack
    Aggressive chemical exposure
    Salt effects (in addition to corrosion)
    Abrasion Resistance

2. Describe fundamental mechanisms of each.

3. Describe how to recognize each form of deterioration.

4. Describe methods of prevention.

5. Describe methods of mitigation.

Desired Student Achievements:

1. From slides, photographs, or hand-samples, recognize various forms of deterioration.

2. Describe the fundamental mechanisms involved in each form of deterioration.

3. Describe quality control/materials selection procedures to prevent such deteriorative mechanisms.

4. Describe remedial or mitigating actions for structures exhibiting signs of distress.

Chapter 7

Other Durability Problems

1. Introduction

1.1 Common Features of Deterioration Mechanisms

Each causes restrained, non-uniform volume change in paste, aggregate or both.

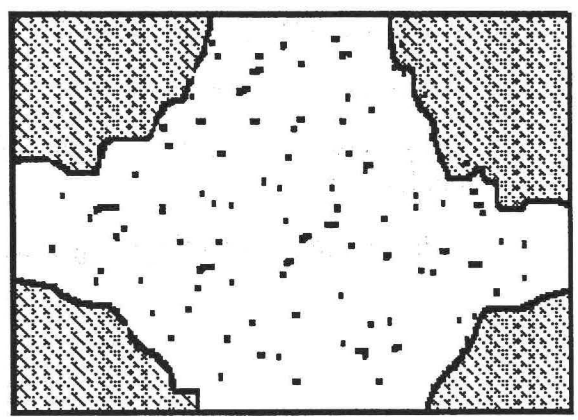
Each requires the presence of moisture.

Each requires penetration of water and other agents into the concrete.

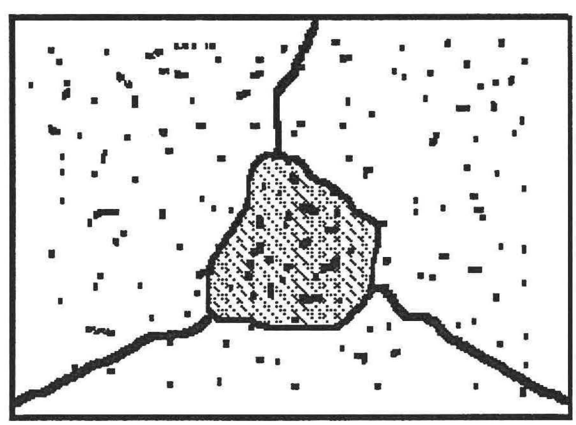
1.2 Examples

1.2.1 Freeze-thaw (discussed in Chapter 6)

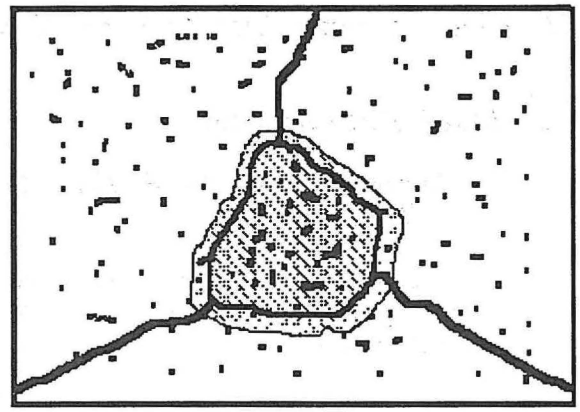
Porous paste



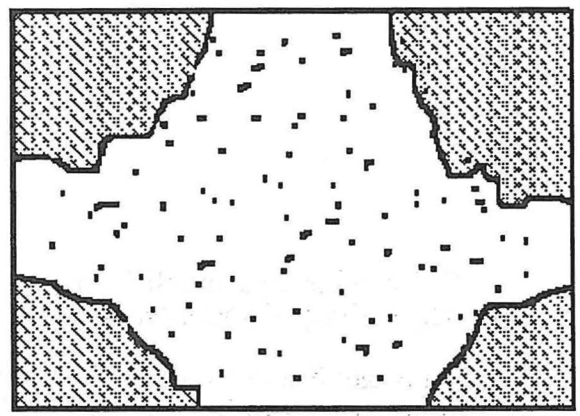
Porous aggregate



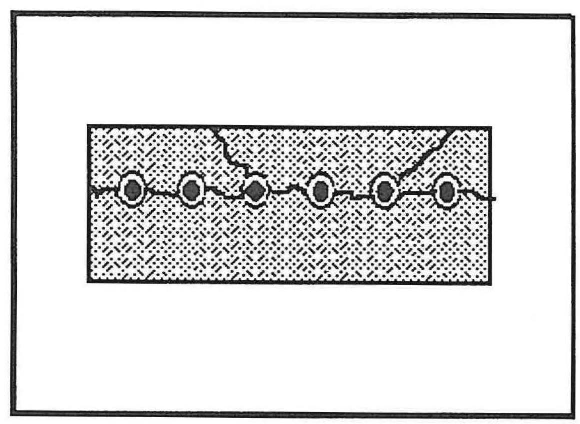
1.2.2 Alkali-aggregate reaction (silicate or carbonate)



1.2.3 Sulfate attack



1.2.4 Corrosion of reinforcing steel

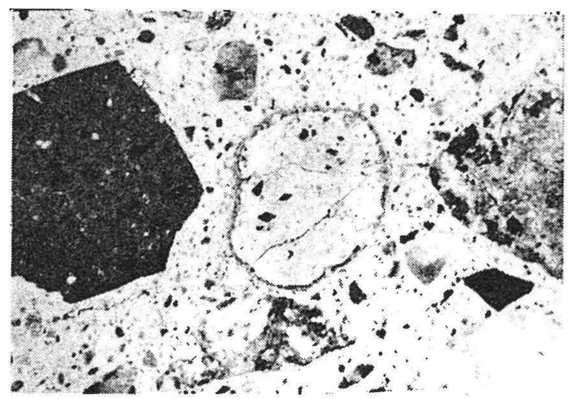


2. Alkali-aggregate Reaction (AAR, ASR)

2.1 Alkali-Silica Reaction

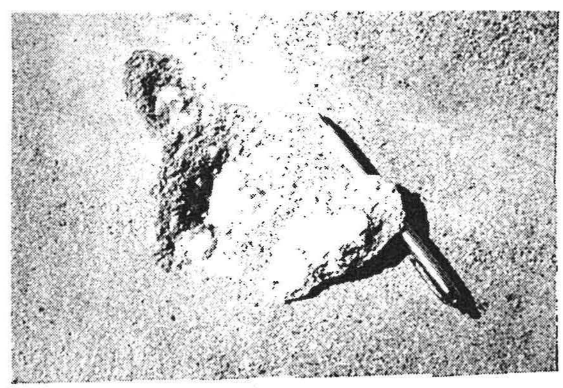
Cement contains alkali oxides (Na_2O, K_2O, etc.).

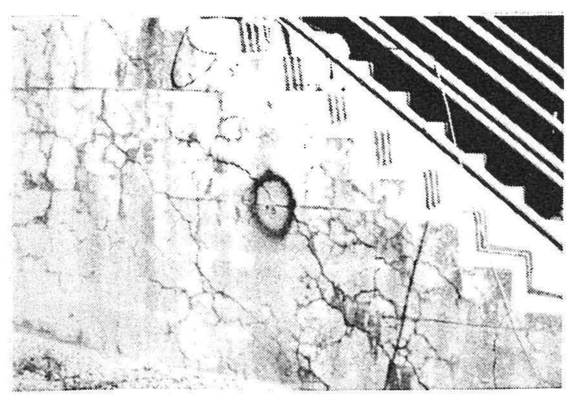
Alkali oxides react with "reactive silica" in aggregate in the presence of water to form alkali-silica "gel."



Silica gel is "hydrophilic" -- it aggressively absorbs water.

Since gel is more viscous than water, the water cannot diffuse back through pores. Osmotic pressure develops, causing cracking.





2.2 Key Issues

2.2.1 Alkali content of cement

Alkali content is fairly easy to measure and control.

Equivalent Na_2O = [Na_2O + $0.685K_2O$]

a. **Low** alkali cement = < 0.6% equivalent Na_2O

b. **High** alkali cement = > 0.6% equivalent Na_2O

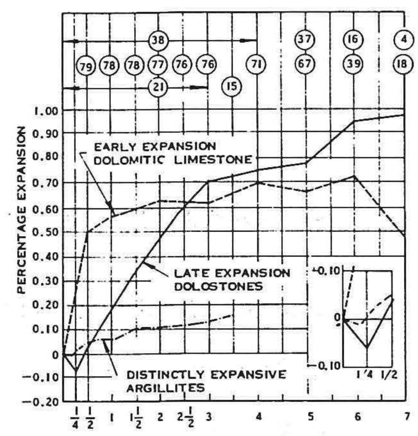
AASHTO M-85 and ASTM C-150 optional *requirements!*

2.2.2 Reactivity of aggregate

Methods of testing

a. Petrographic examination
ASTM C-295
ASTM C-856

b. Rock cylinder test



c. Quick chemical test
ASTM C-289

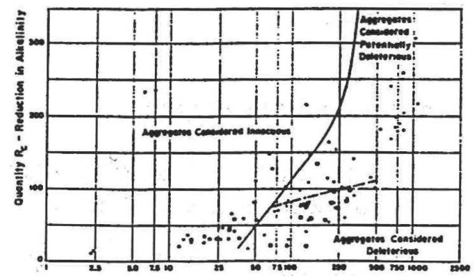
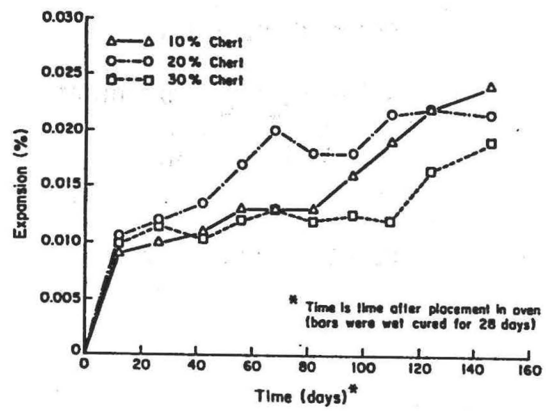


FIG. 2 Illustration of Division Between Innocuous and Deleterious Aggregates on Basis of Reduction in Alkalinity Test

d. Mortar bar test
ASTM C-227



e. Test aggregate in concrete

Factors affecting reactivity:

a. Percent aggregate in mix

b. Size gradation

c. Dispersion

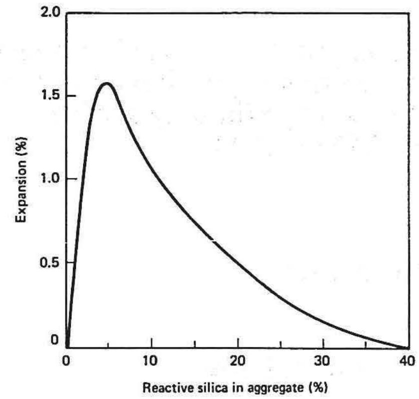
d. Moisture content

e. Temperature

f. Time (delayed reaction)

2.2.3 "Pessimum" concentration

The number of reaction sites can control the severity of the reaction.



2.2.4 Helpful effects of flyash and other pozzolans

a. Dilute cement

b. Dilute aggregate (??)

c. React with alkalies

2.2.5 Effectiveness of testing

Lab simulation of field conditions is very difficult:

a. time

b. temperature

c. moisture

Petrographic analysis may be the most effective tool.

2.3 Alkali-Carbonate Reaction

A rare condition involving coarse aggregate which is about half calcium carbonate and half dolomite, and which is intruded with clay minerals.

Such aggregate is usually unsuitable for physical rather than chemical reasons.

Susceptibility to reaction is tested by measuring expansion of rock prisms stored in sodium hydroxide (ASTM C-586).

3. Sulfate Attack

3.1 Sources of sulfates

Sulfate soils

Groundwater

Wastewater

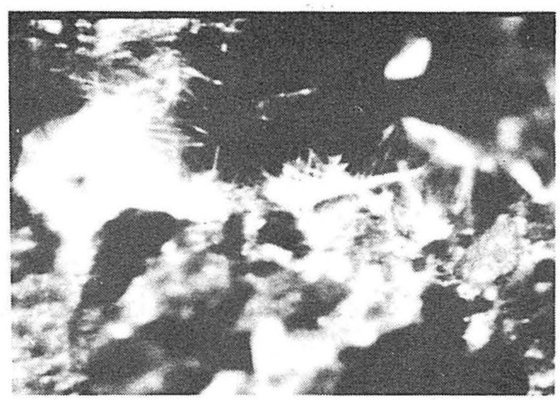
Acid rain

Deicing salts

Seawater

3.2 Mechanism

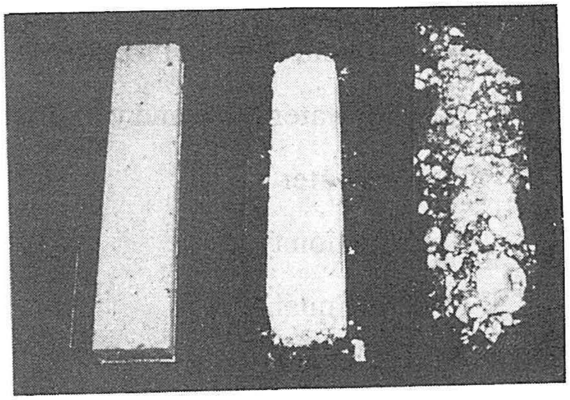
Deleterious reaction between hardened cement paste (C_3AH) and sulfate ions.

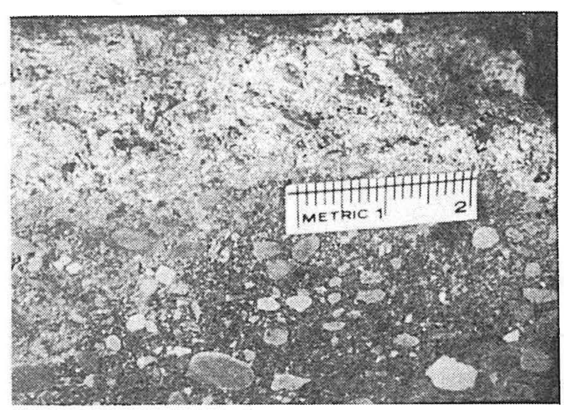


Two forms of deterioration can occur:

a. **Expansion** due to growth of ettringite crystals.

b. Weakening of cement paste **without** expansion -- conversion of $Ca(OH)_2$ to $CaSO_4 \cdot 2H_2O$ (gypsum).





Normal protection is the use of sulfate resistant cement (low C_3A), but tests have shown that paste permeability may be more important than cement chemistry.

For example, Verbeck (1968 California tests) found that a 7 sack mix with 10% C_3A performed 2-3 times better than 5.5 sack mix with 4% C_3A.

3.3 Factors

Amount and nature of sulfate

Level of water table and variation

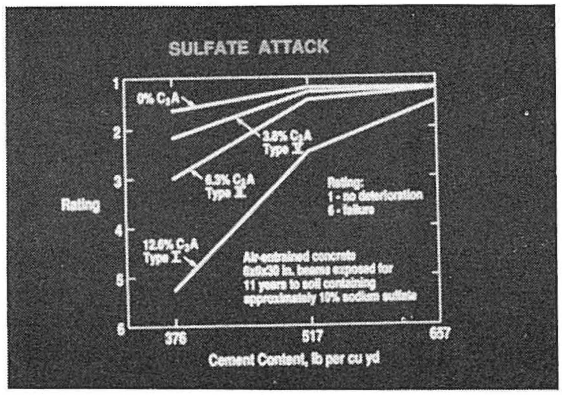
Flow of water

Construction type

Concrete quality

Cement

For moderate sulfate exposure (150 to 1500 ppm), keep $C_3A < 5\%$.



For high sulfate exposure (>1500 ppm):

a. Even Type V may not be enough.

b. Need to reduce $Ca(OH)_2$ content

c. Reduce C_3S

d. Use flyash, slag, or pozzolan -- pozzolans remove $Ca(OH)_2$ and lower permeability.

3.4 ACI Requirements for Concrete Exposed to Sulfates

CEMENTS FOR SULFATE EXPOSURES

Sulfate exposure	SO_4 in soil, %	SO_4 in water, ppm	Cement type
Negligible	0.00–0.10	0–150	—
Moderate*	0.10–0.20	150–1500	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)
Severe	0.20–2.00	1500–10,000	V
Very severe	Over 2.00	Over 10,000	V plus pozzolan**

* Seawater

** Pozzolan that improves sulfate resistance with Type V cement

4. Abrasion Resistance

4.1 Introduction

4.1.1 Typical causes

a. Traffic on a surface

- heavy vehicles
- light vehicles
- foot traffic

b. Air or waterborne particles

Abrasion, erosion, wear, and cavitation are special topics for hydraulic structures.

4.1.2 Four classifications

a. Wear on floors

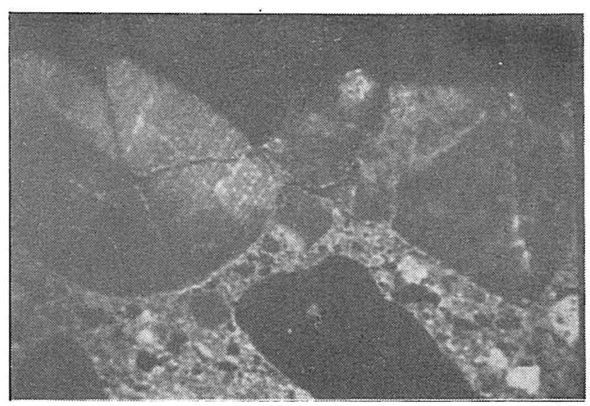
b. Wear on pavements due to studded tires and chains

c. Erosion in hydraulic structures

d. Cavitation in hydraulic structures

4.2 Mechanism

Abrasion resistance is **very sensitive** to the wearing mechanism.



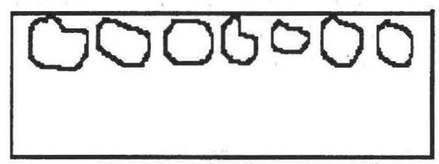
Significant penetration in depth requires wearing away both **paste** and **aggregate.**

Some forms of wear will only go as far as the aggregate layer.

Other forms of wear can reach beyond aggregate -- erosion of hydraulic structures by water and water-borne particles is severe for this reason.

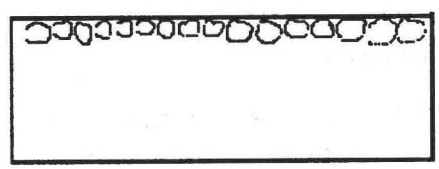
Large aggregate

Large Aggregate
Effect at surface



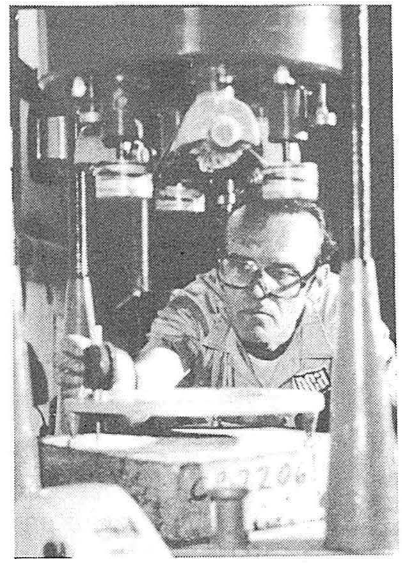
Smaller aggregate

Small Aggregate
Effect at surface



4.3 Tests

Abrasion on horizontal concrete surfaces
ASTM C-779



Three optional procedures:

a. Revolving disk

b. Dressing wheel

c. Ball-bearing machine

Match the abrasion test method to the type of wear anticipated.

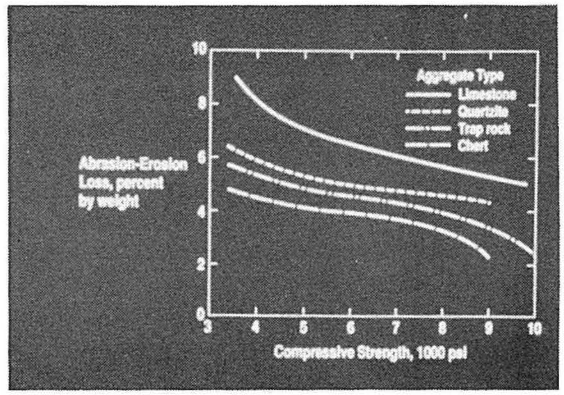
Abrasion test results are relative.

Test results should not be used to estimate service life.

Field observations and data are more reliable than lab tests.

4.4 Factors Affecting Abrasion Resistance

Compressive strength of paste and aggregate



Material properties of paste and aggregate

a. The essential issue is paste and aggregate properties **at the surface** -- bulk properties can be misleading.

b. Aggregate effects are less pronounced as the strength of the mix increases.

Mix proportions

Aggregate size

Finishing method and timing

a. Wait until bleed water is gone.

b. Don't sprinkle water on slab.

Curing

a. Start immediately.

b. Cure as long as possible.

c. Abrasion resistance after a 7-day wet cure is twice that after 3 days.

4.4.7 Surface treatments

A variety of surface treatments including coatings, penetrants, and liquid and solid hardeners are available.

These are effective to various degrees in reducing wear due to abrasion, in addition to reducing scaling and the ingress of water and deicing chemicals.

4.5 Pavements

Abrasion can cause a loss in skid resistance.

Some surface textures with high initial friction numbers suffer significant loss in skid resistance in the first 3 years of service.

See the report of ACI Committee 325 (1988) for more information.

Suggested References

Chapter 7

1. ACI Committee 201, Guide to Durable Concrete. American Concrete Institute, 1982.

2. Scanlon, J., Concrete Durability. SP-100, American Concrete Institute, 1987.

3. Durability of Concrete. SP-47, American Concrete Institute, 1975.

4. Dolar-Mantvani, Handbook of Concrete Aggregates, NOYES Publishers, 1983.

5. ACI Committee 201, Guide for Making a Condition Survey of Concrete Pavements. American Concrete Institute, 1987.

Chapter 8

Corrosion of Reinforcing Steel

Instructional Objectives:

1. Review the fundamental nature of electrochemical corrosion in general from the presentation in the Metals Module.
2. Present additional fundamental information and as it applies to reinforcing and prestressing steel and other metals in concrete.
3. Describe the role of chlorides, as in deicing salts, marine exposure, impurities in raw materials, and as a chemical admixture.
4. Describe the fundamental mechanism of corrosion and subsequent deterioration of surrounding concrete.
5. Describe techniques for preventing or controlling corrosion:

    New concrete:

    - Epoxy coated bars
    - Inhibitors
    - dense, low permeability concrete
    - membranes and asphalt overlays

    Existing concrete:

    - Sealers, membranes
    - partial removal and replacement
    - cathodic protection
    - overlays

Desired Student Achievements:

1. Explain the role of chloride in inducing corrosion of embedded metals.
2. Explain the fundamental mechanism of corrosion product formation and expansion, and subsequent destruction of the concrete.
3. Describe how each of the prevention, control, or mitigation techniques works.
4. Cite concerns and problems with control methods.

Chapter 8

Corrosion of Reinforcing Steel

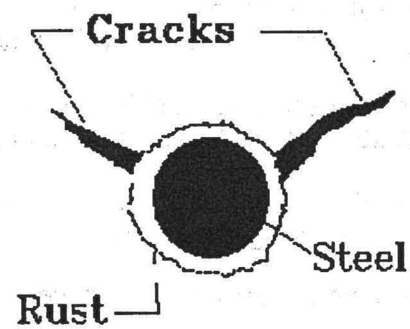
1. Introduction

1.1 Nature of the Problem

Impact on concrete (corrosion leads to volume expansion).

Impact of corrosion on reinforcing steel.

Impact of corrosion on prestressing steel.



1.2 Principal Causes

Chloride induced corrosion:

a. Deicing salts

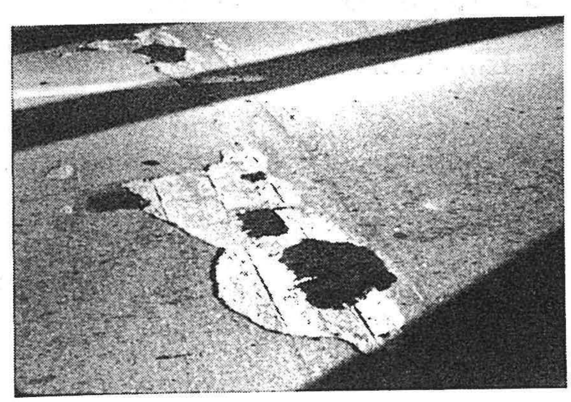
b. Seawater

c. Chloride admixtures

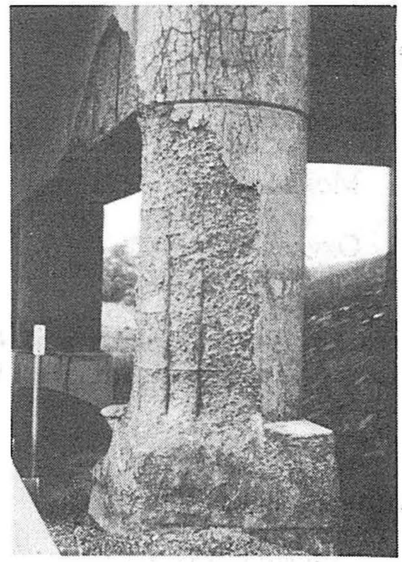
Carbonation effects

1.3 Impact of corrosion in the highway industry as it pertains to reinforced concrete

Loss of ride-ability



Loss of bridge capacity and reliability



Loss of structural integrity of appurtenances, curbs, culverts, etc.

2. Background

2.1 Review from Corrosion Discussions in Metals Module

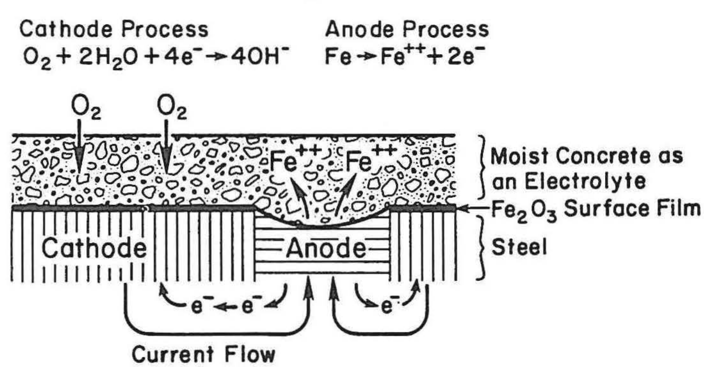
2.1.1 Corrosion is an electrochemical process

The corroding element is the anode. The non-corroding element is the cathode.

Reaction at the cathode generally determines the rate of the corrosion reaction as a whole.

Anode and cathode must be in electrical contact with each other, and in an "electrolyte."

A corrosion cell requires all three elements.



2.1.2 Required agents

Iron (steel)

Moisture

Oxygen

2.2 Corrosion Electrochemistry of Special Interest to Reinforcing Steel in Concrete

2.2.1 Influencing agents:

Chloride ions (Cl^-)

Carbon dioxide (in concrete)

2.2.2 Effects of chloride ions

Crystallization pressure

Osmotic pressure

Thermal shock

Chemical attack

Increased electrical conductivity

Destruction of steel passivity:

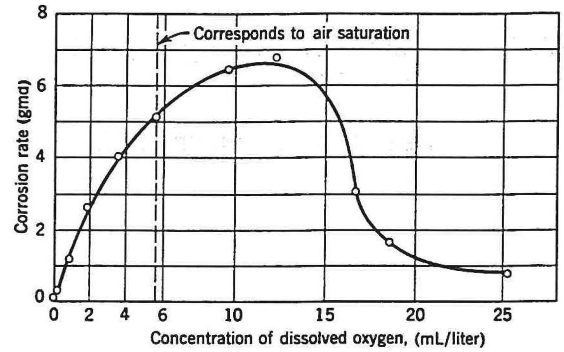
a. Passive oxide layer (film) is normally present on most metals.

b. Corrosion rates are reduced or halted due to presence of film.

c. The passive oxide film on reinforcing steel is stable in a chloride free, high pH environment.

d. Uncontaminated concrete is an ideal environment for controlling the corrosion rate of reinforcing steel.

e. Chloride ions reduce the stability of the passive oxide film, exposing unprotected iron to oxygen and water.



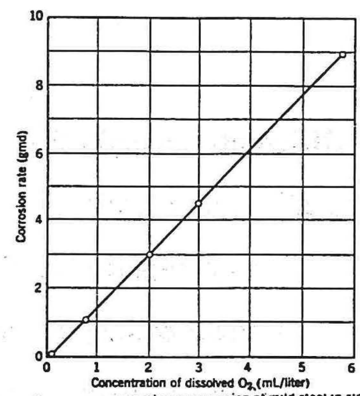


FIGURE 1. Effect of oxygen concentration on corrosion of mild steel in slowly moving water containing 165 ppm $CaCl_2$, 48-h test, 25°C (Uhlig, Triadis, and Stern[1]).

MAXIMUM CHLORIDE-ION LIMITS

(Percentages by weight of cement)

Type of construction	ACI 318 (water soluble)	ACI 222R (acid soluble)
Prestressed concrete	0.06%	0.08%
Reinforced concrete exposed to chloride	0.15%	0.20%
Dry reinforced concrete	1.00%	0.20%
Other reinforced concrete	0.30%	0.20%

2.2.3 Effects of carbon dioxide

Carbon dioxide causes carbonation in concrete.

Carbonation reduces pH.

Reduced pH affects the corrosion rate of iron.

2.2.4 Corrosion cell activity applied to concrete

Micro versus macro cells

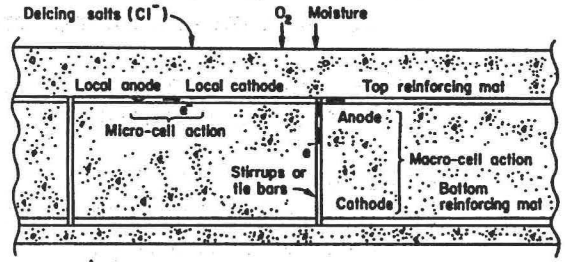
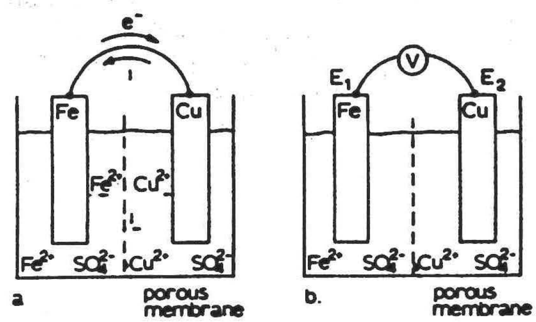


Figure I: Corrosion of Steel in Concrete by Micro-and Macro-cells

Differential metal cells



a. Different metals

- stay-in-place bridge forms
- shear connector studs
- galvanized metal components
- miscellaneous embedded metals

b. Deformations versus flat bar

c. Galvanized versus "black"

d. Variations in metallurgy

e. Bends versus straight sections

Differential concentration cells

a. Variations in chloride content

b. Variations in moisture content

Differential aeration cells

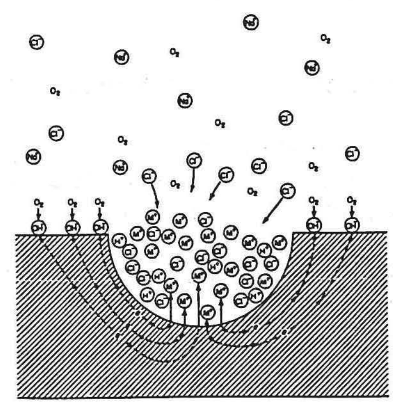
a. Top versus middle bars

b. Top of bar versus bottom of bar

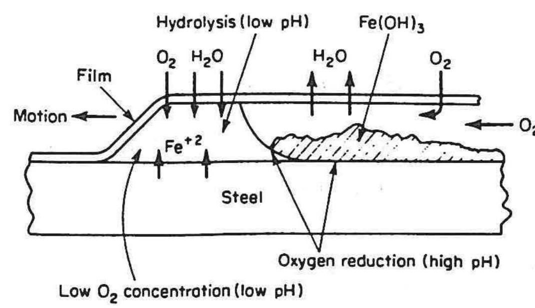
Pitting (cell) corrosion

a. Pitting is the typical corrosion mode for prestressing steel

b. Pitting is enhanced in the presence of chlorides



Underfilm corrosion (variation on pitting) -- typical corrosion at breaks in epoxy coatings.



2.2.5 Importance of the corrosion rate determination by cathode

Large cathode-small anode is the condition for most rapid corrosion.

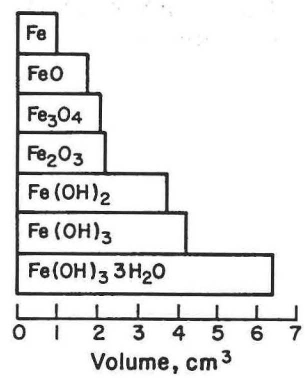
The bottom mat of steel can be the cathode; the top mat the anode.

Pinholes in epoxy coatings become small anodes and uncoated steel becomes large cathode.

2.3 Results of the corrosion of reinforcing and prestressing steel

2.3.1 Expansion of corrosion products

"Piling-Bedworth Ratio": volume of rust occupies 4 to 10 times the volume of parent metal.



Bursting stresses develop from rust expansion

Concrete cracks depend on

a. Bar spacing

b. Bar cover

c. Bar size

d. Concrete properties

Note: cracks permit more rapid entry of air and water

2.3.2 Loss of steel section

Is generally of less concern than damage to concrete.

Can be of significant concern in cases of shear and other fracture of critical concrete members.

Prestressing steel

a. Prestressing steel is more susceptible to corrosion that mild reinforcing steel.

b. Prestressing steel is susceptible to pitting corrosion.

c. Undetectable loss of section can result in failure of prestressing wire.

d. Failure can be progressive from wire to wire.

3. Methods of Detection

3.1 Evaluating Potential Problems

3.1.1 Chloride content (AASHTO T--260)

Total chlorides

Soluble chlorides

3.1.2 Rebar cover

Pachometer

R-meter

Micro-cover meter

3.1.3 Concrete tests

Rapid Chloride Permeability
AASHTO T-277

Water permeability (in-situ)

Depth of carbonation

3.2 Detecting Distress in Concrete

Crack patterns

Rust staining

Sounding (chain)

Sounding (electronic equipment)

Ultrasonic

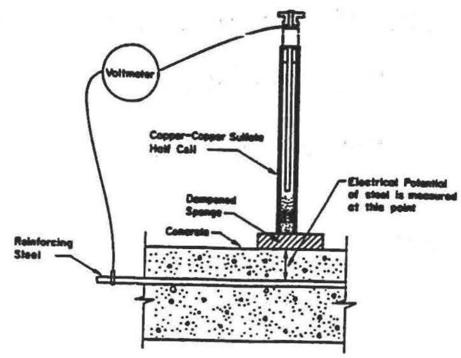
Impact echo

Radar

Thermography

3.3 Detecting Corrosion of Steel

Electrical potential
ASTM C-876



Measurement of Electrical Potential

Electrical resistivity

Rate of corrosion tests

4. Methods of Prevention (New Structures and Pavements)

Prevention is better than cure.

4.1 Reduce Penetrability of the Concrete

Improve quality of as-cast concrete:

Mix design

a. Reduce water/cement ratio.

b. Use water-reducing admixtures (including HRWRA).

c. Use mineral admixtures.

d. Use corrosion inhibitors.

e. Use latex modifiers.

f. Follow FHWA recommendations.

- provide for durable concrete.
- a cost effective protective system is required.
- unproven systems must be considered "experimental."
- remove existing overlays.
- remove and replace all deteriorated components.
- completely remove entire bridge deck.

NOTE: Spot patching is considered "maintenance."

NOTE: Resurfacing is "maintenance" when it only restores riding quality.

Field control

a. Control water addition.

b. Improve consolidation.

c. Improve curing.

4.2 Provide Suitable Concrete Cover Over Steel

2" minimum cover is generally recommended.

Greater than 2" cover must be specified in order to attain 2" cover in practice. (up to 3" may be required in specifications to get 2" in the field with 95% confidence).

4.3 Reduce Corrosion Susceptibility of the Steel

Epoxy coating

a. Fusion bonded

b. Epoxy application QC/QA

c. Handling and installation

d. Field QC/QA

FHWA research indicates a service life increase of 17 to 40 times for epoxy-coated steel reinforcing bars.

Galvanizing

Special systems for reducing corrosion susceptibility of prestressing steels.

4.4 Total System Approach

Concrete quality, cover, and steel treatment work hand in hand to provide corrosion resistance.

"Belt and suspenders" approach.

5. Methods for Controlling Corrosion in Progress (Concrete in Service)

5.1 General comments

The earlier the treatment, the more effective.

Most methods only reduce the rate of corrosion.

If the chloride level is sufficiently high, chances of success are limited.

Most remedial treatments are not permanent, and require periodic renewal.

Performance records demonstrate that no single technique works in all situations.

5.2 Methods to reduce penetrability of the concrete

5.2.1 Concrete overlays

High density-low slump (Iowa)

Sample specification highlights:

- Portland cement concrete or latex modified concrete at contractor's option.
- Typical PCC mix:

  1400 lb coarse agg.
  1400 lb fine agg.
  823 lb cement
  WRA required

- Slump of 3/4" to 1" (2 to 4 minutes after discharge).
- Air content = 6.5% ± 1%.
- Cement/water slurry as bonding agent.

- Special placing and finishing requirements.

- Cure with white pigmented curing compound, followed by burlap and wet cure.

HRWRA

Latex modified

Sample specification highlights:

- Mix proportions:

  Portland cement (1 part)
  Fine aggregate (2.5 parts)
  Coarse Aggregate (2 parts)
  Latex Emulsion (3.5 gallon/bag of cement)

Air Content	3 to 6%
Maximum Slump	5 inches

- Self-contained, mobile, continuous mixing.

- Special placing and finishing requirements.

- Cure with wet burlap for 24 hours, followed by air curing.

Microsilica mixes

Sample specification highlights

- 1 1/2" minimum thickness.

- 2 1/4" minimum total cover.

- Maximum deck surface temperature before placement = 85°F.

- 1/2" minimum slump.

- 5% minimum air content.

- 100% minimum density.

- 96 hour **wet cure.**

Polymer concrete overlay

Some overlays are highly sensitive to construction methods and conditions:

a. surface preparation

b. thermal compatibility

c. age-hardening

Comments on partial depth removal for overlay:

a. Remove delaminated concrete.

b. Remove concrete with high chloride content or in areas of high electrical potential.

c. Use scarification or surface milling.

5.2.2 Surface membranes and coatings

Waterproofing membranes

Asphaltic overlays

a. Require waterproofing between concrete and asphalt

b. Risk of frost damage

5.2.3 Penetrating sealers and treatments

Types

a. Penetrating epoxies

b. Silanes

c. Linseed oil

Common problems:

a. surface preparation

b. rate of application

c. number of applications

d. depth of penetration

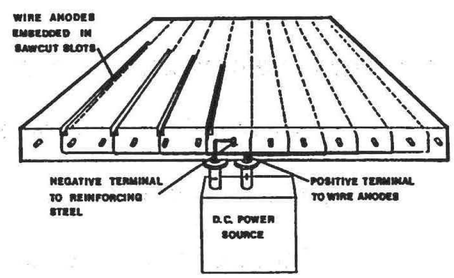
e. loss of surface treatment due to abrasion

f. skid resistance and friction of concrete surface

5.3 Methods to Control Corrosion in Progress

5.3.1 Cathodic Protection

General operating principles



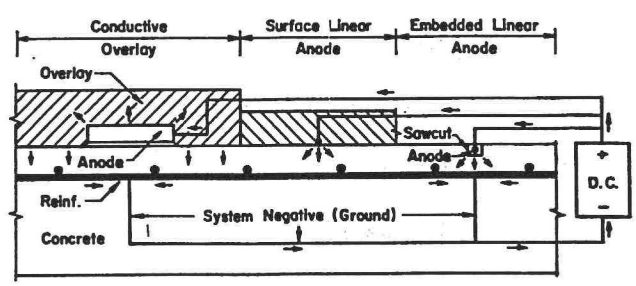
LINEAR ANODE CATHODIC PROTECTION

a. Negatively charge steel to attract positive iron ions.

b. Generate OH^- groups at steel (cathode).

c. Sacrificial anodes

d. Impressed current



Application to field use

Benefits of operation

Problems in application

a. uniform current distribution

b. how to monitor performance

c. possibility of unanticipated side effects such as:

- drive stray current corrosion
- bond loss?
- increased risk to ASR?

Although there has been speculation and some limited evidence of deleterious side effects of cathodic protection, there is no hard evidence to date that the rate of deterioration due to side effects approaches the rate of deterioration due to uncontrolled corrosion of the reinforcing steel.

Suggested References

Chapter 8

1. Cathodic Protection of Reinforced Concrete Bridge Decks. National Association of Corrosion Engineers, Houston, 1985.

2. Slater, J.E., Corrosion of Metals in Association with Concrete. STP 818, American Society for Testing and Materials, 1983.

3. ACI Committee 222, Corrosion of Metals in Concrete. American Concrete Institute, 1985.

4. Fontana, M.G., and N.D. Greene, Corrosion Engineering, 2nd Edition. McGraw-Hill, 1978.

5. Corrosion Basics, An Introduction. National Association of Corrosion Engineers, Houston, 1984.

Appendix A

Mix Design Workshop

The following information must be known:

1. Use of the concrete (pavement or structure).
2. Maximum permitted water-cement ratio for durability.
3. Minimum strength requirement.
4. Air content requirement.
5. Range of permitted slump.
6. Nature of admixtures to be used.
7. Presence or absence of pozzolan.
8. Maximum aggregate size.

Proceed to select the proportions as follows:

1. Select the water content

   The water requirement depends on the aggregate maximum size and grading, the slump, the air content, and the admixtures to be used. If you have information on the water requirement of the aggregates to be used, it may be used for a starting value.

If no information is available, Table 5.3.3 from ACI 211.1-81, reproduced on the following page, may be used. The table provides quantities of water per cubic yard of concrete for air-entrained and non-air-entrained concrete containing angular aggregate for various combinations of slump and maximum aggregate size. The footnotes contain information for correcting the values for rounded aggregates or for use of water-reducing admixtures.

2. Determine the cement content

The cement content is merely the water content divided by the water-cement ratio. There are two considerations which govern the water-cement ratio: durability and strength. The water-cement ratio for durability is usually specified explicitly. Strength is a function of water-cement ratio, but the function varies somewhat for different sets of materials. if the strength characteristics of the materials to be used are known, a water-cement ratio for the specified strength may be selected from experience. Otherwise, Table 5.3.4(a) of ACI 211-1-81, reproduced below, may be used.

TABLE 5.3.4(a) — RELATIONSHIP BETWEEN WATER-CEMENT RATIO AND COMPRESSIVE STRENGTH OF CONCRETE

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

*Values are estimated average strengths for concrete containing not more than 2 percent air for non-air-entrained concrete and 6 percent total air content for air-entrained concrete. For a constant water-cement ratio, the strength of concrete is reduced as the air content is increased.

Strength is based on 6 × 12 in. cylinders moist-cured for 28 days in accordance with the sections on "Initial Curing" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control" of ASTM Method C 31 for Making and Curing Concrete Specimens in the Field. These are cylinders cured moist at 73.4 ± 3 F (23 ± 1.7 C) prior to testing.

The relationship in this Table assumes a nominal maximum aggregate size of about ¾ to 1 inch. For a given source of aggregate, strength produced at a given water-cement ratio will increase as nominal maximum size of aggregate decreases; see Sections 3.4 and 5.3.2.

When both water-cement ratios have been determined, the lower of the two values must be used to compute the cement content.

TABLE 5.3.3 — APPROXIMATE MIXING WATER AND AIR CONTENT REQUIREMENTS FOR DIFFERENT SLUMPS AND NOMINAL MAXIMUM SIZES OF AGGREGATES

	Water, lb per cu yd of concrete for indicated nominal maximum sizes of aggregate							
Slump in.	3/8 in.*	1/2 in.*	3/4 in.*	1 in.*	1-1/2 in.*	2 in.†*	3 in.†‡	6 in.†‡
	Non-air entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	–
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
	Air-entrained concrete							
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	–
Recommended average§ total air content, percent for level of exposure:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5**††	1.0**††
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5**††	3.0**††
Extreme exposure‡‡	7.5	7.0	6.0	6.0	5.5	5.0	4.5**††	4.0**††

*The quantities of mixing water given for air-entrained concrete are based on typical total air content requirements as shown for "moderate exposure" in the Table above. These quantities of mixing water are for use in computing cement contents for trial batches at 68 to 77 F. They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. Rounded aggregate will generally require 30 lb less water for non-air-entrained and 25 lb less for air-entrained concretes. The use of water-reducing chemical admixtures, ASTM C 494, may also reduce mixing water by 5 percent or more. The volume of the liquid admixtures is included as part of the total volume of the mixing water.

†The slump values for concrete containing aggregate larger than 1½ in. are based on slump tests made after removal of particles larger than 1½ in. by wet-screening.

‡These quantities of mixing water are for use in computing cement factors for trial batches when 3 in. or 6 in. nominal maximum size aggregate is used. They are average for reasonably well-shaped coarse aggregates, well-graded from coarse to fine.

§Additional recommendations for air-content and necessary tolerances on air content for control in the field are given in a number of ACI documents, including ACI 201, 345, 318, 301, and 302. ASTM C 94 for ready-mixed concrete also gives air content limits. The requirements in other documents may not always agree exactly so in proportioning concrete consideration must be given to selecting an air content that will meet the needs of the job and also meet the applicable specifications.

**For concrete containing large aggregates which will be wet-screened over the 1½ in. sieve prior to testing for air content, the percentage of air expected in the 1½ in. minus material should be as tabulated in the 1½ in. column. However, initial proportioning calculations should include the air content as a percent of the whole.

††When using large aggregate in low cement factor concrete, air entrainment need not be detrimental to strength. In most cases mixing water requirement is reduced sufficiently to improve the water-cement ratio and to thus compensate for the strength reducing effect of entrained air concrete. Generally, therefore, for these large nominal maximum sizes of aggregate, air contents recommended for extreme exposure should be considered even though there may be little or no exposure to moisture and freezing.

‡‡These values are based on the criteria that 9 percent air is needed in the mortar phase of the concrete. If the mortar volume will be substantially different from that determined in this recommended practice, it may be desirable to calculate the needed air content by taking 9 percent of the actual mortar volume.

3. Determine relative quantities of cement and pozzolan, if applicable.

When fly ash or another pozzolan is to be used, the total quantity of cementitious material must be distributed between portland cement and pozzolan. Frequently, the distribution is stipulated by specifications. If not, experience with the materials to be used may be relied upon. Where no information is available, replacement of 20 percent of the cement by pozzolan is a practical figure.

4. Determine the total absolute volume of aggregate to be used.

All of the concrete volume that is not occupied by cement, pozzolan, water, or air is occupied by aggregate. It is merely necessary to add up the absolute volumes of materials already proportioned and subtract them from the total concrete volume. The absolute volume of each ingredient can be determined by dividing its weight by its density (the product of specific gravity and the unit weight of water). The volume of air is merely the percent air multiplied by the concrete volume. If a cubic yard of concrete (27 cubic feet) is being proportioned and absolute volumes are expressed in cubic feet, the absolute volume of aggregate is the sum of the absolute volumes of the other ingredients subtracted from 27.

5. Distribute the aggregate between fine and coarse aggregate.

There are two ways to distribute the total volume of aggregate bvetween fine and coarse. The most reliable is to determine the void content of the coarse aggregate in the dry rodded condition. When this is known, the volume of dry rodded coarse aggregate in a unit volume of concrete may be determined from Table 5.3.6 of ACI 211-1-81, reproduced below.

TABLE 5.3.6 — VOLUME OF COARSE AGGREGATE PER UNIT OF VOLUME OF CONCRETE

Nominal maximum size of aggregate in.	Volume of dry-rodded coarse aggregate* per unit volume of concrete for different fineness moduli of fine aggregate†			
	2.40	2.60	2.80	3.00
⅜	0.50	0.48	0.46	0.44
½	0.59	0.57	0.55	0.53
¾	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1½	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

*Volumes are based on aggregates in dry-nodded condition as described in ASTM C 29.

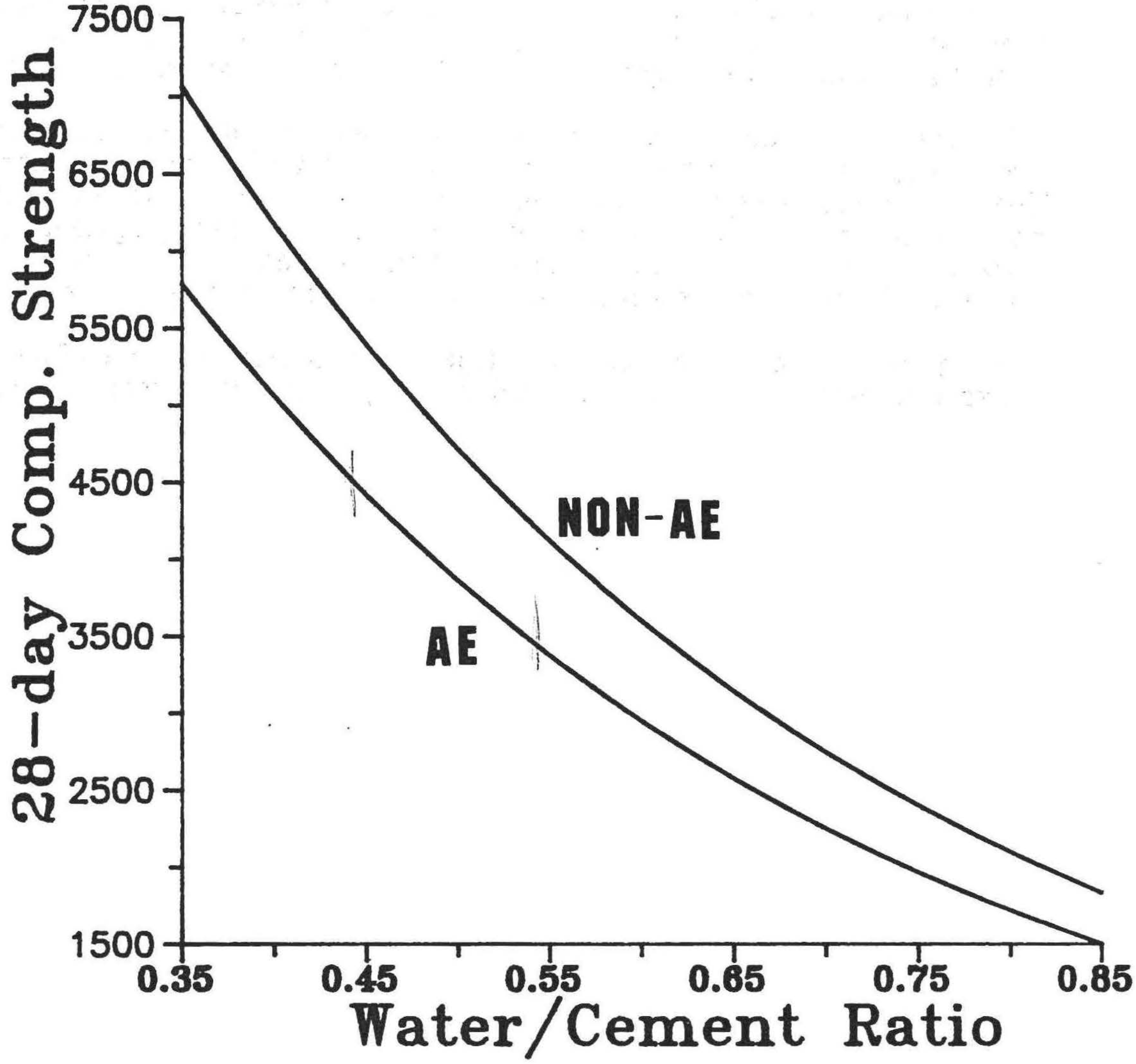
These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete such as required for concrete pavement construction they may be increased about 10 percent. For more workable concrete see Section 5.3.6.1.

†See ASTM method C 136 for calculation of fineness modulus.

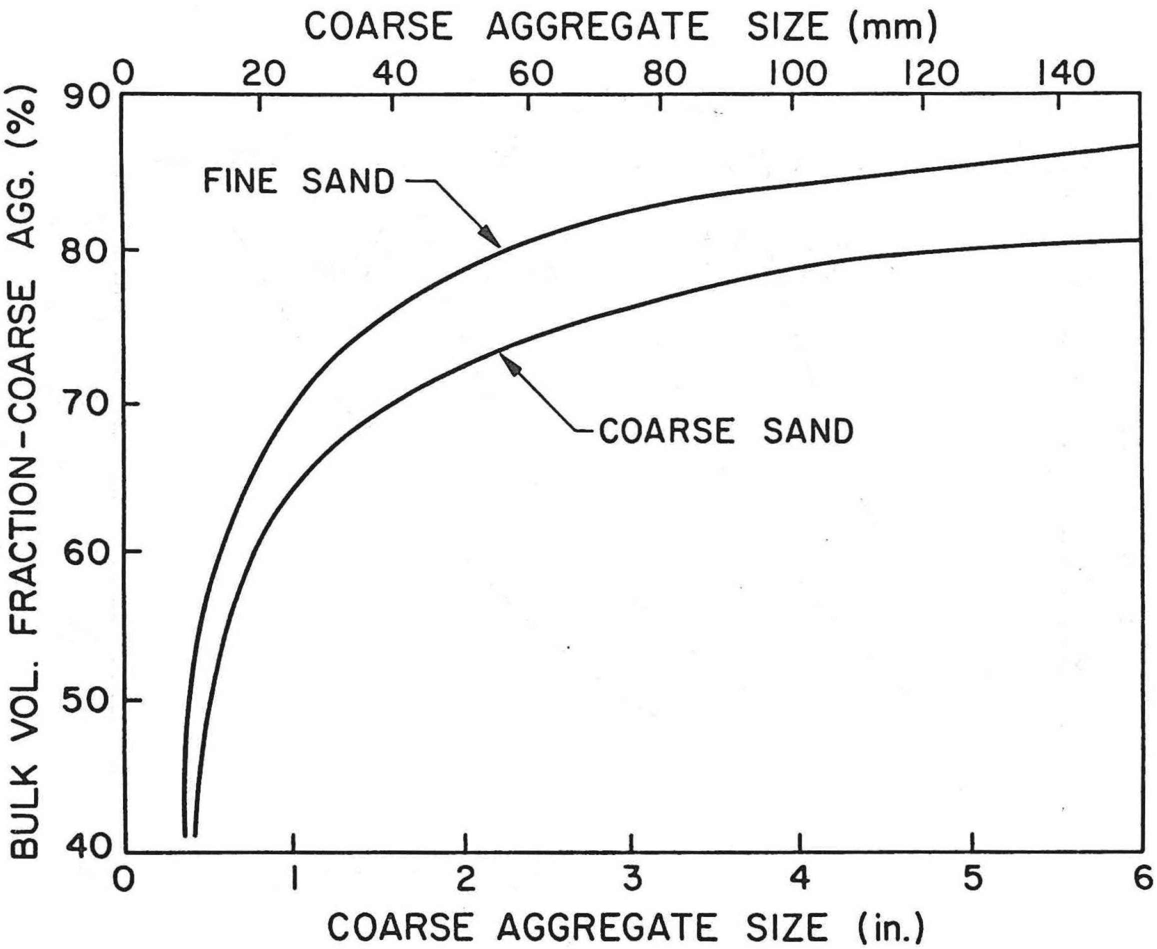
Values for structural concrete corresponding to various maximum aggregate sizes and sand finenesses are given directly. For pavement concrete, the values may be increased by 10 percent. This value multiplied by (1 - void quantity) provides the absolute volume of coarse aggregate in a unit volume of concrete. This valuemultiplied by 27 yields the number of cubic feet of coarse aggregate in a cubic yard of concrete. The fine aggregate is all that remains, and it is obtained by subtracting the coarse aggregate volume from the total aggregate volume.

When the void content of the coarse aggregate has not been determined, the two sizes of aggregate can be distributed on the basis of experience and judgment. The ratio of fine aggregate to total aggregate in structural concrete usually varies from 40 percent for 1-inch aggregate to 32 percent for 3-inch aggregate in air-entrained concrete, with values about 4 units higher in non-air-entrained concrete. For pavement concrete, the values may be reduced by 2 units.

The required volume of fine aggregate depends on the particle shape of the caarse aggregate. Use of the dry rodded unit weight takes the effect into account.

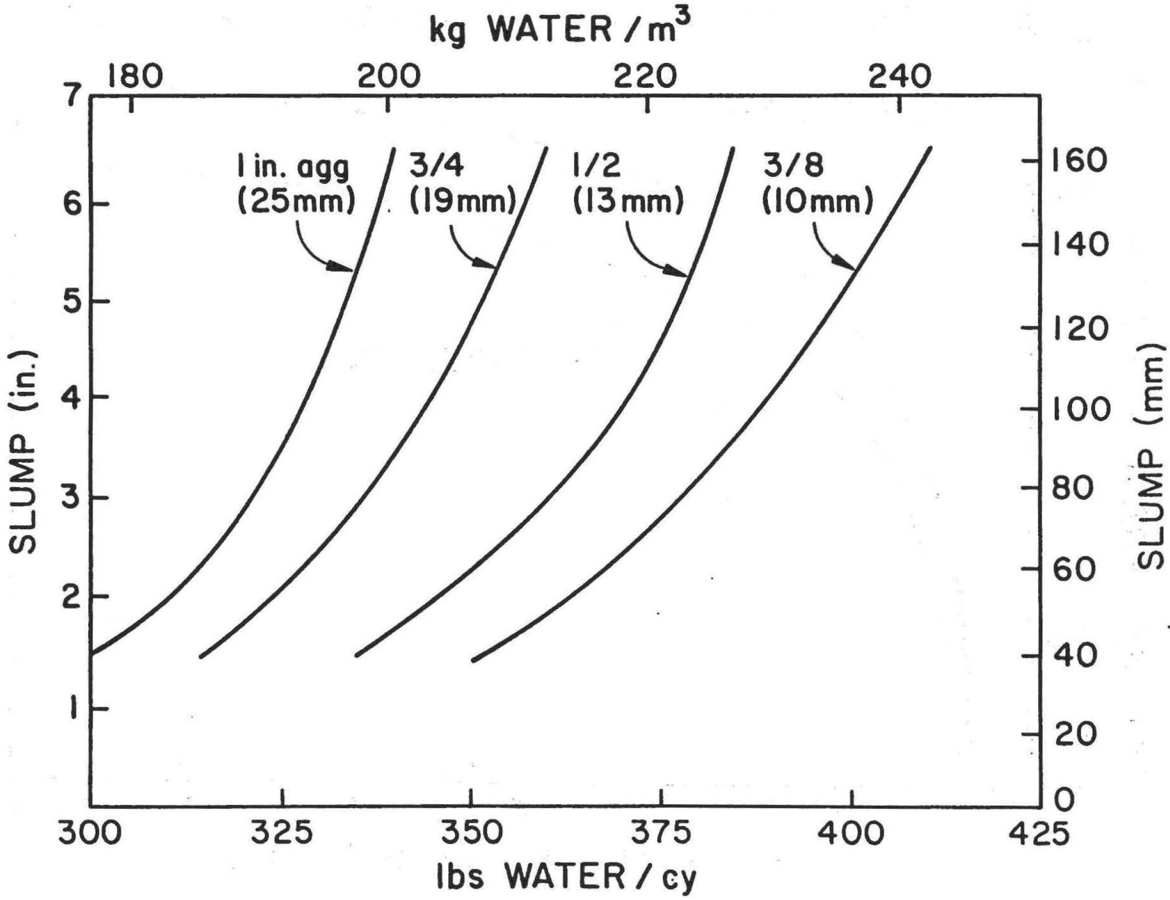


Relationship between water-cement ratio and compressive strength of concrete
(graphical representation of data in Table 5.3.4(a))



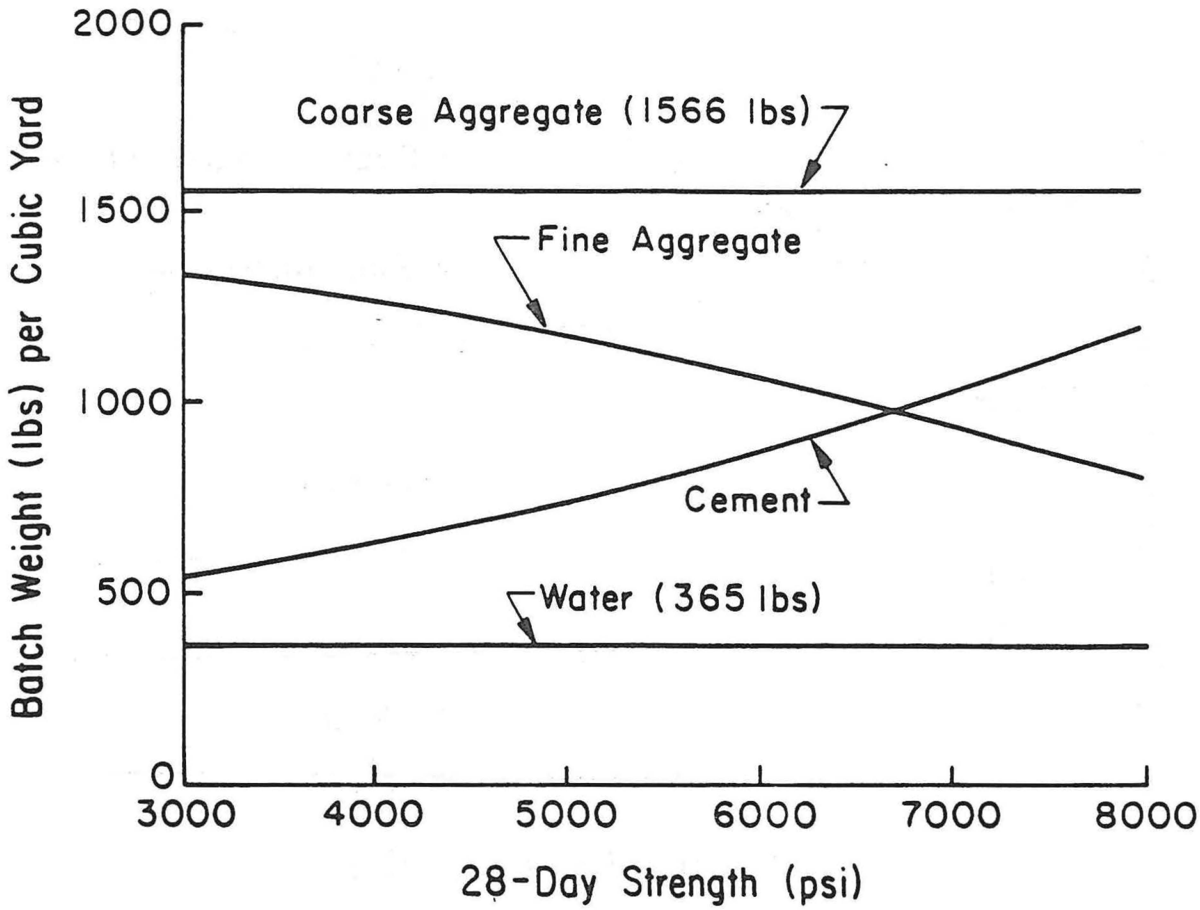
Bulk Volume Fraction of Coarse Aggregate per Unit Volume of Concrete

(graphical representation of data in Table 5.3.6)



Approximate Mixing Water Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates
Non-air-entrained Concrete

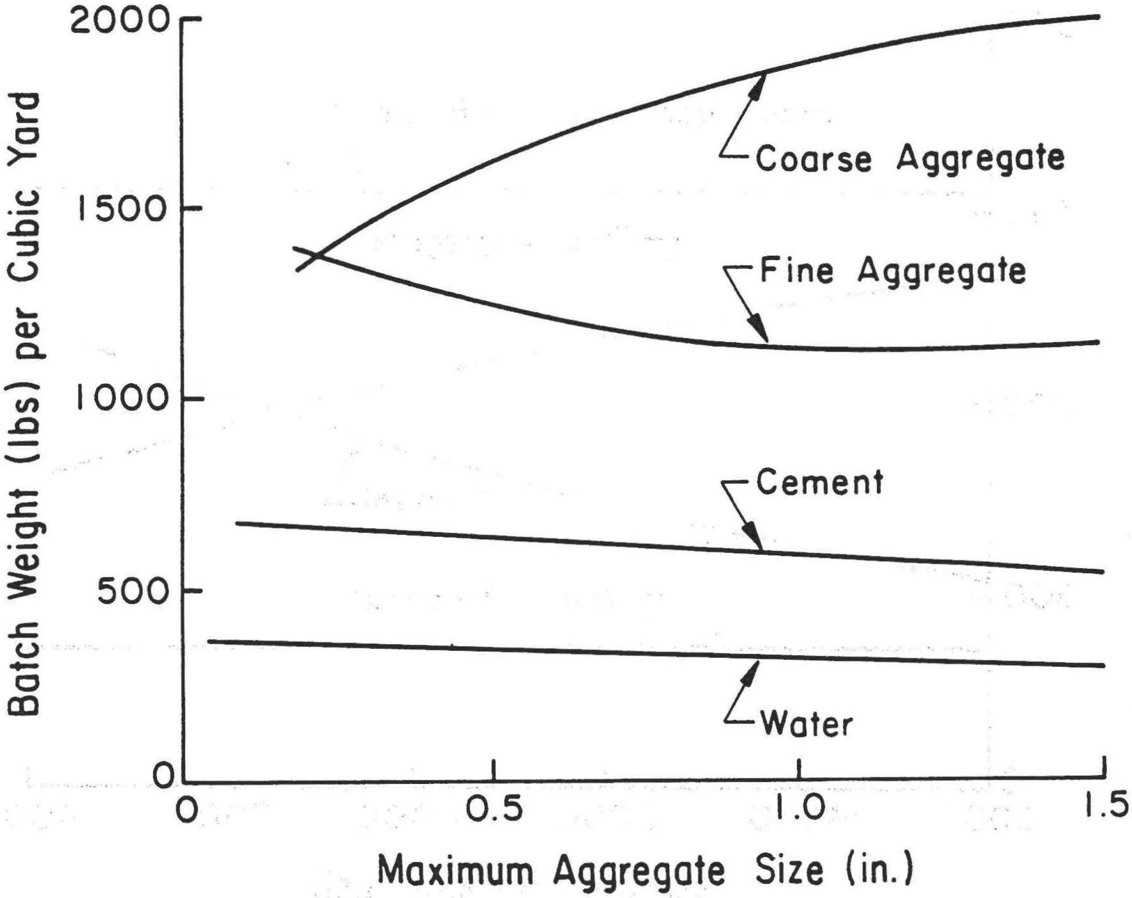
(graphical representation of data in Table 5.3.3)



The above figure is a graphical representation of batch weights as a function of 28-day compressive strength for all **non-air-entrained** mixes meeting the following requirements:

- 1/2" maximum aggregate
- 3 to 4" slump

Coarse aggregate and water content requirements are **independent** of strength, i.e., **independent** of w/c. For a constant water content of 365 lbs/cy, cement weight must increase with strength to provide for the required **decrease** in w/c. Fine aggregate weight decreases with strength to allow for the increased cement volume. Note: coarse and fine aggregate batch weights will vary with values of specific gravity.



The above figure is a graphical representation of batch weights as a function of maximum aggregate size for all **non-air-entrained** mixes meeting the following requirements:

- 3 to 4" slump
- f'_c = 4500 psi
- w/c constant

Water content decreases with increasing aggregate size. At constant w/c, cement content decreases proportionately with water content. Coarse aggregate content increases as aggregate size increases. Fine aggregate content varies to maintain constant total volume of all components. Note: coarse and fine aggregate batch weights will vary with values of specific gravity.

Example Problem

As an example consider the concrete used in the laboratory exercise. It has the following characteristics and performance requirements:

1. Used for concrete pavement
2. Maximum water/cement ratio: 0.45
3. Minimum compressive strength requirement at 28 days: 5,000 psi
   (Mix design target strength)
4. Required air content: 6%
5. Maximum slump: 3-inches
6. Admixtures: Air entraining agent only.
7. Use of pozzolans: None
8. Maximum aggregate size: 1-inch, crushed
9. Specific Gravity of coarse and fine aggregate: 2.65
10. Fineness modulus of fine aggregate: 2.60
11. Dry rodded unit weight of coarse aggregate: 100 lbs/ft^3

Proportions are selected as follows:

1. Select the water content

   From table 5.3.3, required mixing water is 295 lbs/CY.
   (Assuming no water absorbed by or contributed by the aggregates.)

2. Determine the cement content

   From Table 5.3.4(a) the required water/cement ratio for the strength requirement is 0.40. Since this value is lower than that required for durability (0.45 maximum, above), the water cement ratio will be 0.40.

   Thus, the cement content is 295lbs/0.40 = 738 lbs/CY

3. Not applicable.

4. Determine the absolute volume of the aggregate

Cement
738lbs/(3.15x62.4lbs/ft^3) = 3.75 ft^3

Water
295lbs/62.4lbs/ft^3 = 4.73 ft^3

Air
6%/100 x 27ft^3 = 1.62 ft^3

Subtotal = 10.10 ft^3

Aggregate volumes
27.00 ft^3 - 10.10 ft^3 = 16.90 ft^3

5. Distribute the aggregate content between fine and coarse aggregate.

From Table 5.3.6 the relative volume of dry rodded coarse aggregate for structural concrete,, assuming a fine aggregate with a fineness modulus of 2.60, is 0.69, which increased 10% for pavement provides a value of 0.76 (Bulk aggregate volume of 0.76 CY., = 0.76 x 27 ft^3 = 20.52 ft^3)

If the specific gravity of the coarse aggregate is 2.65 and the dry rodded unit weight is 100 lbs/ft^3, the fraction of voids is 1 - 100/(2.65x62.4) = 0.395 (39.5% of the bulk aggregate volume is occupied by void space between the coarse aggregate particles. The solid aggregate particles occupy (1 - 0.395) = 60.5% of the bulk volume.)

The absolute (solid) volume of coarse aggregate in the mixture is therefore 0.76 x (1 - 0.395) x 27 ft^3 = 12.41 ft^3.

The absolute volume of fine aggregate = 16.90 - 12.41 = 4.49 ft^3.

Weight of coarse aggregate =
12.41 ft^3/CY x 2.65 x 62.4 lbs/ft^3 = 2052 lbs.
(Round-off to 2050 lbs)

Weight of fine aggregate =
4.49 ft^3/CY x 2.65 x 62.4 = 742 lbs
(Round-off to 740 lbs)

Final Batch weights:

Cement	738 lbs/CY
Water	295 lbs/CY
fine aggregate	740 lbs/CY
coarse aggregate	2050 lbs/CY

(Assuming no water correction required for aggregate moisture content.)

Total weight/CY =	3823 lbs/CY
Weight/ft^3 =	142 lbs/ft^3

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Chapter 2: The Role of Water and Cement in Concrete

Page 2-7, Graph, Mindess & Young, page 29.

Page 2-16, Graph, Mindess & Young, page 602.

Chapter 3: Admixtures

Page 3-3, Table, Rixom & Mailvaganam, page 115.

Page 3-4, Diagram, Collepardi, page 121.

Page 3-5, Diagrams, Mindess & Young, page 182.

Page 3-7, Diagrams, Ramachandran & Malhotra, page 212.

Page 3-8, Graph, Ramachandran & Malhotra, page 231.

Page 3-9, Graph, Collepardi, page 182.

Page 3-17, Graph, Helmuth, page 62.

Page 3-21, Graph, Mehta, page 271.

Chapter 4: Construction Processes and Fresh Concrete

Page 4-19, Nomograph, National Ready Mixed Concrete Association, "Engineering Information," July, 1960, based on the original work of Carl A. Menzel of the Portland Cement Association.

Chapter 5: Properties and Behavior of Hardened Concrete

Page 5-7, Diagram, Avram, page 106.

Page 5-7, Diagram, Vile, pp. 275-288.

Page 5-9, Graph, Glucklich, pp. 176-189.

Page 5-13, Diagram, Troxell, Davis, & Kelly, page 228.

Page 5-17, Diagram, ASTM C293-79, Figure 1.

Page 5-18, Diagram, ASTM C78-84, Figure 1.

Chapter 6: Freeze-Thaw Durability

Page 6-3, Diagram, Cordon.

Page 6-7, Diagram, Simon, page 9.

Page 6-7, Diagram, Mindess & Young, page 172.

Page 6-8, Diagram, Mindess & Young, page 172.

Chapter 7: Other Durability Problems

Page 7-5, Graph, Dolar-Mantuani, page 227.

Page 7-6, Graph, ASTM C289-87, Figure 2.

Page 7-6, Graph, Natesaiyer, page 54..

Page 7-7, Graph, Mindess & Young, page 143.

Page 7-9, 2nd Photo, PCA collection on Sulfate Attack.

Page 7-11, Photo, PCA Collection on Abrasion.

Page 7-13, Photo, PCA Collection on Abrasion.

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Chapter 8: Corrosion of Reinforcing Steel

Page 8-2, Photo, PCA Collection on Corrosion.

Page 8-3, Photo, Hover.

Page 8-3, Diagram, Mehta, page 152.

Page 8-5, Graph, Uhlig & Revie, page 92.

Page 8-5, Graph, Uhlig & Revie, page 93.

Page 8-6, Diagram, Natesaiyer, page 30.

Page 8-6, Diagram, Gellings, page 7.

Page 8-7, Fontana & Greene, page 52.

Page 8-7, Fontana & Greene, page 48.

Page 8-8, Diagram, Mehta, page 152.

Page 8-10, Diagram, Chou & Hover, page 28.

Page 8-16, Diagram, Hover, page 204.

Page 8-16, Diagram, Hover, page 204.

Appendix A: Mix Design Workshop

Tables from ACI 211.1-81 (Revised 1985).

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