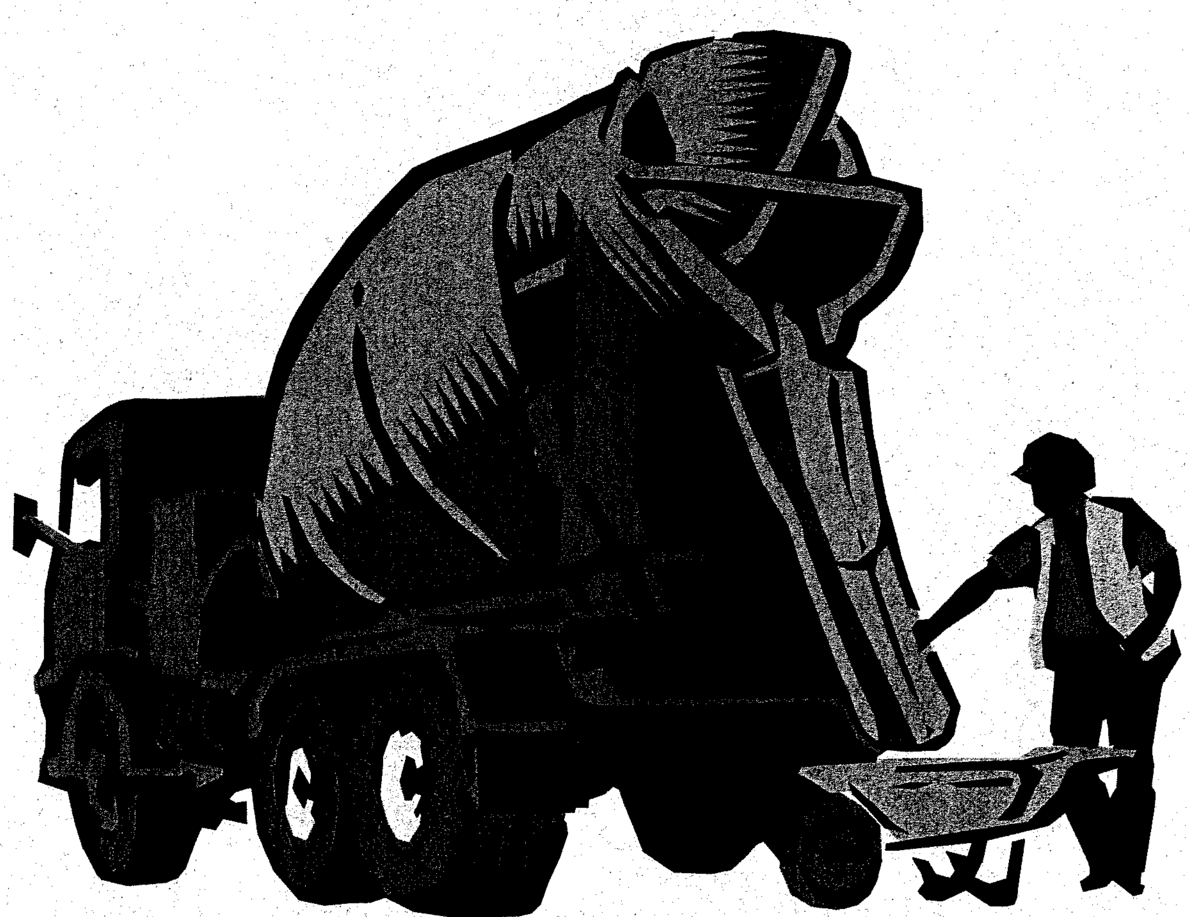
Fundamentals of Concrete

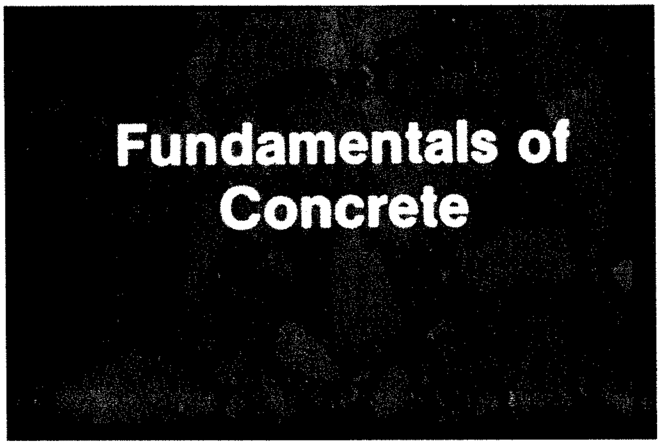
PCA - Design & Control of Concrete Mixtures

Summary of Chapters 1- 8

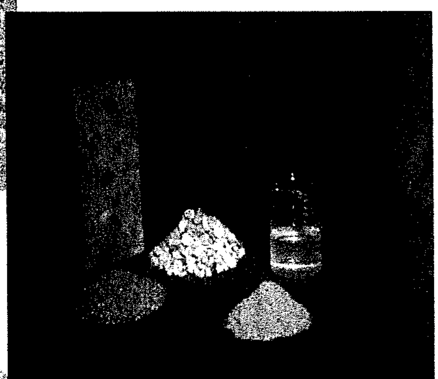


Michigan Concrete Association, 2005 – 2006

Chapter 1



What is concrete?



The principle materials used to produce concrete include water, cement, fine aggregate (sand) and coarse aggregate (stone).

Other materials……

In addition to the four primary materials, concrete may also include the following:

- chemical admixtures
  - air entraining, water reducing, accelerating, retarding
- other cementitious materials
  - fly ash, ground slag, silica fume
- fiber reinforcement
  - polypropylene, steel

Concrete ≠ Cement

These terms are often interchanged, but have very different meanings. Concrete is the finished product. Cement is one of the principle materials used to produce concrete. Think of it this way:

Cement is the flour.
Concrete's the cake.

Material Proportions

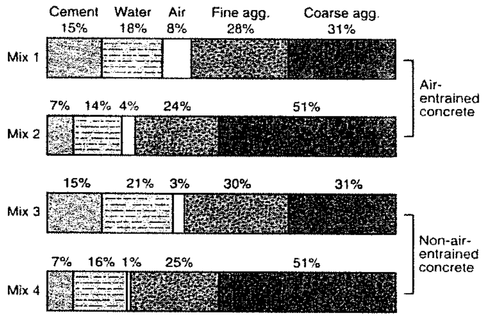


Fig. 1-2. Range in proportions of materials used in concrete, by absolute volume. Bars 1 and 3 represent rich mixes with small size aggregates. Bars 2 and 4 represent lean mixes with large size aggregates.

Why air in concrete?

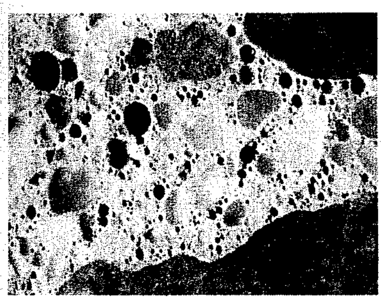


Fig. 8-1. Polished section of air-entrained concrete as seen through a microscope. (67840)

Air entrainment (introduced by an air entraining admixture) will significantly improve the durability of saturated concrete that is exposed to cycles of freezing and thawing.

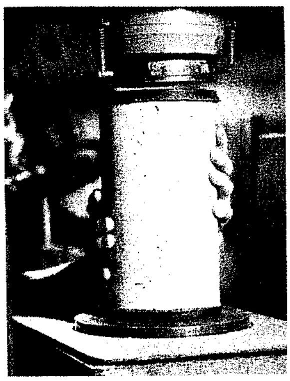
Air that forms in non-air entrained concrete is called entrapped air. Entrapped air bubbles form during the mixing of the materials.

Hydration

The binding quality of cement paste is due to a chemical reaction between the cement and water. This chemical reaction is called hydration.

- the reaction begins immediately on contact and provides concrete its strength
- theory ~ 1/4 lb. water to hydrate 1 lb. cement
  - excess water is water of convenience that is added to enhance the mixing and placing of the concrete
- reaction is affected by ambient temperatures
- reaction stops if the humidity level in the concrete falls below 80%

Strength



The compressive strength of concrete is a primary physical property used in the design calculations for bridges and buildings. It is defined as the maximum resistance to an axial load.

- reported in lbs/in^2 (psi) determined at 28 days of age
- designated by the symbol f'_c
- the test is usually conducted on a 6" x 12" cylinder
  - a 4" x 8" cylinder may be permitted by specification

The Water/Cement Ratio Law

"For given materials, the strength of the concrete (so long as we have a plastic mix) depends solely on the relative quantity of water as compared with the cement, regardless of mix or size and grading of aggregate."

Duff A. Abrams, 1918

Water/Cement Ratio

The water/cement ratio is calculated by dividing the weight (mass) of water by the weight (mass) of cement or combined cementitious materials in a given volume or batch size of concrete (i.e. 9 yd^3).

- abbreviated as w/c or w/cm
- the ratio is dimensionless
- reported to the nearest 2 decimals i.e. 0.48
- includes plant added and site added water
- must include fly ash, ground slag and silica fume as cementitious (cm) materials in calculation
- water in lbs. or gallons, cement in lbs. or bags
  - 1 gal. = 8.33 lb. 1 bag = 94 lbs.

Example Calculation

Batch size = 5 yd^3

type I cement	2000 lbs
ground slag	800 lbs
water	1400 lbs

w/cm = 1400 lbs. ÷ (2000 lbs. + 800 lbs.)
= 1400 lbs. ÷ 2800 lbs.
= 0.50 (dimensionless)

Water/Cement Ratio

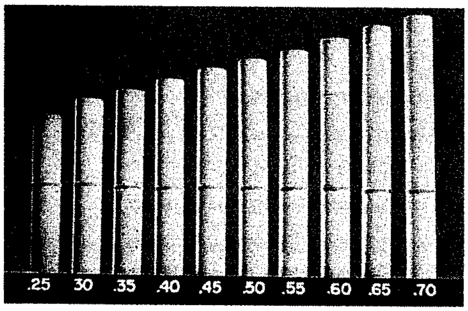


Fig. 1-4. Ten cement-paste cylinders with water-cement ratios from 0.25 to 0.70. The band indicates that each cylinder contains the same amount of cement. Increased water dilutes the effect of the cement paste, increasing volume, reducing density, and lowering strength. (1071)

Water/Cement Ratio

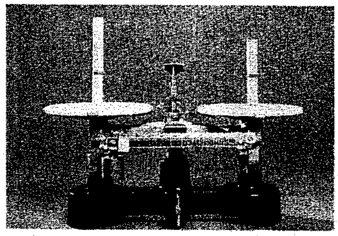
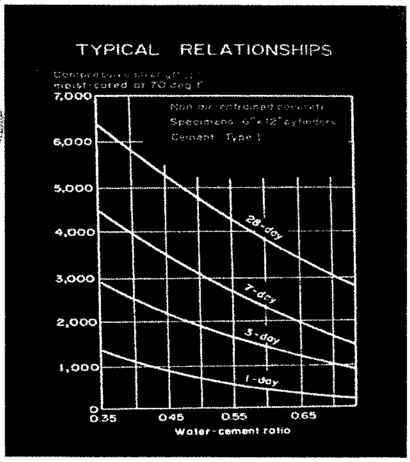


Fig. 2-30. Cement paste cylinders of equal mass and equal cement content, but mixed with different water to cement ratios, after all water has evaporated from the cylinders. (1072)

For any set of materials and conditions of curing, the quality of the hardened concrete is strongly influenced by the amount of water in relation to the amount of cement or cementitious materials. The strength decreases as the water content increases.

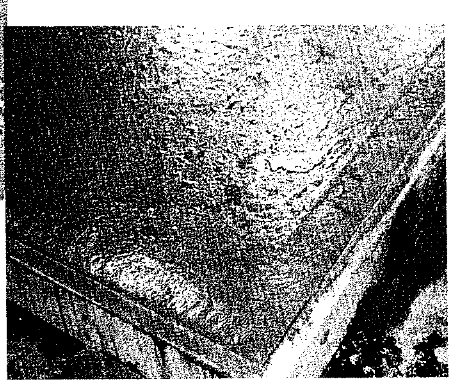
Water/Cement Ratio



In addition to decreasing the strength of the mix, concrete placed at a high w/c ratio will result in :

1. higher permeability
2. decreased resistance to weathering
3. increased cracking
4. increased volume changes during wetting and drying cycles

W/C vs Fresh Concrete



Concrete placed at a high w/c ratio will exhibit the following characteristics in the fresh state:

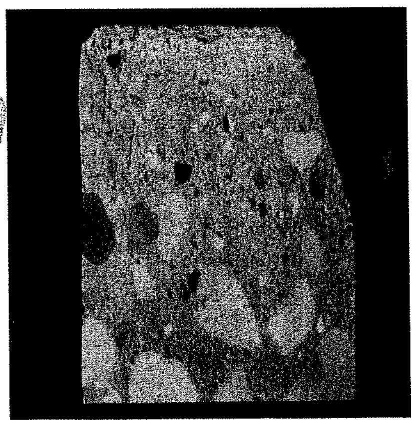
1. segregation of aggregate
2. increased bleeding

- the migration of water to the surface caused by the settlement of the solid materials

3. poor workability

– the ease of placing, consolidating and finishing freshly placed concrete

W/C vs Hardened Concrete



Observations of hardened concrete placed at a high w/c ratio:

1. segregation of aggregate from the mix
2. color variation in concrete from top to bottom
   – lighter at the top
3. plane of potential delamination just beneath the surface

Recommended W/C Ratios

ACI 318-05 Table 4.2.2

Exposure Condition	Max w/c ratio	Min f 'c, psi
Low permeability when exposed to water	0.50	4000
Subject to freezing/thawing when moist or to deicing chemicals	0.45	4500
Corrosion protection of reinforcement from chlorides, deicing chemicals, salt water, seawater	0.40	5000

Slump vs Water

The slump test was developed to measure the consistency of the concrete from load to load. It can also be an indicator of the amount of water in the mix, but other factors need to be considered.

Jobsite Slump Adjustments

The two rules of thumb for adjusting slump at the jobsite are as follows (they are guidelines and should not be taken as an exact science):

A. increase/decrease slump 1 inch
- add/subtract 10 lbs. of water per yd^3 ACI 211

B. increase/decrease slump 1 inch
- add/subtract 1 gal. water per yd^3 NRMCA

Water/Cement Ratio Summary

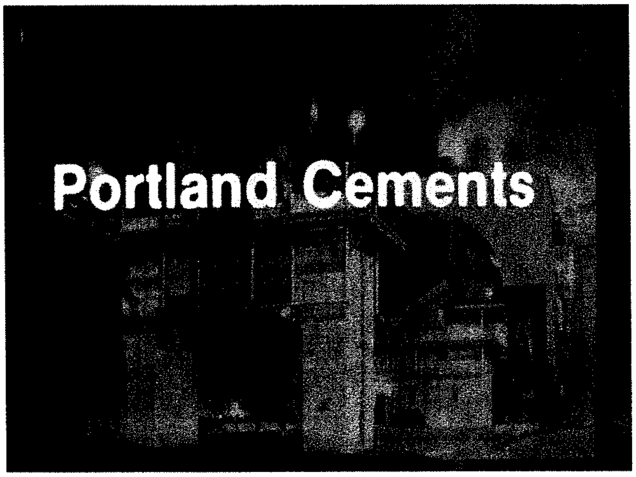
w/c ratio ↑ strength ↓

w/c ratio ↓ strength ↑

The benefits of maintaining the lowest possible w/c ratio include:

- increased durability
- lower permeability
- reduced shrinkage cracking

Chapter 2



Raw Materials for Cement

Lime ~ limestone, calcite, marl, shale

Iron ~ clay, iron ore

Silica ~ clay, marl, sand, shale

Alumina ~ aluminum ore, clay, fly ash, shale

"LISA"

Rotary Kiln

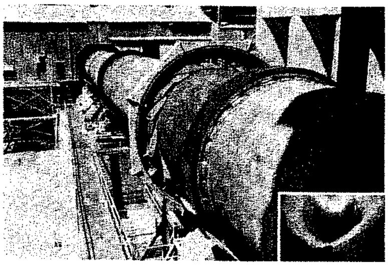


Fig. 2-8. Rotary kiln (furnace) for manufacturing portland cement clinker. Inset view inside the kiln. (58927, 25139)

The kiln, typically fueled by powdered coal, burns the raw materials at a temperature between 2600-3000°F to produce clinker.

Cement Clinker

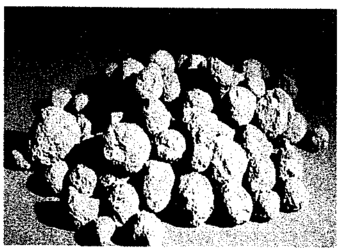
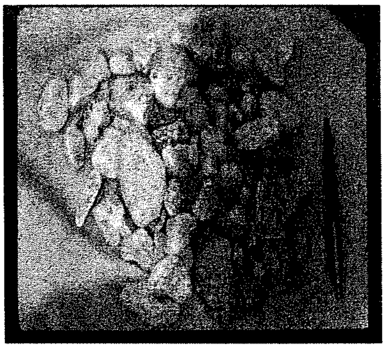


Fig. 2-9. Portland cement clinker is formed by burning calcium and siliceous raw materials in a kiln. This particular clinker is about 20 mm (¾ in.) in diameter. (60504)

Clinker is predominantly the size of marbles but can range in size from that of a small pebble to larger than a golf ball.

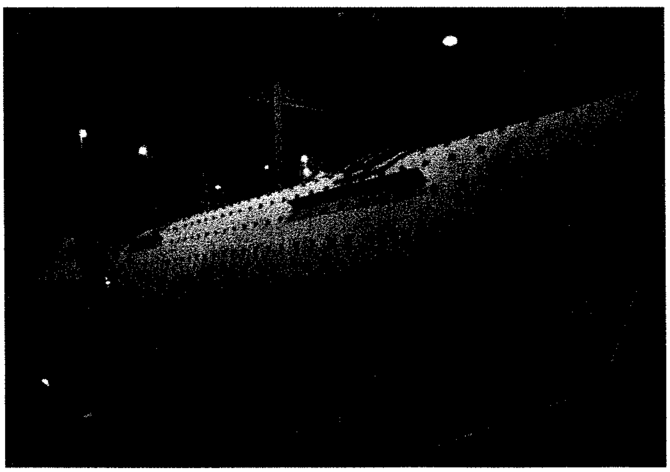
The Role of Gypsum



Gypsum is added to regulate the setting time of the cement and to improve the shrinkage and strength properties.

- use 3-5% by weight

Finish Mill Grinding



Portland Cement

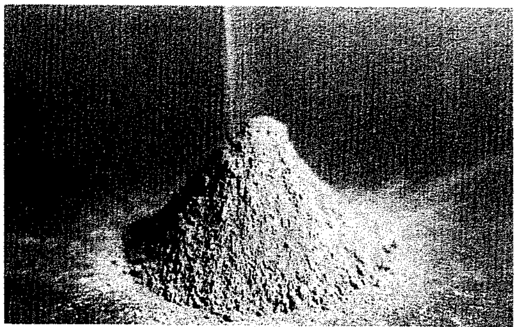


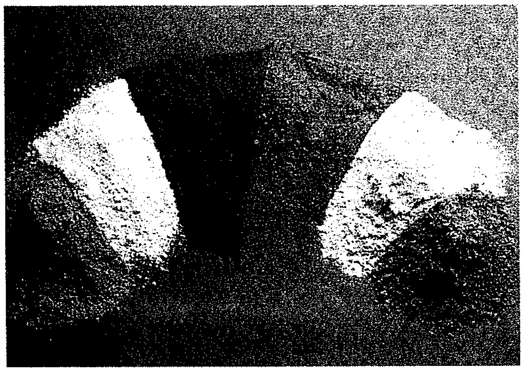
Fig. 2-1. Portland cement is a fine powder that when mixed with water becomes the glue that holds aggregates together in concrete. (58420)

Classifications of Portland Cement - ASTM C150

Type I	General Purpose
Type II	Moderate Sulphate Resistant
Type III	High Early Strength
Type IV	Low Heat
Type V	Sulphate Resistant

Chapter 3

Supplementary Cementitious Materials



Supplementary Cementitious Materials

The practice of incorporating supplementary cementitious materials such as fly ash, ground slag and silica fume in concrete mixtures has been growing steadily in North America since the 1970's. These materials may be used as an addition to or as a partial replacement for the portland cement depending on the properties of the materials and the desired effect on the concrete.

Fly Ash

Fly ash, the most widely used supplementary material, is used in approximately 50% of all ready mixed concrete (PCA 2000). It is a finely divided byproduct resulting from the combustion of pulverized coal in an electric power generating plant. In accordance with ASTM C618, there are two classification for fly ash:

1. class C
   - high calcium, low carbon
   - tan or buff in color
   - replaces 15-40% by mass of cement
2. class F
   - low calcium, high carbon
   - grey to black in color
   - replaces 15-25% by mass of cement

Fly Ash

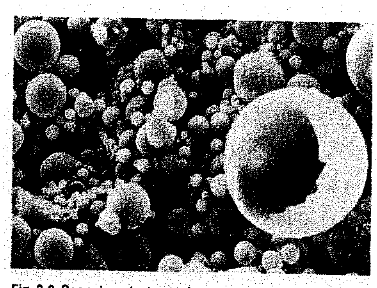


Fig. 3-2. Scanning electron microscope (SEM) micrograph of fly ash particles at 1000X. Although most fly ash spheres are solid, some particles, called cenospheres, are hollow (as shown in the micrograph). (54048)

While cement particles are angular in shape, fly ash particles are spherical consisting of both hollow and solid spheres.

Effects on Fresh Concrete

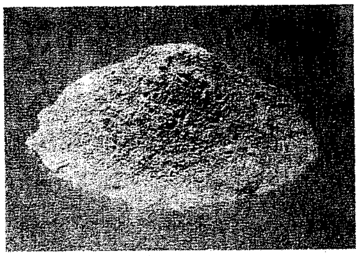


Fig. 3-3. Fly ash, a powder resembling cement, has been used in concrete since the 1930s. (69799)

The effects of fly ash on the fresh properties of concrete include:

- reduced water demand
- improved workability
- less bleeding
- increased dosage of air entraining admixture
- delayed set times
- improved pumpability

Effects on Hardened Concrete

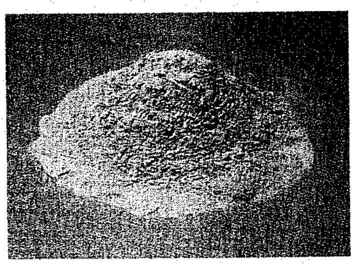


Fig. 3-3. Fly ash, a powder resembling cement, has been used in concrete since the 1930s. (69799)

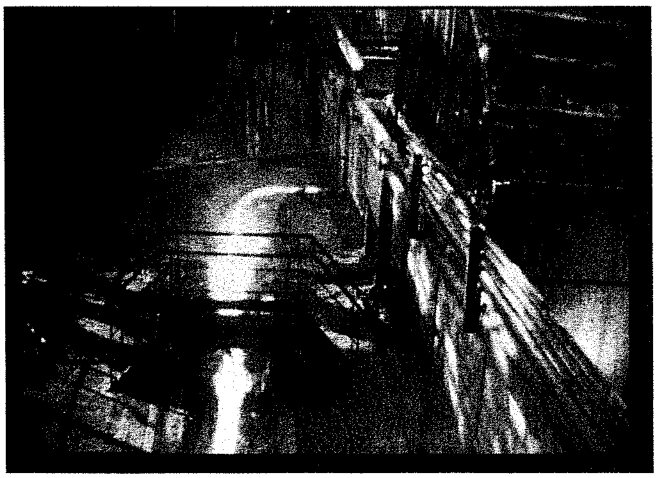
The effects on hardened concrete properties include:

- class C increases strength while class F stays the same or decreases strength
- class C has the same freeze/thaw resistance while class F may decrease
- class F increases sulphate resistance while class C decreases

Ground Granulated Blast Furnace Slag

Ground slag is the non-metallic product developed in a molten condition together with iron in a blast furnace. The molten slag (~ 2730 F) is tapped from the furnace and rapidly cooled either by air or water to form glassy granules that are ground to a fine powder in a mill. Slag must meet the requirements of ASTM C989. When used for general purpose concrete, it typically replaces 30-40% of the portland cement.

Tapping of Molten Slag



Processing of Molten Slag

Ground Granulated Blast Furnace Slag

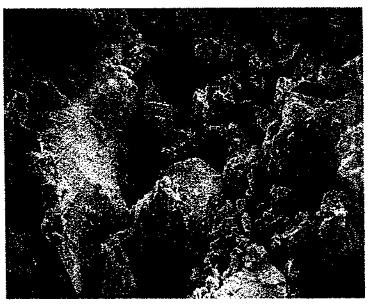


Fig. 3-6. Scanning electron microscope micrograph of slag particles at 2100X. (69541)

Ground-granulated blast furnace slag is rough and angular shaped.

Effects on Fresh Concrete

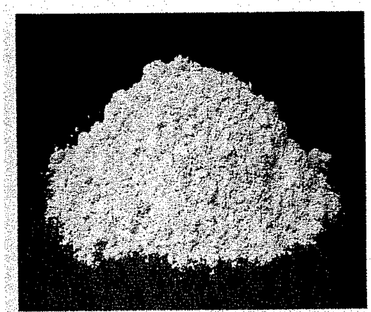


Fig. 3-5. Ground granulated blast-furnace slag. (69800)

The effects of ground slag on the fresh properties of concrete include:

- decreased water demand
- improved workability
- increased rate and amount of bleeding (depends on fineness)
- variable effects on dosage of air-entraining admixture
- retarded set times
- improved pumpability

Effects on Hardened Concrete

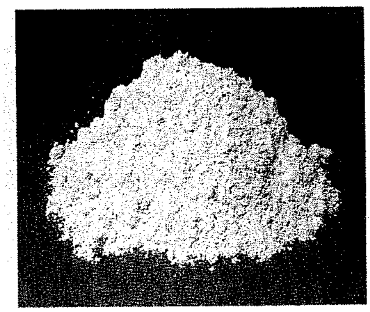


Fig. 3-5. Ground granulated blast-furnace slag. (69800)

The effects on hardened concrete properties include:

- generally, increased strength
- at normal replacements, freeze/thaw resistance is not affected
- improved sulphate resistance
- whiter, brighter concrete color

Silica Fume

Silica fume, also referred to as microsilica or condensed silica fume is a byproduct that results from the reduction of high purity quartz with coal in an electric arc furnace. A powder-like material, the color of silica fume ranges from grey to black. Silica fume is often used in projects where high strength or low permeability is required such as parking structures or bridge decks. It must meet ASTM C1240 and is used at an addition rate of 5-10% by mass of the total cementitious materials.

Silica Fume

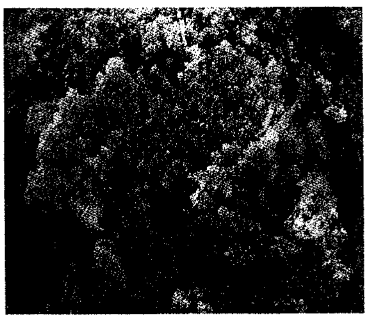


Fig. 3-8. Scanning electron microscope micrograph of silica-fume particles at 20,000X. (54095)

Silica fume particles, like fly ash, are spherically shaped. It is extremely fine with particles about 100 times smaller than the average cement particle.

Effects on Fresh Concrete

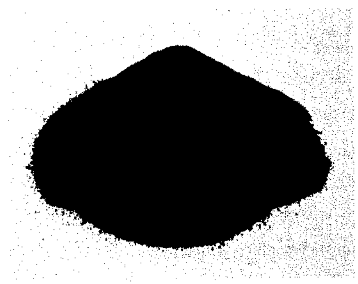


Fig. 3-7. Silica fume powder. (69801)

The effects of silica fume on the fresh properties of concrete include:

- increased water demand unless a plasticizer is used
- increased stickiness, reducing finishability
- increased amount of air entraining admixture
- acts as a lubricant or pumping aid

Effects on Hardened Concrete

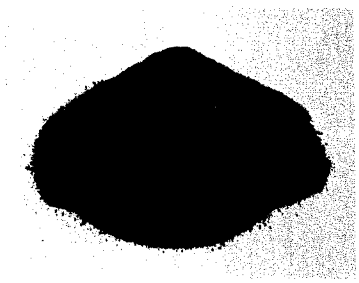
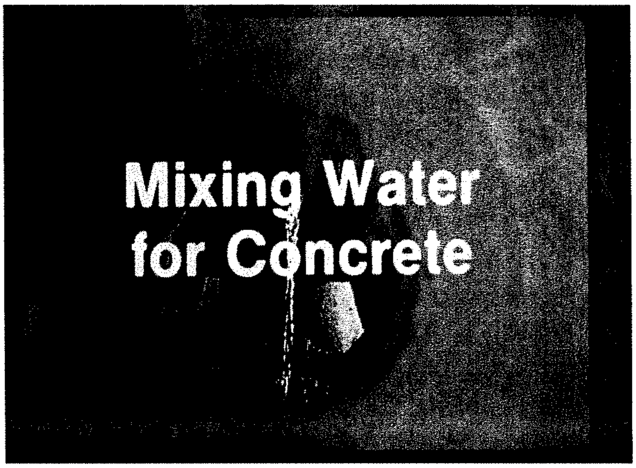


Fig. 3-7. Silica fume powder. (69801)

The effects of silica fume on hardened concrete properties include:

- increased strength
- decreased permeability
- improved resistance to sulphate attack
- may darken the color of concrete

Chapter 4



Acceptance Testing of Water

Water that is safe to drink (potable) and has no pronounced taste or odor is safe to use in concrete.

General Specifications

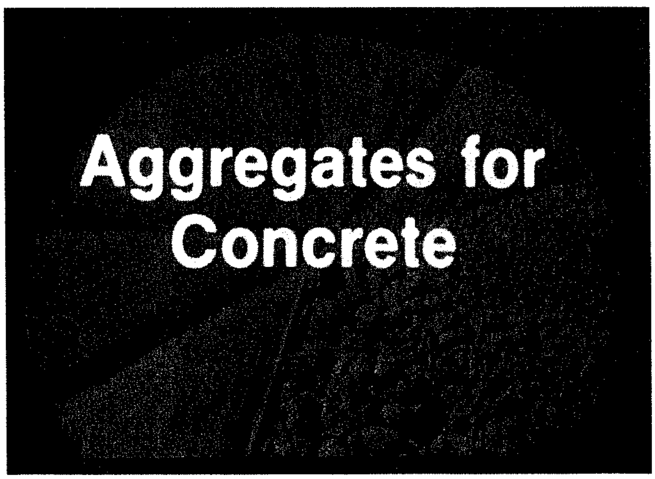
Water not fit for drinking may be used provided that additional testing, in accordance with ASTM C94, has been conducted.

Excessive impurities may affect setting time, strength, staining corrosion and durability

ACCEPTANCE CRITERIA FOR QUESTIONABLE MIXING WATER

	Limits	ASTM test method
7-Day compressive strength, min., compared to control specimens	90 %	C 109
Time of set, deviation from control specimens	minus 60 min. to plus 90 min.	C 191

Chapter 5



Fine and Coarse Aggregates

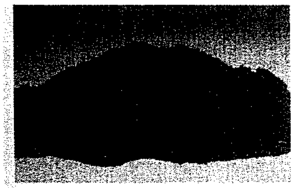


Fig. 5-1. Closeup of fine aggregate (sand). (69792)

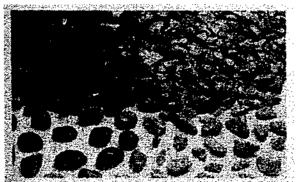


Fig. 5-2. Coarse aggregate. Rounded gravel (left) and crushed stone (right). (69791)

Aggregates generally occupy 60-75% of the concrete volume.

- normal weight aggregates must meet ASTM C33
- lightweight aggregates must meet ASTM C330
- the #4 sieve distinguishes between fine/coarse
- aggs. must be well graded
- aggregates must consist of clean, hard, durable particles free of materials that could affect hydration and bond of the cement paste

Grading of Aggregates

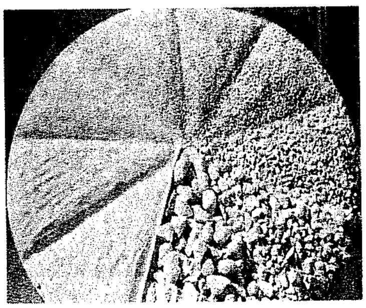


Fig. 5-4. Range of particle sizes found in aggregate for use in concrete. (8985)

Grading refers to the particle size distribution as determined by sieve analysis. Variations is grading can effect the uniformity of the concrete from load to load.

Grading of Aggregates

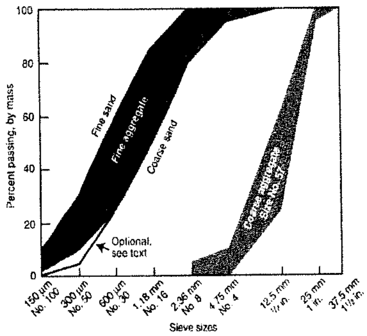


Fig. 5-6. Curves indicate the limits specified in ASTM C 33 for fine aggregate and for one commonly used size number (grading size) of coarse aggregate.

Smaller sized aggregates generally require more cement and water to coat the individual particles. A fine sand often results in a sticky concrete mix while a coarse sand contributes to a harsh mix that is difficult to close during finishing.

Coarse Aggregate Gravel vs. Limestone

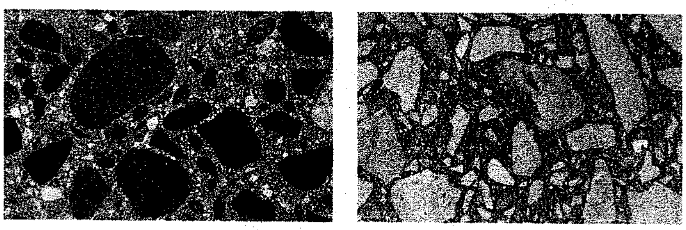


Fig. 1-3. Cross section of hardened concrete made with (left) rounded siliceous gravel and (right) crushed limestone. Cement-and-water paste completely coats each aggregate particle and fills all spaces between particles. (1051, 1052)

Coarse Aggregate

Maximum vs. Nominal Maximum Size

Maximum Size

The smallest sieve opening through which the entire amount of aggregate is ***required*** to pass.

Nominal Maximum Size

The smallest sieve opening through which the entire amount of aggregate is ***permitted*** to pass.

Aggregate Specifications (see handout)

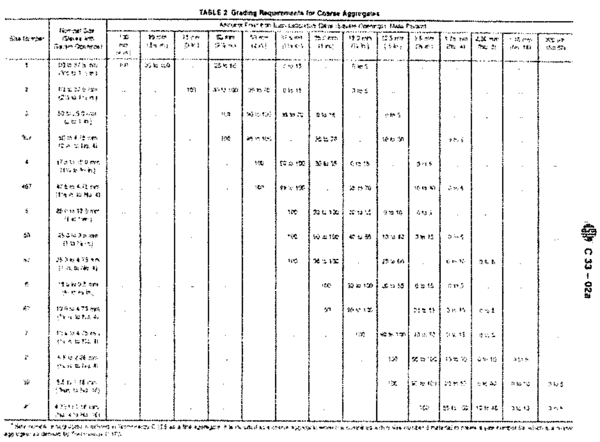


TABLE 2 Grading Requirements for Coarse Aggregates

C 33 – 02a

Coarse Aggregate

Selection of Maximum Size

The maximum size should not exceed:

- 1/5 the narrowest dimension between sides of forms
- 1/3 the slab depth
- 3/4 the minimum clear spacing between reinforcing bars, bundles of bars or pretensioning strands

Economics of locally available materials will also dictate the maximum size of the coarse aggregate

Moisture Conditions for Aggregates

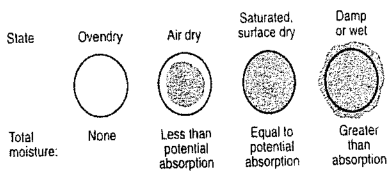


Fig. 5-12. **Moisture conditions of aggregate.**

- oven dry – no moisture present (only attainable in lab)
- air dry – dry at surface, capable of absorbing additional water
- saturated-surface dry (SSD) – fully saturated, neither absorbs nor contributes water to the mix
- wet – contains an excess amount of surface moisture

Deleterious Materials

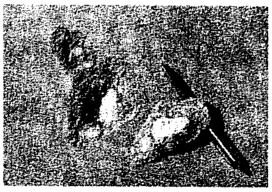


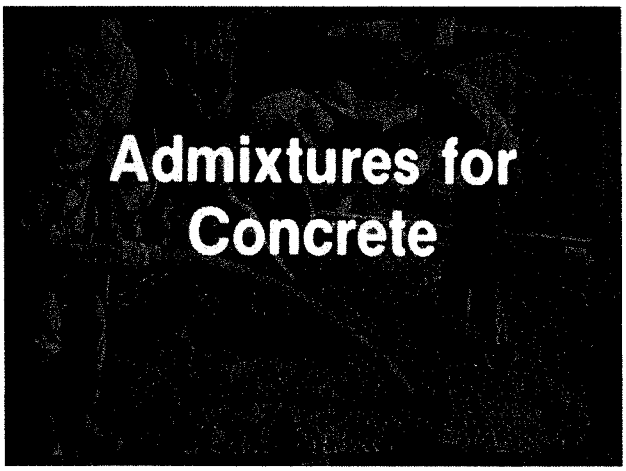
Fig. 5-18. A popout is the breaking away of a small fragment of concrete surface due to internal pressure that leaves a shallow, typically conical depression. (113)

Fig. 5-19. Iron oxide stain caused by impurities in the coarse aggregate. (70024)

Deleterious materials are defined as soft, porous, highly absorptive aggregates that when subjected to cycles of freezing/thawing or wetting/drying fracture spall from the surface of the concrete.

- ASTM/MDOT specs limit the amount of deleterious
- include chert, lignite, shale, etc.

Chapters 6 & 8



Admixtures for Concrete

A material other than water, aggregates, hydraulic cement and fiber reinforcement that is added to concrete immediately before or during mixing.

The four primary categories (see PCA text for a complete list) include:

1. air entraining admixtures
2. accelerating admixtures
3. retarding admixtures
4. water-reducing admixtures

Why Admixtures?

The principle reasons for using admixtures in concrete are (in no particular order):

1. To reduce the cost of construction
2. To achieve certain properties in concrete more effectively
3. To maintain the quality of concrete during stages of mixing, transporting, placing and curing in adverse weather
4. To overcome certain emergencies during concreting operations.

Admixture Specifications

Fig. 6-1. Liquid admixtures, from left to right: antiwashout admixture, shrinkage reducer, water reducer, foaming agent, corrosion inhibitor, and air-entraining admixture. (69795)

Admixtures for concrete must meet the following ASTM specifications:

1. ASTM C260
   - air entraining admixtures
2. ASTM C494
   - water reducing, retarding and accelerating admixtures

Air Entrainment

Concrete that is saturated and exposed to cycles of freezing and thawing must be air entrained. Air entrained concrete is produced by one of two methods:

A. using an air entraining cement or

B. adding an air-entraining admixture during batching of the concrete

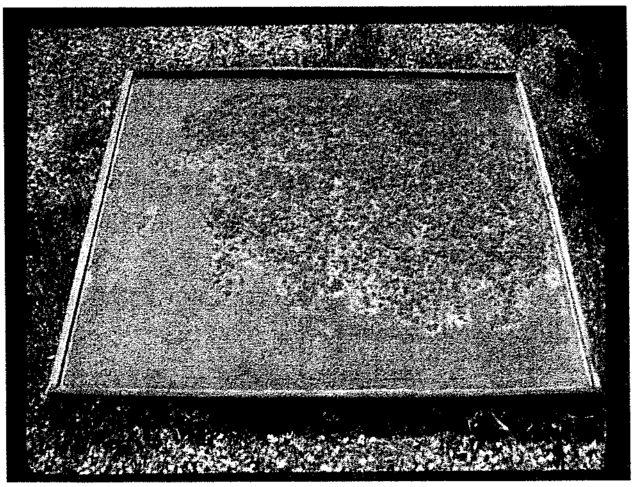
- millions of microscopic bubbles are introduced per cubic yard
- air entraining admixtures are measured by ounces per hundred weight of cement or cementitious material - oz/cwt

Entrained vs Entrapped Air

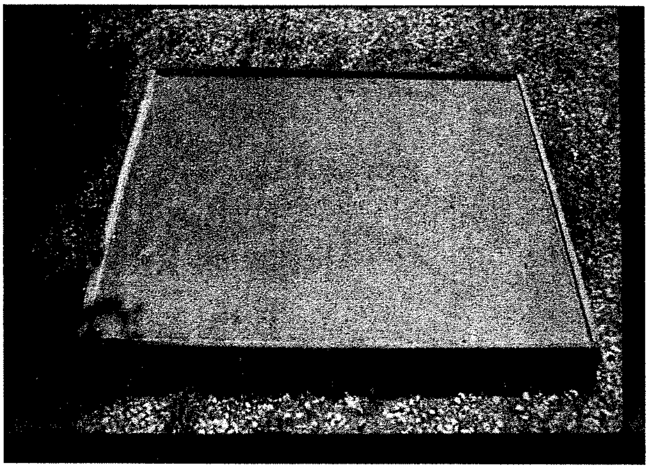
Entrained air bubbles form as a result of introducing an air entraining admixture into the concrete. The bubbles are extremely small – 0.01 to 1.0 mm in diameter – are randomly distributed and not interconnected.

Entrapped air bubbles form in all concretes as a result of mixing, handling, and placing and are largely a function of aggregate characteristics. The bubbles are usually 1.0 mm in diameter and larger.

Non-Air Entrained Concrete



Air Entrained Concrete



Air Entrained Concrete

Advantages

Air entrainment was developed in the 1930s to improve the freeze-thaw resistance of concrete exposed to water and deicing chemicals. In addition to its primary role, the advantages of adding air in concrete include:

- reduced segregation and bleeding
- reduced w/c ratio
- improved mix pumpability
- increased watertightness

Percent Volume of Air

Industry Rule of Thumb

Total air = 6 ± 1%

Total air = entrapped + entrained

Air Entrained Concrete

The two acceptable ASTM methods for measuring the total air content of concrete are:

1. pressure method (ASTM C231)
   - applicable for field testing all concretes except those made with highly absorptive and lightweight aggregates

2. volumetric method (ASTM C173)
   - applicable for field testing all concretes, but required for concretes made with lightweight and porous aggregates

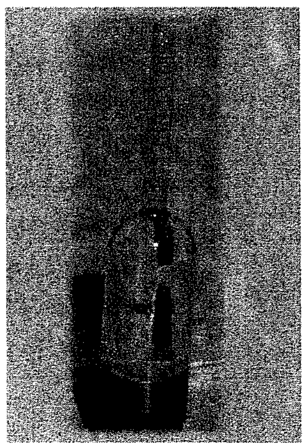
Air Content of Concrete

Fig. 16-5. Pressure-type meter for determining air content. (69766)

Fig. 16-6. Volumetric air meter. (69886)

Chace Air Indicator

The chace air indicator, AASHTO test method T 199, is a simple and inexpensive method for determining the approximate amount of air in concrete. ***It is not a substitute for the more accurate pressure and volumetric methods.***



Factors Affecting Air Content
(based on a fixed dosage - i.e. 1.0 oz/cwt)

- cement - air content ↓ as cement content ↑
- coarse aggregate - air content ↑ as max. aggregate size ↓
- fine aggregate - air content ↑ as % fine aggregate ↑
- mix water/slump - air content ↑ as slump ↑ (up to 7 inches)
- temperature - air content ↓ as temperature ↑
- mixing time - air content ↓ with extended mix times
- agitation - varies depending on initial slump
- vibration - air content ↓ as vibration time ↑

Accelerating Admixtures

- used to accelerate the rate of hydration (setting) and strength development of concrete at an early age
- most common accelerator is calcium chloride
  - inexpensive, but is not an anti-freeze agent
  - dosage up to 2% by weight of cement
- non-chloride accelerators must be used when concrete contains reinforcing steel, moisture is present and corrosion can occur

Retarding Admixtures

Retarding admixtures delay the setting or hardening rate of concrete during the following situations:

- hot weather conditions
- difficult placements – large piers/foundations
- high strength concreting
- special decorative finishes
  - i.e exposed aggregate concrete

Water Reducing Admixtures

Water reducing admixtures are essentially cement dispersing agents that were developed to improve the efficiency of the available mix water in the concrete resulting in:

A. A reduction in the mix water required to produce concrete of a given slump.

B. An increase in slump without changing the design water content.

The three categories of water reducing admixtures are:

- regular - 5-10% water reduction
- mid-range - 6-15% water reduction
- high range (superplasticizer) - 12-30% water reduction

High Range Water Reducers

Fig. 6-6. Low water to cement ratio concrete with low chloride permeability—easily made with high-range water reducers—is ideal for bridge decks. (69924)

Chapter 7

Fiber Reinforcement

Fig. 7-1. Steel, glass, synthetic and natural fibers with different lengths and shapes can be used in concrete. (69965)

Fiber Reinforcement

Fibers are manufactured from steel, plastic, glass and other natural materials (wood cellulose).

- available in a variety of shapes, sizes and thicknesses
- may be round, flat, crimped or deformed with lengths from ¼ inch to 6 inches
- added to concrete in low volume dosages
- acts as secondary reinforcement
- depending on fiber type can improve impact resistance, abrasion resistance, plastic shrinkage crack resistance, toughness

Synthetic Fibers

Fig. 7-7. Polypropylene fibers are produced either as (left) fine fibrils with rectangular cross section or (right) cylindrical monofilament. (69993)

Man-made fibers consisting of nylon, polyester, polypropylene. Polypropylene the most popular fiber type. Useful in reducing plastic shrinkage and subsidence cracking. Synthetic fibers are an alternative to welded wire mesh reinforcement.

Steel Fibers

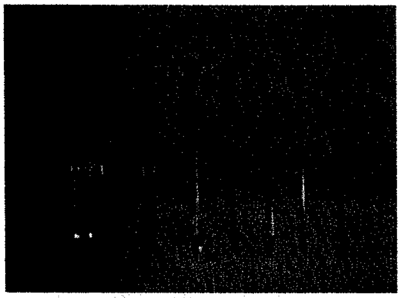


Fig. 7-2. Steel fibers with hooked ends are collated into bundles to facilitate handling and mixing. During mixing the bundles separate into individual fibers. (69992)

Steel fibers are short, discrete lengths of steel of any number of cross sections. Applications include bridge decks, airport runways, industrial floors and highway pavements. Surface corrosion is cosmetic as opposed to a structural concern.

QUESTIONS?