

Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete

Reported by ACI Committee 221

Joseph F. Lamond
Chairman

William P. Chamberlin
Hormoz Famili
Stephen W. Forster
Truman R. Jones, Jr.
Dah-Yinn Lee
Donald W. Lewis

Kenneth MacKenzie
Gary R. Mass
Richard C. Meininger
Frank P. Nichols, Jr.
Everett W. Osgood
Michael A. Ozol

James S. Pierce
Raymond Pisaneschi
John M. Scanlon, Jr.
Charles F. Scholer
David C. Stark
Robert E. Tobin

Robert F. Adams, Consulting Member

This guide presents information on selection and use of normal weight and heavyweight aggregates in concrete. The selection and use of aggregates in concrete should be based on technical criteria as well as economic considerations and knowledge of types of aggregates generally available in the area of construction. The properties of aggregates and their processing and handling influence the properties of both plastic and hardened concrete. The effectiveness of processing, stockpiling, and aggregate quality control procedures will have an effect on batch-to-batch and day-to-day variation in the properties of concrete. Aggregates that do not comply with the specification requirements may be suitable for use if the properties of the concrete using these aggregates are acceptable. This is discussed under the topic of marginal aggregates (Chapter 6). Materials that can be recycled or produced from waste products are potential sources of concrete aggregates; however, special evaluation may be necessary.

Keywords: aggregate grading; aggregate shape and texture; air entrainment; blast-furnace slag; bleeding (concrete); coarse aggregates; concretes; crushed stone; degradation resistance; density (mass/volume); fine aggregates; mix proportioning; modulus of elasticity; pumped concrete; quality control; recycling; shrinkage; strength; tests; workability.

CONTENTS

Chapter 1—Introduction, p. 221R-2

Chapter 2—Properties of hardened concrete influenced by aggregate properties, p. 221R-2

2.1—Durability

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

- 2.2—Strength
- 2.3—Shrinkage
- 2.4—Thermal properties
- 2.5—Unit weight
- 2.6—Modulus of elasticity
- 2.7—Surface frictional properties
- 2.8—Economy

Chapter 3—Properties of freshly mixed concrete influenced by aggregate properties, p. 221R-12

- 3.1—General
- 3.2—Mixture proportions
- 3.3—Slump and workability
- 3.4—Pumpability
- 3.5—Bleeding
- 3.6—Finishing characteristics of unformed concrete
- 3.7—Air content
- 3.8—Other properties

Chapter 4—Effects of processing and handling of aggregates on properties of freshly mixed and hardened concrete, p. 221R-15

- 4.1—General
- 4.2—Basic processing
- 4.3—Beneficiation
- 4.4—Control of particle shape
- 4.5—Handling of aggregates
- 4.6—Environmental concerns

ACI 221R-96 supersedes ACI 221R-89 and became effective May 5, 1996.
Copyright © 1997, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.



Documents

Document Sharing Hub

Chapter 5—Quality assurance, p. 221R-20

- 5.1—General
- 5.2—Routine visual inspection
- 5.3—Routine control testing
- 5.4—Acceptance testing
- 5.5—Record keeping and reports

Chapter 6—Marginal and recycled aggregates, p. 221R-23

- 6.1—Marginal aggregates
- 6.2—Use of marginal aggregates
- 6.3—Beneficiation of marginal aggregates
- 6.4—Economy of marginal aggregates
- 6.5—Recycled aggregates and aggregates from waste products

Chapter 7—Heavyweight aggregates, p. 221R-25

- 7.1—Introduction
- 7.2—Heavyweight aggregate materials
- 7.3—Properties and specifications for heavyweight aggregates
- 7.4—Proportioning heavyweight concrete
- 7.5—Aggregates for use in radiation-shielding concrete
- 7.6—Heavyweight aggregate supply, storage, and batching

Chapter 8—References, p. 221R-26

- 8.1—Recommended references
- 8.2—Cited references

CHAPTER 1—INTRODUCTION

Aggregates, the major constituent of concrete, influence the properties and performance of both freshly mixed and hardened concrete. In addition to serving as an inexpensive filler, they impart certain positive benefits that are described in this guide. When they perform below expectation, unsatisfactory concrete may result. Their important role is frequently overlooked because of their relatively low cost as compared to that of cementitious materials.

This guide is to assist the designer in specifying aggregate properties. It also may assist the aggregate producer and user in evaluating the influence of aggregate properties on concrete, including identifying aspects of processing and handling that have a bearing on concrete quality and uniformity. The report is limited primarily to natural aggregates, crushed stone, air-cooled blast-furnace slag, and heavyweight aggregate. It does not include lightweight aggregates. The types of normal weight and heavyweight aggregates listed are those covered by ASTM C 33, ASTM C 63, and other standardized specifications. In most cases, fine and coarse aggregate meeting ASTM C 33 will be regarded as adequate to insure satisfactory material. Experience and test results of those materials are the basis for discussion of effects on concrete properties in this guide. Other types of slag, waste materials, and marginal or recycled materials may require special investigations for use as concrete aggregate. Definitions and

classifications of concrete aggregates are given in ACI 116R.

This guide is divided into six major parts: (1) properties of hardened concrete influenced by aggregate properties, (2) properties of freshly mixed concrete influenced by aggregate properties, (3) aspects of processing and handling which have a bearing on concrete quality and uniformity, (4) quality control, (5) marginal and recycled aggregates, and (6) heavyweight aggregate.

While a designer or user does not normally specify the methods and equipment to be used in aggregate processing or beneficiation, processing may influence properties important to performance. Therefore, Chapter 4 is included not only as a guide for aggregate producers but for the benefit of anyone who must frequently handle aggregates.

Aggregate selection should be based on technical criteria and economic considerations. When available in sufficient detail, service records are a valuable aid to judgment. They are most useful when the structures, concrete proportions, and exposure are similar to those anticipated for the proposed work. Petrographic analysis can be used to determine whether the aggregate to which the service record applies is sufficiently similar to the proposed aggregate for the service record to be meaningful. It also provides useful information on acceptability of aggregate from a new source. As circumstances change or as experience increases, it may be desirable to reexamine acceptance criteria and to modify or change them accordingly.

Poor performance of hardened concrete discussed in Chapter 2 may not be the fault of the aggregate. For example, an improper air void system in the cement paste can result in failure of a saturated concrete exposed to freezing and thawing conditions. Chemical agents, such as sulfate, may cause serious deterioration even though the aggregate used is entirely satisfactory.

Table 1.1 lists concrete properties and relevant aggregate properties that are discussed in this guide.

Test methods are indicated in Table 1.1 and are listed with their full title and source in **Chapter 8**. In many cases, the aggregate properties and test methods listed are not routinely used in specifications for aggregates. Their use may be needed only for research purposes, for investigation of new sources, or when aggregate sources are being investigated for a special application. Typical values are listed only for guidance. Acceptable aggregates may have values outside the ranges shown, and conversely, not all aggregates within these limits may be acceptable for some uses. Therefore, service records are an important aspect in evaluating and specifying aggregate sources. Some of the more routinely performed tests are described in ACI Education Bulletin E1.

A summary of data on aggregate properties and their influence on the behavior of concrete is contained in *Significance of Tests and Properties of Concrete and Concrete Making Materials* (ASTM, 1994). Information on exploration of aggregate sources, production, and rock types is in **Chapter 2** of the *Concrete Construction Handbook* (Gardell, 1974).

Table 1.1—Properties of concrete influenced by aggregate properties

Relevant aggregate property	Standard test	Typical values	Text reference	Comments
Concrete property—Durability: Resistance to freezing and thawing				
Sulfate soundness	ASTM C 88	Fine agg - 1 to 10% Coarse agg - 1 to 12%	2.1.1	Magnesium sulfate (MgSO ₄) gives higher loss percentages than sodium sulfate (Na ₂ SO ₄); test results have not been found to relate well to aggregate performance in concrete.
Resistance to freezing and thawing	ASTM C 666 and CRD-C-114 - Performance of aggregate in air-entrained concrete by rapid cycles	Durability factor of 10 to 100%	2.1.1	Normally only performed for coarse aggregate since fine aggregate does not affect concrete freezing and thawing to any large extent; results depend on moisture conditioning of coarse aggregates and concrete.
	ASTM C 682 - Aggregate in concrete, dilation test with slow freeze	Period of frost immunity from 1 to more than 16 weeks		Results depend on moisture conditioning of aggregate and concrete. For specimens that do not reach critical dilation in the test period, no specific value can be assigned.
	AASHTO T 103 - Test of unconfined aggregate in freeze-thaw	—		Used by some U.S. Departments of Transportation; test is not highly standardized between agencies. Results may help judge quality of aggregate in regional area.
Absorption	ASTM C 127 - Coarse aggregate	0.2 to 4%	2.1.1	Typical values are for natural aggregates. Most blast-furnace slag coarse aggregates are between 4 and 6%, fine aggregate about one percent less.
	ASTM C 128 - Fine aggregate	0.2 to 2%		Some researchers have found a general trend of reduced durability for natural coarse aggregate in concrete exposed to freezing and thawing with increased absorption.
Porosity	None	1 to 10% by volume for coarse aggregate	2.1.1	Porosity - The ratio, usually expressed as a percentage, of the volume of voids in a material to the total volume of the material, including the voids.
Pore structure	None	—	2.1.1	Mercury intrusion methods and gas or vapor absorption techniques can be used to estimate pore size distribution and internal surface area of pore spaces.
Permeability	None	—	2.1.1	Permeability of aggregate materials to air or water is related to pore structure.
Texture and structure and lithology	ASTM C 295 - Petrographic examination	Quantitative report of rock type and minerals present		Estimation of the resistance of the aggregate to freezing damage; type of particles that may produce popouts or disintegration
Presence of clay and fines	ASTM C 117 - Amount by washing	Fine agg - 0.2 to 6% Coarse agg - 0.2 to 1%	3.70	Larger amounts of material finer than the 75 µm sieve can be tolerated if free of clay minerals. Does not include clay balls.
	ASTM D 2419 - Sand equivalent	50 to 90%		Used only for fine aggregate; the presence of active clay may increase water demand or decrease air entrainment.
Resistance to degradation	ASTM C 131 and C 535	15 to 50% loss	2.1.4	These tests impart a good deal on impact to the aggregate as well as abrasion; therefore, results not directly related to abrasion test of concrete.
	C 1137			Degradation of fine aggregate
Abrasion resistance	ASTM C 418 - Sand blasting	Volume of concrete removed per unit area	2.1.4	These tests are performed on concrete samples containing the aggregate(s) under investigation and may provide the user with a more direct answer.
	ASTM C 779 - Three procedures	Depth of wear with time		No limit established. Test provides relative differences.
	ASTM C 944 - Rotating cutter	Amount of loss in time abraded		No limit established. Test provides relative differences.
	ASTM C 1138 - Underwater method	Abrasion loss vs. time		
Durability index	ASTM D 3744	Separate values are obtained for fine and coarse aggregate ranging from 0 to 100		This test was developed in California and indicates resistance to the production of clay-like fines when agitated in the presence of water.
Concrete property—Durability: Alkali-aggregate reactivity				
Aggregate reactivity	ASTM C 295 - Petrographic examination	Presence and amount of potentially reactive minerals	2.1.5	For important engineering works. Tests for potential expansion due to aggregate reactivity in moist exposure are often conducted using the cement-aggregate combinations expected on the project.
	ASTM C 227 - Mortar bar expansion	0.01 to 0.20% or more after 6 months	2.1.5.1	Both fine and coarse aggregate can be tested. Coarse aggregates must be crushed to fine aggregate sizes.

Table 1.1— Properties of concrete influenced by aggregate properties (cont.)

Relevant aggregate property	Standard test	Typical values	Text reference	Comments
	ASTM C 289 - Chemical method	Values are plotted on a graph	2.1.5.1	Degree of risk from alkali-aggregate reactivity is surmised from the position of the points on the graph. Many slowly reacting aggregates pass this test.
	ASTM C 586 - Rock cylinder method	0.01 to 0.20% or more after 6 months	2.1.5.3	Used for preliminary screening of potential for alkali-carbonate reactivity.
	ASTM C 1105 - Length change test			Used to determine the susceptibility to alkali-carbonate reaction.
	Accelerated concrete prism test			Under development in ASTM.
Concrete property—Durability: Resistance to heating and cooling				
Coefficient of thermal expansion	CRD-C-125 - Aggregate particles	1.0 to 9.0 x 10 ⁻⁶ /F	2.1.3	Normally not a problem for concrete. FHWA has developed a procedure for concrete.
Concrete property—Durability: Fire endurance				
Lithology	ASTM C 295 - Petrographic examination	Rock and mineral types present	2.1.6	ACI 216R provides data and design charts.
Quantity of fines	ASTM C 117 - Amount by washing	F.A - 0.2 to 6% C.A. - 0.2 to 1%	4.5	Material passing 75 µm sieve.
Concrete property—Strength				
Tensile strength	ASTM D 2936 - Rock cores	300-2300 psi	2.2	Strength tests are not normally run on aggregates, per se.
Compressive strength	ASTM D 2938 - Rock cores	10,000-40,000 psi		
Organic impurities	ASTM C 40	Color Plate No. 3 or less	4.5	Color in sodium hydroxide (NaOH) solution.
	ASTM C 87	85 to 105%		Strength comparison with sand washed to remove organics.
Particle shape	ASTM C 295 - Petrographic	Appearance of particles	4.4	A variety of particle shape tests are available. None are widely used as specific values.
	ASTM D 4791 - Coarse aggregate	% flat or elongated	5.1	
	CRD-C-120 - Fine aggregate	% flat or elongated		
	ASTM D 3398	Particle shape index		More angular particle produces a higher index value.
	ASTM C 29	38 to 50%		NAA-NRMCA and others have test methods; one is under development in ASTM for fine aggregate.
Clay lumps and friable particles	ASTM C 142	0.5 to 2%	4.3.1	Breaking soaked particles between fingers.
	CRD-C-141 - Attrition of fine aggregate	Amount of fines generated	5.1	Uses a paint shaker.
	ASTM C 1137	Same as above		
Maximum size	ASTM C 136 - Sieve analysis	1/2 to 6 in	4.2.2	
Concrete property—Volume change				
Grading and fineness modulus	ASTM C 136	Grading	4.2	
Modulus of elasticity	None	1.0-10.0 x 10 ⁶ psi	2.3, 2.1.2, and 2.1.3	
Presence of fines	ASTM C 117	See above		Presence of clay and other fines can increase drying shrinkage.
Presence of clay	ASTM D 2419	70 to 100%		
Maximum size	ASTM C 136	1/2 to 6 in		
Grading	ASTM C 136	See ASTM C 33		Grading can affect paste concrete.
Concrete property—Thermal characteristics				
Coefficient of thermal expansion	CRD-C-125	1.0-9.0 x 10 ⁻⁶ /F	2.4	For coarse aggregate.
Modulus of elasticity	None	1.0-10.0 x 10 ⁶ psi		
Specific heat	CRD-C-124			For aggregates and concrete.
Conductivity	None			$K = hcp$ - diffusivity x specific heat x density.
Diffusivity	None			$h = k/cp$ = conductivity (specific x density).
Concrete property—Density				
Specific gravity	ASTM C 127	1.6-3.2	2.5	
	ASTM C 128	1.6-3.2		
Particle shape	ASTM C 295			Affects water demand and workability.
	ASTM D 4791			
	CRD-C-120			
	ASTM C 1252			
	ASTM D 3398			
Grading	ASTM C 136			
Fineness modulus	CRD-C-104	5.5-8.5		For coarse aggregate.

Table 1.1— Properties of concrete influenced by aggregate properties (cont.)

Relevant aggregate property	Standard test	Typical values	Text reference	Comments
Fineness modulus	ASTM C 136	2.2-3.1		For fine aggregate.
Maximum size	ASTM C 136	3/8-6 in		
Lightweight particles	ASTM C 123	0-5%		Lighter than 2.40 specific gravity; natural aggregate values may be higher.
Density	ASTM C 29	75-110 lb/ft ³		Dry-compacted amount in a container of known volume.
Concrete property—Modulus of elasticity				
Modulus of elasticity	None	1.0-10.0 x 10 ⁶ psi	2.6	Not a normal test for aggregate.
Poisson's ratio		0.1-0.3		Not a normal test for aggregate.
Concrete property—Strain capacity				
Strain capacity	CRD-C 71			For mass concrete.
Concrete property—Frictional properties of pavements				
Tendency to polish	ASTM D 3042		2.7	
	ASTM D 3319			
Hardness, lithology	ASTM C 295—Petrographic examination	Quantitative report of rock type and minerals present	2.1.4	Hard minerals in fine and coarse aggregates tend to improve concrete resistance to abrasion and to improve surface frictional properties in pavement.
Surface texture	ASTM C 295		5.1 and 5.3	Particle angularity and surface texture affect surface friction in wet weather.
	ASTM C 295			
Particle shape and texture	ASTM D 3398			
Concrete Property—Workability of freshly mixed concrete				
Grading	ASTM C 136		5.1 and 5.3	
Fineness modulus	ASTM C 136 and 125			
Particle shape and texture	ASTM C 295			
	ASTM D 3398			
	ASTM D 4791			
	CRD-C-120			
	ASTM C 1252			
Presence of fines	ASTM C 117	0.2-6%	5.1 and 5.3	Typical value for fine aggregate.
		0.2-1.0%	5.1 and 5.3	Typical value for coarse aggregate.
Presence of clay	ASTM D 2419	70-100%	5.1 and 5.3	Presence of clay and other fines may increase mixing water demand and decrease entrained air.
Friable particles and degradation	CRD-C-141			
	ASTM C 142			
Voids	ASTM C 29		3.2 and 3.4	Voids between particles increase with angularity.
	ASTM C 1252			
Organic impurities	ASTM C 40	Color 1 or 2		If darker than Color Plate 3 organic material may affect setting or entrained air content.
	ASTM C 87			
Concrete—Economic Considerations				
Particle shape and texture	ASTM C 295		2.8	
	ASTM D 3398			
	ASTM D 4791			
	CRD-C-120			
	ASTM C 1252			
Grading	ASTM C 136			
Maximum size	ASTM C 136			
Required processing			4.2	
Concrete making characteristics	ACI 211		3.2	
Availability				

See Chapter 8 for titles and sources of test methods.

CHAPTER 2—PROPERTIES OF HARDENED CONCRETE INFLUENCED BY AGGREGATE PROPERTIES

2.1—Durability

For many conditions the most important property of concrete is its durability. There are many aspects of concrete durability, and practically all are influenced by properties of the aggregate.

2.1.1 Freezing and thawing—Concrete containing freeze and thaw resistant paste may not be resistant to freezing and thawing if it contains aggregate particles that become critically saturated. An aggregate particle is considered to be critically saturated when there is insufficient unfilled pore space to accommodate the expansion of water which accompanies freezing (Verbeck and Landgren, 1960). Field observations, laboratory studies, and theoretical analysis indicate there is a critical particle size above which the particle will fail under repeated freezing-thawing cycles if critically saturated. This size is dependent on pore structure, permeability, and tensile strength of the particle. Experience has yet to show that fine aggregates are directly associated with freezing-thawing deterioration of concrete. Some porous coarse aggregates can, on the other hand, cause deterioration of concrete due to freezing. For fine-grained coarse aggregates with fine-textured pore systems and low permeability, the critical size may be in the range of normal aggregate sizes. For coarse-grained materials with coarse-textured pore systems or materials with a capillary system interrupted by numerous macropores, the critical size might be so large as to be of no practical consequence, even though the absorption might be high. In such cases, stresses are not sufficiently high enough to damage the concrete.

It is well recognized that laboratory freezing and thawing tests of coarse aggregate in concrete can be used to judge comparative performance. However, results can vary between laboratories, and performance may be affected by the degree of saturation of the aggregate prior to incorporation in concrete, the curing of the concrete prior to freezing, and whether the concrete is maintained in a saturated condition during freezing cycles. ASTM Method C 666 and U.S. Army Corps of Engineers Procedure CRD-C-114 involve automatic equipment in which concrete specimens are subjected to a number of freezing and thawing cycles per day. Concrete performance is evaluated by weight changes, decrease in dynamic modulus of elasticity, and length increase as indicators of damage. Durability factor is computed from the relative dynamic modulus of elasticity at the conclusion of the test compared to the initial value before freezing.

ASTM C 682 involves evaluating an aggregate in concrete through the use of a continuous soaking period and then a slow cycle of freezing and thawing every two weeks. Damage has occurred when a dilation or length increase is noted above the normal contraction as the concrete is cooled below freezing. The “period of frost immunity” is the total number of weeks of test necessary to cause the critical dilation to occur.

A number of laboratory tests performed on unconfined aggregates are intended as a measure of soundness, resistance to freezing and thawing, and a general indicator of quality. These methods are not as well related to freezing and thawing performance in the field as the tests discussed previously using the

aggregate in concrete. Two examples of the unconfined soundness tests are listed in Table 1.1, ASTM C 88 using cycles of soaking and oven drying with a solution of magnesium or sodium sulfate, and AASHTO T 103 where a collection of aggregate particles is subjected to a freezing-thawing test.

In many cases results of these unconfined tests are used as an indicator of quality, but limits may not be imposed if service records indicate the aggregate source is satisfactory or if it performs well in a prescribed laboratory freezing and thawing test in concrete.

Various properties related to the pore structure within the aggregate particles, such as absorption, porosity, pore size and distribution, or permeability, may be indicators of potential durability problems for an aggregate used in concrete that will become saturated and freeze in service. Generally, it is the coarse aggregate particles with higher porosity or absorption values, caused principally by medium-sized pore spaces in the range of 0.1 to 5 μm , that are most easily saturated and contribute to deterioration of concrete. Larger pores usually do not become completely filled with water. Therefore, damage does not result from freezing.

Petrographic examination of aggregates may help identify the types of particles present that may break down in freezing and thawing. This may be particularly helpful when it is known what types of particles produce popouts from a particular source. A count of the percentage of that material above the previously determined critical size to produce freezing and thawing damage would be a helpful indicator, particularly where appearance is important. Presence of increased amounts of clays and fines in an aggregate can lower strength and durability if significantly more mixing water is required for workability. Fines containing clay are more critical than rock fines from other minerals. Excessive fines can also lower the entrained air content obtained in concrete with a given admixture dosage.

Distress due to freezing and thawing action in critically saturated aggregate particles is commonly manifested in the occurrence of general disintegration or popouts and/or in a phenomenon known as D-cracking. A popout is characterized by the breaking away of a small portion of the concrete surface due to excessive tensile forces in the concrete created by expansion of a coarse aggregate particle, thereby leaving a typical conical spall in the surface of the concrete through the aggregate particle. These popouts may develop on any surface directly exposed to moisture and freezing and thawing cycles. Chert particles of low specific gravity, limestone containing clay, and shaly materials are well known for this behavior. Occasional popouts in many applications may not detract from serviceability. Popouts may also occur due to alkali-silica reactions as discussed under the section on alkali-silica reactivity (Section 2.1.5.1).

D-cracking occurs in slabs on grade exposed to freeze, thaw, and moisture, particularly in highway and airfield pavements. Here it is manifested in the development of fine, closely spaced cracks adjacent and roughly parallel to joints, and along open cracks and the free edges of pavement slabs. When D-cracking is observed in the surface, deterioration in the bottom part of the slab is usually well

advanced. Distress is initiated in the lower and middle levels of the slabs where critical saturation of the potentially unsound aggregate particles is most often reached. Nearly all occurrences of D-cracking are associated with sedimentary rocks, including limestone, dolomite, shale, and sandstone. Aggregate particles that cause popouts can also be expected to cause D-cracking when present in large quantities, but particles that cause D-cracking do not necessarily cause popouts. In both cases, reduction of particle size is an effective means of reducing these problems, and present laboratory freezing and thawing tests of concrete containing the coarse aggregate are capable of identifying many potentially nondurable aggregates.

2.1.2 Wetting and drying—The influence of aggregate on the durability of concrete subjected to wetting and drying is also controlled by the pore structure of the aggregate. This problem, occurring alone, is usually not as serious as damage caused by freezing and thawing. Differential swelling accompanying moisture gain of an aggregate particle with a fine-textured pore system may be sufficient to cause failure of the surrounding paste and result in the development of a popout. The amount of stress developed is proportional to the modulus of elasticity of the aggregate. Many times friable particles or clay balls in aggregate, which are detected by ASTM C 142, are weakened on wetting and may degrade on repeated wetting and drying.

2.1.3 Heating and cooling—Heating and cooling induce stresses in any nonhomogeneous material. If the temperature range is great, damage may result. For aggregates commonly used and for temperature changes ordinarily encountered, this is not usually a critical factor in concrete. However, it has been reported (Willis and DeReus, 1939; Callan, 1952; Pearson, 1942; Parsons and Johnson, 1944; and Weiner, 1947) that large differences in the coefficient of expansion or thermal diffusivity between the paste and the aggregate can result in damaging stresses in concrete subject to normal temperature change. In interpreting laboratory tests and field observations, it is difficult to isolate thermal effects from other effects such as moisture changes and freezing and thawing. Although the usual practice is not to restrict the expansion coefficient of aggregate for normal temperature exposure, aggregates with coefficients that are extremely high or low may require investigation before use in certain types of structures. Normally, concrete containing aggregate with a low modulus of elasticity withstands temperature strains better than that containing aggregate with a high modulus (Carette, et al., 1982).

2.1.4 Abrasion resistance—Abrasion resistance and localized impact resistance of concrete is a property that is highly dependent on the quality of both the cement paste and the aggregate at and near the surface receiving localized impact and abrasive stresses. In those cases where the depth of wear is not great, there will be little exposure of coarse aggregate, and only the presence of a hard and strong fine aggregate in a good quality cement paste may be necessary to provide needed surface toughness. Examples of this might be industrial floors, certain hydraulic structures, and pavements. In other uses, such as highways, some exposure of coarse ag-

gregate is usually acceptable as long as the coarse material is not easily worn away by traffic, particularly where studded tires or chains are used.

ASTM C 131 (or C 535 for aggregate larger than $\frac{3}{4}$ in. [19 mm]), generally referred to as the Los Angeles abrasion test, is used as a quality test for abrasion, impact, or degradation of coarse aggregates. The test involves impact and tends to break hard, brittle aggregates that may not break in service. It is generally known that there is a poor relationship between percent loss or wear in the test and concrete wear or durability in service (ASTM, 1994). It may provide a means of identifying obviously inferior materials that tend to degrade in production handling or in service. However, the specification of an unrealistically low test value may not guarantee good abrasion resistance of a concrete surface. Conversely, a high test value may not preclude a good abrasion resistance of concrete. Aggregate hardness is required to resist scratching, wearing, and polishing types of attrition in service. According to Stiffler (1967 and 1969), who conducted tests where minerals were subjected to wear using abrasives, "Hardness is the single most important characteristic that controls aggregate wear." For uses of concrete where abrasion resistance is critical, abrasion tests of concrete containing the proposed aggregates should be performed by an appropriate test procedure. ASTM C 418, C 779, and C 944 provide a selection of abrasive actions on dry concrete and ASTM C 1138 provides an underwater method.

2.1.5 Reactive aggregates—The use of some aggregates may result in deleterious chemical reaction between certain constituents in the aggregates and certain constituents in the cement, usually the alkalis. All aggregates are generally believed to be reactive to some degree when used in portland cement concrete, and some reaction evidence has been identified petrographically in many concretes that are performing satisfactorily. It is only when the reaction becomes extensive enough to cause expansion and cracking of the concrete that it is considered to be a deleterious reaction. Moisture condition and temperature range of the concrete in service may significantly influence the reactivity and its effects. In most cases, it is not necessary to further consider aggregate reactivity if aggregates have a known good service record when used with cement with similar alkali levels. Two principal deleterious reactions between aggregates and cement alkalis have been identified. These are:

- Alkali-silica reaction, and
- Alkali-carbonate reaction

In both cases, a deleterious reaction may result in abnormal expansion of the concrete with associated cracking, popouts, or loss of strength. Other damaging chemical reactions involving aggregates can also occur (Section 2.1.8).

2.1.5.1 Alkali-silica reaction—Deterioration of concrete due to the expansive reaction between siliceous constituents of some aggregates and sodium and potassium oxides from cements has occurred in numerous locations in the U.S. and elsewhere (Helmuth, et al., 1993; Mid-Atlantic Regional Technical Committee, 1993 and 1993a; Portland Cement Association, 1994; Stark, et al, 1993). Typical manifestations of alkali-silica reaction are expansion, closing of joints, disloca-

tion of structural elements and machinery, cracking (usually map or pattern cracking), exudations of alkali-silicate gel through pores or cracks which then form jellylike or hard beads on surfaces, reaction rims on affected aggregate particles within the concrete, and occasionally, popouts. It should be noted that some of these manifestations also can occur from other phenomena such as sulfate attack. Petrographic examination must be used to identify the causes of the reaction.

Rock materials identified as potentially deleteriously reactive are opal, chalcedony, microcrystalline to cryptocrystalline quartz, crystalline quartz that is intensely fractured or strained, and latitic or andesitic glass, or cryptocrystalline devitrification products of these glasses. All of these materials are highly siliceous. Some of the principal rock types that may contain the reactive minerals are cherts, siliceous limestones and dolomites, sandstones, quartzites, rhyolites, dacites, andesites, shales, phyllites, schists, granite gneisses, and graywackes. However, these rock types do not necessarily contain any of the reactive minerals. Manufactured glass, such as bottle glass, may be reactive when present as a contaminant in otherwise suitable aggregate. Recycled crushed glass aggregate should not be used in concrete.

The principal factors governing the extent of expansive reactivity of the aggregates are:

1. Nature, amount, and particle size of the reactive material,
2. The amount of soluble alkali contributed by the cementitious material in the concrete, and
3. Water availability.

One way to avoid expansion of concrete resulting from alkali-silica reaction is to avoid using reactive aggregates. Sometimes this is not economically feasible. When reactive aggregates must be used, it should be only after thorough testing to determine the degree of reactivity of the aggregate. Moisture condition and temperature range of the concrete in service may significantly influence the reactivity. Once this is known, appropriate limits on the alkali content of the cement can be established, use of an effective pozzolan or ground slag can be considered, or a combination to reduce the potential for reaction, as discussed in ACI 201.2R.

Evaluation of aggregates for potential damage due to alkali-silica reaction requires judgment based on service records of the aggregate source, if available, and possible use of one or more ASTM laboratory procedures such as C 295 for petrographic examination, C 227 for mortar bar expansion of the aggregate used with cement, and the quick chemical method C 289. In some cases, one or more of the tests will indicate potential reactivity, but if the source has a good service record for a long period of time in a similar environment, and if the aggregate in such concrete is petrographically similar to the aggregate under evaluation, it may be acceptable for use, particularly with a low-alkali cement. However, use of low-alkali cement (less than 0.60 percent alkali as equivalent sodium oxide) may not be sufficient to prevent expansive reactivity, particularly where reactive volcanic rocks are to be used. That is, the more important measure is pounds of alkali per cubic yard of concrete because a rich mixture with a

low-alkali cement may have as much alkali per cubic yard as a lean mixture with a high-alkali cement. Certain pozzolans, blended cements, or slag cements are being used to eliminate the risk of deleterious alkali-silica reaction and may be evaluated by ASTM C 441 (Mather, 1975).

2.1.5.2 Cement-aggregate reaction—Cement-aggregate reaction is a name given to a particular alkali-silica reaction when the reaction occurs even though low-alkali cement had been used in the concrete. Sand-gravel aggregates occurring along some river systems in the states of Kansas, Nebraska, Iowa, Missouri, and Wyoming have been involved in concrete deterioration attributed to cement-aggregate reaction. Later research indicates that this is actually alkali-silica reaction wherein moisture migration and drying can cause a concentration of alkalis in localized areas of the concrete. Aggregates from the various states often are not similarly constituted and have various expansive tendencies. The principal manifestation of the expansion is map cracking. To avoid the problem, only aggregates with good service records should be used.

If these aggregates have to be used, the alkalis in the cement should be limited; however, this has not always been a suitable remedial measure. Two techniques that may help are use of an effective pozzolan or partial replacement with nonreactive limestone coarse aggregate.¹⁶

2.1.5.3 Alkali-carbonate rock reaction—Certain dolomitic limestone aggregates found in the U.S. and elsewhere are susceptible to this reaction. However, most carbonate rocks used as concrete aggregate are not expansive. All of the expansive reactive carbonate rocks are generally thought to have the following features:

1. They are dolomitic but contain appreciable quantities of calcite.
2. They contain clay and/or silt.
3. They have an extremely fine-grained matrix.
4. They have a characteristic texture consisting of small isolated dolomite rhombs disseminated in a matrix of clay or silt and finely divided calcite.

The clay may contribute to expansion by providing mechanical pathways to the reacting dolomite rhombs by disrupting the structural framework of the rock, thus weakening the carbonate matrix. Research on this reaction (Buck, 1975) has been performed, and control measures have been developed to use potentially expansive rocks (U.S. Army Corps of Engineers, 1985). These include selective quarrying to eliminate the deleterious rock or to restrict its amount and use of cement with not more than 0.40 percent alkali as equivalent sodium oxide.

2.1.6 Fire-resistance—Aggregate type has an influence on the fire resistance of concrete structures as discussed in ACI 216R. Laboratory tests (Selvaggio and Carlson, 1964, and Abrams and Gustaferro, 1968) have shown concrete with lightweight aggregate to be more fire-resistant than concrete with normal weight aggregate. This lighter material reduces the thermal conductivity of the concrete and thus insulates the concrete better from the heat source. Also, blast furnace slag is more fire-resistant than are other mineral aggregates (Lea, 1971) because of its lightness and mineral

stability at high temperature. Very little research has been done on the fire resistance of heavyweight aggregate.

Carbonate aggregates are generally more resistant to fire than are certain siliceous aggregates. Dolomites calcine at 1110-1290 F (600-700 C) and the calcite in limestone calcines at about 1650 F (900 C) in a 100 percent carbon dioxide atmosphere. As the calcined layer is formed, it insulates the concrete from the heat source and reduces the rate at which the interior of the concrete becomes heated.

Aggregates containing quartz such as granite, sandstone, and quartzite are susceptible to fire damage. At approximately 1060 F (570 C), quartz undergoes a sudden expansion of 0.85 percent caused by the transformation of "alpha" quartz to "beta" quartz. This expansion may cause concrete to spall and lose strength.

2.1.7 Acid resistance—Siliceous aggregates (quartzite, granite, etc.) are generally acid resistant. The opposite is true of carbonate aggregates (limestone and dolomite) which, under most conditions, react with acids. However, the cement paste of concrete will also react with acid, and under mild acid conditions a concrete with carbonate aggregates may be more acid-tolerant than if made with siliceous aggregates. This is because under these conditions the sacrificial effect of the carbonate aggregate can significantly extend the functional life of the concrete. Where concrete is routinely exposed to severe acid environments an appropriate protective coating or non-portland (such as epoxy) cement concrete with acid resistant aggregate may be required.

2.1.8 Other reactions—Other chemical reactions that involve the aggregate, and that may lead to distress of the hardened concrete, include hydration of anhydrous minerals, base exchange and volume change in clays and other minerals, soluble constituents, oxidation and hydration of iron compounds, and reactions involving sulfides and sulfates. These problems have been discussed in some detail by Hansen (1963) and Mielenz (1963). Materials that may cause such reactions can usually be detected in standard aggregate tests and particularly by petrographic examination.

Calcium and magnesium oxides may contaminate aggregates transported in railroad cars or trucks previously used to transport quicklime or dolomitic refractories. Under rare conditions of blast furnace malfunctions, incompletely fused pieces of flux stone may be discharged with the slag. Unless hydrated prior to incorporation in concrete, these materials may produce spalls and popouts after the concrete has set. Care must also be taken to avoid contamination of concrete aggregates with materials intended for non-concrete applications. These materials may be deleterious in concrete.

Oxidation and hydration of ferrous compounds in clay ironstone and of iron sulfides (such as pyrite and marcasite) in limestones and shales are known to have caused popouts and staining in concrete. Metallic iron particles in blast furnace slags may oxidize if exposed at or very near the concrete surface, resulting in minor pitting and staining.

Sulfates may be present in a variety of aggregate types, either as an original component or from oxidation of sulfides originally present. Water soluble sulfates may attack the aluminates and calcium hydroxide in the cement paste, causing expansion and general deterioration. Gypsum is the most common sulfate in aggregates, occurring as coatings on gravel and sand, and as a component of some sedimentary rock, and may be formed in slags by longtime weathering in pits or banks. Aggregates made from recycled building rubble may contain sulfates in the form of contamination from plaster or gypsum wall board.

Other water soluble salts, such as sulfates and chlorides, may occur in natural aggregates in some areas and contribute to efflorescence or corrosion of embedded steel. If routine measurements of total chlorides exceed limits in ACI 201.2R or ACI 318, then testing the concrete or aggregates for water soluble chlorides, using AASHTO method T 260 or ASTM methods C 1218 or D 1411, as appropriate, is recommended. Some zeolitic minerals and clays are subject to base exchange that may influence alkali-aggregate reactions and have been suspected of causing expansion in concrete.

2.2—Strength

Perhaps the second most important property of concrete, and the one for which values are most frequently specified, is strength. The types of strength usually considered are compressive and flexural. Strength depends largely on the strength of the cement paste and on the bond between the paste and aggregate. The strength of the aggregate also affects the strength of the concrete, but most normal weight aggregates have strengths much greater than the strength of the cement paste with which they are used. Consideration of factors affecting the strength of the paste is beyond the scope of this report. The bond between the paste and aggregate tends to set an upper limit on the strength of concrete that can be obtained with a given set of materials, particularly in the case of flexural strength. Bond is influenced by the surface texture, mineral composition, particle size and shape, and cleanliness of the aggregate. Cement paste normally bonds better to a rough-textured surface than a smooth surface. Surface texture is more important for coarse aggregates than for fine aggregates. Coatings that continually adhere to the aggregate even during the mixing process may interfere with bond. Those that are removed during mixing have the effect of augmenting the fines in the aggregates. If those coatings that remain on the aggregate particle surface after mixing and placing are of a certain chemical composition, they may produce a deleterious reaction with alkalis in cement as detailed in ASTM STP 169C Chapter 36 (ASTM, 1994). Clay coatings will normally interfere with bond, while nonadherent dust coatings increase the water demand as a consequence of the increase in fines (Lerg, 1941).