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Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete

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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.

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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* (Waddell, 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 ($NaSO_4$); 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 at 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 aggregate 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 $^3/_4$ 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 alkalies. 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 alkalies 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, dislocation 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 alkalies 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 alkalies 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 normal weight 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 alkalies 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 (Lang, 1943).

Angular particles and those having rough, vesicular surfaces have a higher water requirement than rounded material. Nevertheless, crushed and natural coarse aggregates generally give substantially the same compressive strengths for a given cement factor. For high-strength concrete, crushed cubical coarse aggregate generally produces higher compressive strength than rounded gravel of comparable grading and quality. Some aggregates, which are otherwise suitable, have a higher than normal water requirement because of unfavorable grading characteristics or the presence of a large proportion of flat or elongated particles. With such materials it is necessary to use a higher than normal cement factor to avoid excessively high water-cement ratios and, as a result, insufficient strength. Water requirements also may be increased by nonadherent coatings and by poor abrasion resistance of the aggregate in that both increase the quantity of fines in the mixer. Fine aggregate grading, particle shape, and amount all have a major influence on the strength of concrete because of their effect on water requirements. Within limits, proportions should be adjusted to compensate for changes in fine aggregate grading, more of a coarse fine aggregate should be used in concrete, less of a fine fine aggregate.

There is experimental evidence (Walker and Bloem, 1960) to show that at a fixed water-cement ratio, strength decreases as maximum size of aggregate increases, particularly for sizes larger than $1^1/_2$ in. (38 mm). However, for the same cement content, this apparent advantage of the smaller size may not be shown because of the offsetting effects of the required increased quantity of mixing water. For high-strength concretes, optimum maximum aggregate size will usually be less than $1^1/_2$ in. (38 mm), and this size tends to decrease with increasing strength (Cordon and Thorpe, 1975).

2.3—Shrinkage

Aggregate has a major effect on the drying shrinkage of concrete. With cement paste having a high shrinkage potential, aggregate introduced into the paste to make mortar or concrete reduces paste shrinkage due to the restraint provided by the aggregate, and to the dilution effect (less paste). The resulting shrinkage of the concrete is a fraction of the shrinkage of the paste due to these effects. Therefore, the shrinkage of concrete under given drying conditions is dependent on the shrinkage potential of the paste and the properties and amount of the aggregate. The relative importance of these factors will vary.

Table 2.1— Drying shrinkage of concrete

Aggregate	Specific gravity	Absorption, percent	One-year shrinkage, 50 percent relative humidity, millionths	One-year shrinkage, percent
Sandstone	2.47	5.0	1160	0.12
Slate	2.75	1.2	680	0.07
Granite	2.67	0.5	470	0.05
Limestone	2.74	0.2	410	0.04
Quartz	2.65	0.3	320	0.03

Factors associated with the aggregate that affect drying shrinkage of concrete are as follows:

1. Stiffness, compressibility, or modulus of elasticity of the aggregate.
2. Properties of the aggregate such as grading, particle shape, and maximum aggregate size that influence the amount of water required by the concrete and the amount of aggregate used in the concrete.
3. Properties of the aggregate (texture, porosity, etc.) that affect the bond between the paste and aggregate.
4. Clay on or within the aggregate that contributes to an actual shrinkage of the aggregate on drying or that contributes clay to the paste. Some aggregates which shrink on drying have high absorption values.

Carlson (1938) reported the following results of drying shrinkage of concrete made with different types of aggregate (Table 2.1).

Tests were made under identical exposure conditions.

Aggregates containing quartz or feldspar and limestone, dolomite, granite, and some basalts can generally be classified as low shrinkage-producing aggregates. Aggregates containing sandstone, shale, slate, graywacke, or some types of basalt have been associated with high-shrinkage concrete. However, the properties of a given aggregate type, such as limestone, granite, or sandstone, can vary considerably with different sources. This can result in significant variation in shrinkage of concrete made with a given type of aggregate.

Drying shrinkage of concrete is influenced by the water content of the concrete. Therefore, the various aggregate properties that influence the amount of water used are a factor in the amount of drying shrinkage. These factors are particle shape, surface texture, grading, maximum aggregate size, and percentage of fine aggregate.

Neville (1981) reports that some Scottish dolerites shrink on drying. Some South African aggregates have considerable shrinkage on drying (Stutterheim, 1954). Aggregate with high absorption should be a warning sign that the aggregate may produce concrete with high shrinkage.

If one needs to know the drying shrinkage potential of concrete made with a given aggregate, drying shrinkage tests made under carefully controlled conditions are required. The magnitude of the shrinkage obtained is dependent on the test procedure and specimen.

2.4—Thermal properties

The properties of aggregate that have an effect on the thermal characteristics of concrete are the specific heat, coefficient of thermal expansion, thermal conductivity, and thermal diffusivity.

The coefficient of thermal expansion for concrete can be computed approximately as the average of the values for the constituents weighted in proportion to the volumes present (Walker, et al., 1952, and Mitchell, 1953). Similarly, each of the materials composing the concrete contributes to the conductivity and specific heat of the concrete in proportion to the amount of the material present. Moisture content of the concrete particularly influences the thermal coefficient of the concrete, as well as the thermal diffusivity (U.S. Bureau of Reclamation, 1940).

The coefficient of thermal expansion of commonly used aggregates varies with the mineralogical composition of the aggregate, particularly with the amount of quartz the rock contains. The more quartz present, the higher the coefficient of thermal expansion. Cement paste has a coefficient of thermal expansion approximately 1.5 times larger than quartz, which has the highest coefficient of thermal expansion of the common minerals. Therefore, aggregate that has a low thermal coefficient would be preferred when overall differential thermal stresses through a section of concrete are a concern. However, using an aggregate with a lower coefficient would increase the differential thermal stresses between the paste and aggregate. It therefore must be decided which of these stress situations is of greater concern.

Thermal conductivity varies directly with the unit weight of the concrete. Generally, the denser the aggregate used, the higher the value of the thermal conductivity. Cement paste has a lower thermal conductivity than most aggregates. Therefore, the more aggregate used in the mixture the higher the value of thermal conductivity.

2.5—Unit weight

The unit weight of the concrete depends on the specific gravity of the aggregate, on the amount of air entrained, mix proportions, and the properties previously discussed that determine water requirement. Since the specific gravity of cement paste is less than that of normal weight aggregate, unit weight normally increases as the amount of paste decreases.

2.6—Modulus of elasticity

The influence of aggregate on concrete modulus of elasticity is normally determined by testing concrete mixtures containing the aggregate in question. Both in compression and tension, the stress-strain curves for rock specimens are normally a fairly linear relationship indicating that the aggregate is reasonably elastic. Concrete mortar, on the other hand, has a curved stress-strain relationship when the stress exceeds about 30 percent of ultimate strength. This is due to the nonlinear behavior of the cement paste and formation of bond cracks and slipping at the aggregate-paste interface. Because of this there is no simple relationship between aggregate and concrete modulus of elasticity. LaRue (1946) found that for a given cement paste the modulus of elasticity of the aggregate has less effect on the modulus of elasticity of the concrete than can be accounted for by the volumetric proportions of aggregate in concrete. Hirsch (1962) gives data where aggregates with modulus of elasticity values of about 2, 5, 9, 11, and 30 x 10^6 psi (13, 34, 62, 76, and 207 GPa) did indicate “that the modulus of elasticity of concrete is a function of the elastic moduli of the constituents.” In general, as the modulus of elasticity of the aggregate increases so does the modulus of elasticity of the concrete, and as the volume of the aggregate increases, the modulus of the concrete will approach the modulus of elasticity of the aggregate. However, where the modulus of elasticity of the concrete must be known fairly accurately, tests of the concrete are recommended instead of the computation of modulus of elasticity from the properties of the aggregate based on empirical or theoretical relationships.

2.7—Surface frictional properties

The coefficient of friction or slipperiness of concrete surfaces is influenced by the properties of the aggregates used at the surfaces. Initially the finished texture of the surface and hardness of the fine aggregate are important. The coarse aggregate will become involved only if there is enough loss of surface material to expose a significant amount of the coarse particles. Polishing is a special form of wear where abrasive size is quite small, such as typical road grit at 10 to 40 micrometers, and the action is such that the texture present is gradually smoothed and polished. Skid resistance of pavement surfaces in wet weather depends on microtexture and, also, on macrotexture if significant speeds are involved. Macrotexture of a concrete surface is produced by the finishing operation, and is important to provide escape channels for excess water from between the tire and pavement during wet weather. Microtexture is controlled by the grading of the fine aggregate and any exposed coarse aggregate, and the texture and polishing characteristics of the cement paste, fine aggregate, and coarse aggregate exposed at the surface. Aggregate polishing characteristics are related to aggregate petrology. Some carbonate aggregates polish more rapidly than most other aggregate types, and the acid insoluble residue test (ASTM D 3042) has been used to measure the amount of harder noncarbonate minerals present in carbonate aggregates in an attempt to better define the polish susceptibility of various aggregate sources from that group.

Most mineral aggregate material used in concrete will gradually polish when exposed at the pavement surface, with the softer minerals polishing more rapidly than the hard minerals (Colley, et al., 1969, and Mullen, et al., 1971). Exceptions are friable or vesicular aggregate, which, as it wears, tends to have pieces break off, thus exposing new unpolished surfaces. These materials may result in higher rates of wear in the wheelpaths, creating ruts. However, they can provide a higher level of friction over a long period of time. Meyer (1974), in using a number of concrete finishing textures, silica gravel and limestone coarse aggregates, and silica or lightweight fine aggregate, found good skid resistance in all cases, but the lightweight fines did wear faster. In other studies where calcareous fine aggregates were used in concrete, low skid resistances have been found.

The highest long-term pavement skid resistance is obtained by aggregates whose sacrificial surfaces are continually renewed by traffic. Fine aggregate usually has a greater effect than coarse aggregate on skid resistance, at least until surface wear extensively exposes the coarse aggregate. The AASHTO "Guidelines for Design of Skid Resistant Pavements" suggests a minimum siliceous particle content of 25 percent in the fine aggregate, while stating that coarse aggregate will not affect skid resistance until exposed. Even then, a skid resistant mortar will insure adequate microtexture, although macrotexture may have to be restored by grooving, milling, or other coarse texturing techniques. Aggregates composed of hard minerals in a medium-hard mineral matrix will resist polishing and maintain higher levels of skid resistance than will aggregates composed predominantly of the same mineral or of minerals having the same hardness (except the friable or vesicular aggregate as noted previously). The more angular the hard mineral grains and the more uniform their distribution in the softer matrix, the higher the resulting skid resistance will be for the aggregate. A mixture of approximately equal portions of hard and soft mineral grains appears to be optimum for maximum skid resistance. Polishing resistance of limestone aggregates has been investigated (Sherwood and Mahone, 1970, and Nichols, 1970).

Laboratory and field testing of pavement materials and aggregates for polishing rate and skid resistance have become widespread. Many highway agencies have a minimum aggregate rating for surface-course material on the basis of either field performance of each material, material classifications, or on the basis of laboratory tests. The requirements are often graduated on the basis of the projected traffic.

2.8—Economy

Generally, the cost that aggregates contribute to the total in-place cost of concrete is relatively low unless special aggregates are specified. Costs of aggregates are usually governed by availability, cost of processing, and distance transported. Frequently, there are other factors which, if properly considered, can have a much greater economic or environmental impact than direct aggregate cost. Some of the more important factors are aggregate quality (cleanliness, durability), particle shape, grading, water requirements, cement requirements, density and yield, effect on concrete strength, and effect on placeability and finishability. A thorough understanding of these factors and their interrelation when used in the proportioning of concrete mixtures can significantly affect the cost of in-place concrete.

CHAPTER 3—PROPERTIES OF FRESHLY MIXED CONCRETE INFLUENCED BY AGGREGATE PROPERTIES

3.1—General

Aggregates may vary greatly in composition due to geologic factors involved in the formation, subsequent deformation, and mineralogy of the source material. Other compositional differences in the aggregates may be due to the processes used in crushing, sizing, and cleaning. There can be a wide range in the various physical and chemical properties of aggregates. Differences in properties among aggregate sources as well as variation in the properties of an aggregate from a single source can affect the performance of freshly mixed concrete.

Physical properties of the aggregate affecting freshly mixed concrete proportions include grading, maximum size, particle shape and texture, bulk unit weight, absorption, specific gravity, and amount of clay fines. For example, by limiting the amount of material passing the 9.5 mm ($^3/_8$ in.) sieve in the coarse aggregate, the concrete properties for workability, pumpability, finishing, and response to vibration are improved (Tuthill, 1980). In the fine aggregate, the amount of material on the 300 μm (No. 50) sieve influences the finishability. The presence of excessive quantities of organic materials or soluble salts can affect freshly mixed concrete properties—for example, slump loss, setting time, water demand, and air content.

While concrete varies greatly in its properties, satisfactory concrete for most purposes can be made with a wide range of aggregates by selection of materials and mixture proportioning to provide concrete having the required properties in both the freshly mixed and hardened state. Past experience with the materials is an excellent source of information. Local experience with specific aggregates, especially as gathered by State Transportation Departments, should be reviewed. Trial mixtures are highly advisable to make the best use of available materials unless there is a substantial amount of information on previous experience. Aggregates should not be substituted in a mixture proportion without prior testing due to potential changes in water demand of the system.

3.2—Mix proportions

The grading and particle shape of aggregates influence the proportions needed to obtain workable freshly mixed concrete and at the same time provide needed hardened concrete properties with reasonable economy. ACI 211 provides guidance on the use of maximum density curves to determine the optimal combined aggregate grading. The amount of mixing water needed to obtain a desired slump or workability depends on the maximum size of the coarse aggregate, particle shape and texture of both the fine and coarse aggregates, and particle size range of coarse aggregate.

Significant differences in the water requirement of concrete using fine aggregates from different geographic areas were noted by Blanks (1952). In comparable concrete mixtures, one fine aggregate needed 80 lb/yd^3 (48 kg/m^3) more mixing water. Examination of these fine aggregates under magnification revealed that one was smooth and rounded and the other was rough and very angular. The angular fine aggregate required the greater amount of mixing water and also needed more portland cement to maintain the water-cement ratio.

The presence of mica—layered silicate minerals, occurring as flaky particles in fine aggregates—will reduce workability, causing an increase in water demand (Dewar, 1963, and Schmitt, 1990). Gaynor and Meininger (1983) suggest an upper limit of 15 percent mica in the 300 to 150 m (No. 50 to No. 100) sieve fraction, as determined by microscopical particle count, will minimize the effect of mica on concrete properties.

Increased angularity and roughness of coarse aggregate can also increase the mixing water requirement (and needed mortar content) of concrete for a given level of workability; however, its effect is generally not as great as the shape and texture properties of fine aggregate. Large amounts of flat and elongated pieces of aggregate in concrete can make it too harsh for some placement methods, resulting in voids, honeycombing, or pump blockages. Substitution of a natural aggregate for a manufactured (crushed) aggregate often results in significantly changed characteristics. In particular, the more rounded natural sands improve pumpability of concrete mixtures.

The shape of aggregate particles can be evaluated visually or through the use of quantitative tests. However, there is currently little use of these properties as actual specification criteria. Visual examination of aggregate shape and estimation of its effect on concrete requires experience and personal judgment. Numerical results can be obtained by classification of particles by dimensional measurement of particle length, thickness, and width to arrive at an amount of flat and elongated particles. This is more feasible for coarse aggregate than for fine aggregate where (1) a flat particle is defined in ASTM C 125 as one in which the ratio of width to thickness is greater than a specified value (such as 3, for example), and (2) an elongated piece of aggregate is one with a ratio of length to width greater than a specified value (a value of 3 has also been used for this ratio). Generally, most concern with flat and elongated particles is in relation to crushed aggregates, although they can occur in natural gravels derived from thinly bedded rock.

A third method of evaluating the particle shape, roundness, and texture of aggregates involves determining its flow rate through an orifice or the percentage of voids of the loose material after it has fallen into a container. Voids are computed from the known volume of the container and the specific gravity of the aggregate. Methods have been reported by several researchers, including Wills (1967), Gray and Bell (1964), Malhotra (1964), and Tobin (1978). Recently, three procedures have been standardized in ASTM C 1252.

Wills (1967), in extensive tests of concrete made with natural sands and gravels from nine sources, found considerable differences in water requirement and strength. The water demand was found to correlate well with void and orifice flow tests made on both sand and gravel. For the nine fine aggregates, the loose voids ranged from about 39 to 50 percent (by Method A in ASTM C 1252), the water demand for concrete made with a control gravel ranged about 50 lb/yd^3 (30 kg/m^3) and the compressive strength ranged about 2000 psi (14 MPa). [The mixtures were made with a cement content of about 517 lb/yd^3 (307 kg/m^3)]. For the nine gravels, voids in the aggregate compacted by rodding ranged from about 33 to 42 percent, and the water demand for concrete made with a control sand ranged about 33 lb/yd^3 (20 kg/m^3). When the sands and gravels from the same sources were used together, the water demand had a range of 75 lb/yd^3 (45 kg/m^3) and the strength varied almost 2500 psi (17 MPa). If these concrete mixtures had been made at a constant water-cement ratio, the cement content would have had a considerable range, but the strength differences would have been smaller.

An interesting point in the work of Wills (1967) was that one sand had a higher water demand than predicted from the void content. Examination of this aggregate showed it to contain clay in its finer size fractions. The strength of concrete containing this aggregate was also lower than predicted.

While the work by Wills was done with natural sands and gravels, the same sort of relationships would be expected with crushed coarse aggregate, manufactured sand, or combinations of these materials.

Gray and Bell (1964) recommended a maximum void content in manufactured fine aggregate of 53 percent as determined by the void test that they developed (Method B in ASTM C 1252). This method differs from that of Wills primarily in that it averages the results obtained on the individual sieve fractions rather than on a graded sample. This method yields void contents approximately 6 percent higher than that of Wills. Gray and Bell noted that manufactured fine aggregates having this void content are in successful use, and this value restricts the use of screenings that almost invariably have poor particle shape, uncontrolled grading, and are usually troublesome. Furthermore, a void content of 53 percent or lower assures that the manufactured fine aggregate has a reasonably good particle shape that is obtained only with good processing.

The third method included in ASTM C 1252 measures the voids content of a fine aggregate sample in the grading as received (or as proposed for a job) rather than the standard grading. This can be useful for determining the fine aggregate voids for a specific mix, as opposed to comparing different fine aggregates.

Grading and particle shape of the coarse aggregate influence the amount of mortar needed to provide workable concrete. Any change in grading or angularity that decreases or increases the interparticle voids of the coarse aggregate will require a corresponding decrease or increase in the mortar fraction of the concrete. For example, in the ACI 211.1 mix proportioning procedure, the loose volume of coarse aggregate estimated for a cubic yard of concrete depends on the dry-rodded unit weight of the coarse aggregate which is in turn dependent on the grading and particle shape of the aggregate—as they influence percent voids—and the specific gravity of the particles. In addition, the coarse aggregate factor selected from Table 5.3.6 in ACI 211.1 is also dependent on the maximum size of the coarse aggregate and the fineness modulus of the fine aggregate. With finer fine aggregates, less fine aggregate is required and more coarse aggregate can be used for comparable workability.

Another method of measuring the angularity of coarse aggregate is the particle index test (ASTM D 3398), which is a practical test for coarse aggregate particle shape (but not fine aggregate).

3.3—Slump and workability

The strength, appearance, permeability, and general serviceability of concrete is dependent on the effective placement and consolidation of freshly mixed concrete without undesirable voids and honeycombing. It must be workable enough for the given formwork, reinforcement spacing, placement procedure, and consolidation technique to completely fill spaces around the reinforcement and flow into corners and against form surfaces to produce a reasonably homogeneous mass without undue separation of ingredients or entrapment of macroscopic air or water pockets in the concrete.

Aggregate properties must be considered in proportioning concrete for adequate workability. Changes in the aggregate grading or particle shape affect mixing water requirement. Therefore, a change in particle shape or grading can change the consistency of the concrete if the amount of mixing water is held constant. Slump is a measure of concrete consistency. However, it is not, by itself, a measure of workability. Other considerations such as cohesiveness, harshness, segregation, bleeding, ease of consolidation, and finishability are also important, and these properties are not entirely measured by slump. The workability requirements needed for a particular placement depend to a large extent on the type of construction and on the equipment being used to convey and consolidate the concrete. For instance, workability needs for slipform operations will be different than for placement in a congested reinforced column or post-tensioned girder.

One important aspect of workability, particularly if mixtures of plastic or flowable consistency are being placed, is the tendency of the mix to segregate—the separation of coarse particles from the mortar phase of the concrete and the collection of these mortar-deficient particles at the perimeter or toe of a concrete placement. The effect of aggregate on the cohesive properties of a concrete mixture depends on factors such as the maximum size of the coarse aggregate, if larger than $^3/_8$ in. (9.5 mm), the overall combined grading fine and coarse aggregate (and percentage of fine aggregate on the basis of total aggregate), and the amount of clay-size fines present. For example, an excess of aggregate in any one size may cause harshness in the mixture. In some instances, gap gradings with reduced amounts of aggregate in the coarse fine aggregate sizes and small coarse aggregate sizes (particularly if angular particles are present in these sizes) have been found to be very workable where consolidation is by vibration even though slump is not high (Ehrenburg, 1980; Li and Ramakrishnan, 1974; and Li, et al., 1969). If these gap-graded mixtures are fluidized, there may be a tendency for the mortar to separate from the coarse aggregate structure. In rich (high cement factor) concrete, the cement fines tend to provide sufficient cohesion, even if fines are lacking in the aggregate, and the best concrete properties may be obtained with very clean fine and coarse aggregates. In lean (low cement factor) concrete, workability may be improved and cohesion increased with the presence of higher amounts of silt- and clay-size fines in the aggregate. This would particularly be the case in non-air-entrained concrete, where fines are lacking. Air entrainment, chemical admixtures, or a mineral admixture such as fly ash may be added to specifically improve cohesion and workability.

It is difficult to evaluate workability on an objective basis because of the lack of a good test method. Normally, workability problems only become apparent during a concrete placement requiring either a change in the placement equipment, or procedures, or an adjustment in the mixture proportions to provide better workability for prevailing conditions.

Significant and troublesome breakdown of aggregate particles during batching, mixing, and handling of concrete is not usually a problem, but occasionally some aggregates may be subject to this phenomenon, particularly with longer mixing times. Such aggregate degradation and generation of fines may result in an increased water requirement, slump loss, and decreased air content of the concrete. Fine aggregates that break down easily have been studied by attrition tests using methods described by Davis, et al., (1967) and Higgs (1975). The Corps of Engineers Test Method CRD-C-141, the NAA-NRMCA attrition test method (ASTM C 1137), and the California durability index test (ASTM D 3744) are all attrition tests. Additional work on the Micro-Deval test for assessing the degradation of fine and coarse aggregate has been done in Ontario (Rogers, et al., 1991, and Senior and Rogers, 1991). The first two tests use agitation of a water-fine aggregate mixture by a rotating vane or by shaking a sample of the slurry in a can using a paint shaker. Degradation is based on the additional amount of material produced passing the 75 μm (No. 200) sieve or by the reduction in the fineness modulus of the fine aggregate in comparison with tests of satisfactory aggregates. The durability index measures the tendency of fine aggregates to generate detrimental clay fines when degraded. It involves shaking a washed fine aggregate for 10 min in a standard sand-equivalent graduated plastic cylinder.

The susceptibility of coarse aggregate to degradation can be evaluated by increased shaking times in a sieve shaker or by use of the durability index test. This test uses agitation, in a portable sieve shaker, of a pot containing coarse aggregate and water. The fines generated are measured using a technique similar to the Sand Equivalent Test (ASTM D 2419). The Los Angeles abrasion test (ASTM C 131 and C 535) or the sulfate soundness test (ASTM C 88) have not been found to correlate well with degradation of aggregate in concrete during mixing, handling, and placement.

Another source of slump loss may be the absorption of mixing water into porous aggregate that has been batched dry or at a moisture content less than its absorption. If this is suspected as a problem, proper wetting of aggregate stockpiles at least a day prior to use in concrete or adjusting batch water quantities for aggregate absorption should greatly reduce the problem. For short haul times, consideration should be given to extending mixing times.

3.4—Pumpability

Concrete made with more angular or poorly graded aggregates is expected to be more difficult to pump because of its higher internal friction. The particle shape of coarse aggregate will have a modest effect on pumpability and line pressure. The properties of fine aggregate play an important part in proportioning pumpable mixtures.

ACI Standards 211.1 and 304R provide that, for concrete that is to be pumped, the amount of coarse aggregate may be decreased by up to 10 percent. This means that the mortar-coarse aggregate ratio may be increased if necessary to provide for more workable concrete. Whether adjustments are needed in the mixture proportions or aggregate grading depends to a large extent on the original proportions, the use of chemical and mineral admixtures, the size of the pump line, and the characteristics and condition of the pump.

One method of concrete proportioning uses the dry-rodded unit weight of the coarse aggregate, which is affected by the particle shape, grading, and specific gravity of the coarse aggregate. Lower dry-rodded unit weight may result from angular particle shape, coarser grading, and lower specific gravity of the aggregate. Using this dry-rodded unit weight concept results in less coarse aggregate being used when it is angular, requiring a higher mortar-coarse aggregate ratio for the same workability. ACI 211.1 recommendations do not satisfactorily recognize differences in particle shape of fine aggregate and their effect on workability and water demand, although grading differences in form of fineness modulus are considered. Several test methods have been developed to determine the effect of particle shape of fine aggregate on workability and water demand (Wills, 1967; Gray and Bell, 1964; Malhotra, 1964; and Tobin, 1978) and are discussed in Section 3.2.

For some fine aggregates, particularly poorly graded manufactured fine aggregate, close control of the fine aggregate may be needed to produce pumpable concrete. This may include improving particle shape, increasing the amount of finer sizes in the fine aggregate, using a natural blending fine aggregate, or the use of a higher cement content, (perhaps with fly ash or other pozzolans) to improve workability and decrease bleeding. Concrete that bleeds excessively is more difficult to pump and may be unpumpable if the pumping pressure squeezes water out of the concrete.

3.5—Bleeding

The bleeding of concrete is influenced by mixture proportions and by the characteristics of the materials, air content, slump, use of mineral and chemical admixtures, and particularly the angularity and grading of the fine aggregate. A high rate and amount of bleeding may be undesirable, particularly for pumping and in finishing fresh concrete. Conversely, a high rate and amount of bleeding is desirable in vacuum-processed concrete as the water can be more easily removed. Also, sand streaking may occur in walls. Finishing of concrete can be damaged and it can weaken the concrete surface. Bleeding may also reduce potential for plastic shrinkage cracking.

Where bleeding is excessive, attention should be given to the grading and angularity characteristics of the fine aggregate and to the mixture proportions. The use of finer fine aggregates, blending sand, improved control and grading of manufactured fine aggregate, increased cement and/or pozzolan content, use of some chemical admixtures, and air entrainment are all factors that can reduce bleeding.

3.6—Finishing characteristics of unformed concrete

The angularity and grading of aggregate, the amount of bleeding, and mixture proportions of the concrete are factors that may influence finishing. Where finishing problems occur, the work should be observed very critically, and the material properties and mixture proportions should likewise be reviewed to determine what might be done to improve the situation. Possible remedies to improve finishing of concrete include the use of additional fines in the fine aggregate, the use of a blending sand, more cement, more pozzolan, the use of some chemical admixtures, the use of air entrainment, adjustments to the aggregate grading (both fine and coarse), or changes in mixture proportions. If stickiness is the problem, less fines in the fine aggregate, less cement, less pozzolan, adjustments of chemical admixtures, or reduction in air content might help. If the problem is excessive bleeding, its reduction may be accomplished as discussed previously in Section 3.5. Bleed water can be removed by drags or vacuum mats. If the problem is either fine or coarse aggregate in the 9.5 to 2.36 mm ($^3/_8$ in. to No. 8) sieve sizes "kicking up" or "rocking" as the trowel is passed over the concrete, the amount of these sizes may be excessive. Also, this problem may be attributed to a large amount of very flat and elongated particles in the 9.5 to 4.75 mm ($^3/_8$ in. to No. 4) sieve sizes. Reduction of the amount of these sizes or elimination of these sizes completely can usually improve both the workability and finishing characteristics.

3.7—Air content

A significant amount of material passing the 75 µm (No. 200) sieve, particularly in the form of clay, can reduce the air content in concrete; therefore, more air-entraining admixture must be used. Sometimes this material results from the use of "dirty" fine or coarse aggregate and is quite variable, thereby causing problems in controlling the air content, as well as causing other problems, which include variations in water requirement, slump, and strength (Blick, 1964). Gaynor (1977) reports that increased minus 75 or 150 µm (No. 200 or No. 100) sieve size material in fine aggregate required an increased dosage of air-entraining admixture to obtain required air content but produced smaller bubbles and a better air-void system with a low spacing factor. Conversely, increased amounts of 600 to 300 µm (No. 30 to No. 50) sizes of the fine aggregate will decrease the dosage of air-entraining admixture required for the same air content. Angularity of fine aggregate has not been shown to have a significant effect on dosage rate needed at air contents less than eight percent.

Organic materials contained in some aggregates require a change in the dosage of air-entraining admixtures and may result in large air bubbles and an unfavorable air-void system (McNaughton and Herbich, 1954). Where this problem occurs, a possible remedy is to use an air-detraining admixture (defoamer) with the air-entraining admixture. This procedure is generally not recommended due to the difficulties encountered in maintaining the required air content. Air-detraining admixtures are primarily used to produce non-air-entrained concrete due to the organic material. Air-entraining admixture dosages may vary with different aggregate sources.

3.8—Other properties

Setting time of concrete is not normally affected by aggregate. However, the presence of soluble salts or organic materials in the aggregate may influence this property. Concrete temperature, as mixed, is influenced by the temperatures and specific heat properties of the constituent materials. Aggregate, being present in the greatest amount, has a large effect on concrete temperature. In hot weather, sprinkling or shading of stockpiles of aggregate reduces concrete temperature. In cases where very cool concrete is needed, coarse aggregate may be cooled by immersion in chilled water or by spraying the stockpile (ACI 305R). In cold weather the heating of the aggregate may be necessary to obtain desired concrete temperatures (ACI 306R). Frozen aggregates should not be used in concrete mixtures.

The specific gravity and quantity of each aggregate used in concrete will affect the resulting unit weight of the fresh concrete. With aggregates of fairly high porosity, the unit weight of concrete may vary depending on whether the absorption has been satisfied by premoistening the aggregate prior to batching.

CHAPTER 4—EFFECTS OF PROCESSING AND HANDLING OF AGGREGATES ON PROPERTIES OF FRESHLY MIXED AND HARDENED CONCRETE

4.1—General

Basic physical and chemical characteristics of aggregate cannot generally be altered by processing, although the quantities of certain deleterious particles can be reduced. Aggregate characteristics that can be controlled include grading, moisture content, cleanliness, removal of abnormally light particles, and to some degree, particle shape. Economic factors usually determine the degree to which processing can be directed to produce the best compromise between desirable aggregate properties and economy.

The extent to which exacting specifications should be applied to aggregate depends on how critical an end use the concrete is expected to serve. For ordinary commercial concrete it is seldom necessary to specify the highest quality or the most rigid control. On the other hand, if the concrete is expected to maintain high stresses or serve in a severe environment, both high quality and careful control are strongly advised.

Aggregate processing may be divided into two broad classifications: (1) basic processing to achieve suitable grading, uniformity, and cleanliness, and (2) beneficiation to remove deleterious constituents.

4.2—Basic processing

Processes typically employed to provide aggregate of satisfactory grading begin at the face of the quarry or pit. In the case of quarried ledge rock, finished product grading and cleanliness may be influenced by the effectiveness of the operations of stripping overburden, drilling, and blasting. In addition, the moisture content of the “shot rock” in the muck pile can have an effect on the balance of the processing operations. In the excavation or dredging of sand and gravel, it is necessary to properly remove overburden and excavate to charted depth, thickness, and location of the material having the desired raw feed grading for the processing plant. Blending of materials excavated from different parts of the deposit may be required to produce product target gradings or other properties. It is necessary to have a well-designed plant for efficient production of consistently graded concrete aggregates.

4.2.1 *Crushing*—In this phase of the processing of quarried ledge rock, the first operation is primary crushing. Primary crushers may be of the compression type (jaw or gyratory) or the impact type (single or double impeller). Impact crushing is seldom used on harder, more abrasive rocks because of excessive wear and high maintenance. Feed size to primary crushers may be controlled to maximize output through the use of grizzly feeders, sloping heavy bars, or rails variably spaced such that quarry fines can be separated out and pieces too large for the crusher “scalped off.”

The primary crusher product will normally contain particles as large as 6 to 10 in. (150 to 250 mm). Further reduction is generally required to produce concrete aggregate. At some plants the largest particles may be separated for sale as rip rap, and in many plants the finer sizes from about $1^1/_2$ in. (38 mm) down are separated and stocked as a “crusher run” product for road work. The intermediate sizes are then conveyed to the secondary and subsequent crushing stages. These later stage crushers are most often of the compression type (cone crushers) or, where the rock is not too abrasive, the impact type (single or double impeller, hammermill, or cage mill). Impact type crushers have a desirable feature in their ability to beneficiate certain products by selective crushing of softer, deleterious particles that can be removed in subsequent screening operations.

Crushing may be required in the production of concrete aggregates from unconsolidated stream bed or bank gravel deposits. Where the deposits contain sound boulders or cobbles, the necessary operations are similar to those described above for ledge rock. Where the top size in the deposit is about 3 in. (75 mm) or less, the primary crushing stage is unnecessary. In the case where a crushed gravel product requires a specified percentage of crushed particles, it may be necessary to introduce to the crusher only particles coarser than the top size of the product to assure a high level of crushed count. Some aggregate plants may regularly run two coarse aggregate production circuits—one for crushed and the other for uncrushed gravel. Production of aggregate from slag generally requires crushing and screening of a nature similar to that required for quarried ledge rock.

4.2.2 *Screening*—Once the raw materials, stone, gravel, or slag have been reduced to the desired overall size range, usually below 3 in. (75 mm), it is then necessary to separate them further into fine aggregate, finer than the 4.75 mm (No. 4) sieve, and coarse aggregate, usually two or more size ranges as described in ASTM C 33. This is most often accomplished by means of vibrating screens or perforated plates with appropriate square, round, or rectangular openings and in some cases by means of cylindrical revolving screens (trommels).

The screening equipment operates best, producing the most consistently graded products, when fed at a uniform rate. Surge bins and specially designed feeders often are used to accomplish this. The ideal feed rate is that which distributes the particles full width to a uniform depth across the screen. Plant screens are never 100 percent efficient (they never accomplish completely clean separation of all particles small enough to pass the screen openings), but their efficiency is optimized by insuring uniformity of feed so that all particles have the opportunity to pass through the openings.

Uniform operation of a well-designed processing plant should accomplish the intended purpose of producing consistent products. It is important to note that while a wide variety of aggregate gradings may be accommodated, extreme variations in the grading cannot be tolerated. The reason this is important is clear from the ACI 318 requirement regarding concrete quality, such that the average strength of the concrete produced must exceed the specified compressive strength f'_c used in structural design by amounts that become greater as the standard deviation of the strength determinations becomes greater. The uniformity of the concrete depends on the uniformity of the constituent materials, the bulk of which are aggregates.

4.2.3 *Washing*—Processing of many aggregates requires washing to remove salt, clay, or other tenacious coatings that may adhere to the particles and interfere with the cement paste to aggregate bond. Washing is more often necessary for gravel aggregates from deposits that contain clays than for ledge rock or slag aggregates produced as described above. However, some sedimentary ledges are interbedded with clay or shale and do require vigorous washing to remove these materials. Many specifications, such as ASTM C 33, set limits on material finer than the 75 µm (No. 200) sieve that are less restrictive where this material is primarily dust of fracture from the crushing operation, "essentially free of clay or shale." Under such conditions it may not be necessary to include washing in the production process for crushed stone or slag coarse aggregates unless coatings must be washed off or high absorption must be satisfied.

Some specifications may require a more restrictive limit on minus 75 µm (No. 200) material in coarse aggregate than permitted by ASTM C 33 and the maximum amount of material passing the 75 µm (No. 200) sieve may be limited to 0.25 to 0.50 percent. These more restricting requirements usually are associated with special work where very high quality concrete is needed. It must be recognized, however, that each handling of a coarse aggregate will generally cause a slight increase in the fines content, making the extremely restrictive limits difficult to meet without rewashing.

4.2.4 *Water classification*—Control of grading and removal of some of the excess fines in fine aggregate are usually accomplished by classification in water. A wide variety of classifying devices are used for this purpose, all of which are based on the different settling rates of different-sized particles. Water classification is not feasible for sizes larger than about $^1/_4$ in. (6 mm). The grading can be controlled with considerable accuracy by suitable reblending, in spite of the overlap in sizes within adjacent cells of typical classification devices.

4.2.5 *Rescreening*—Most of the basic processing steps should be performed at the aggregate producer's plant. Intermediate handling and stockpiling will cause degradation. Rescreening will effectively reduce objectionable and undersize materials. If specified, rescreening should be done immediately prior to storage in batch plant bins. Further details are noted in ACI 304R.

4.3—Beneficiation

"Beneficiation" is a term used in the mining industry to describe the improvement in quality of a material through the removal of unwanted constituent materials. Success of a process depends on significant differences in physical properties like hardness, density, and elasticity of desirable and undesirable constituents. The method to be employed, if any are practical, depends on the nature of the individual deposit. Processes used with variable degrees of success are mentioned below.

4.3.1 *Crushing*—Certain impact crushers such as cage mills are particularly adaptable to "selective" crushing, as previously noted. Soft, friable, or otherwise deleterious material is degraded, producing excess fines in the

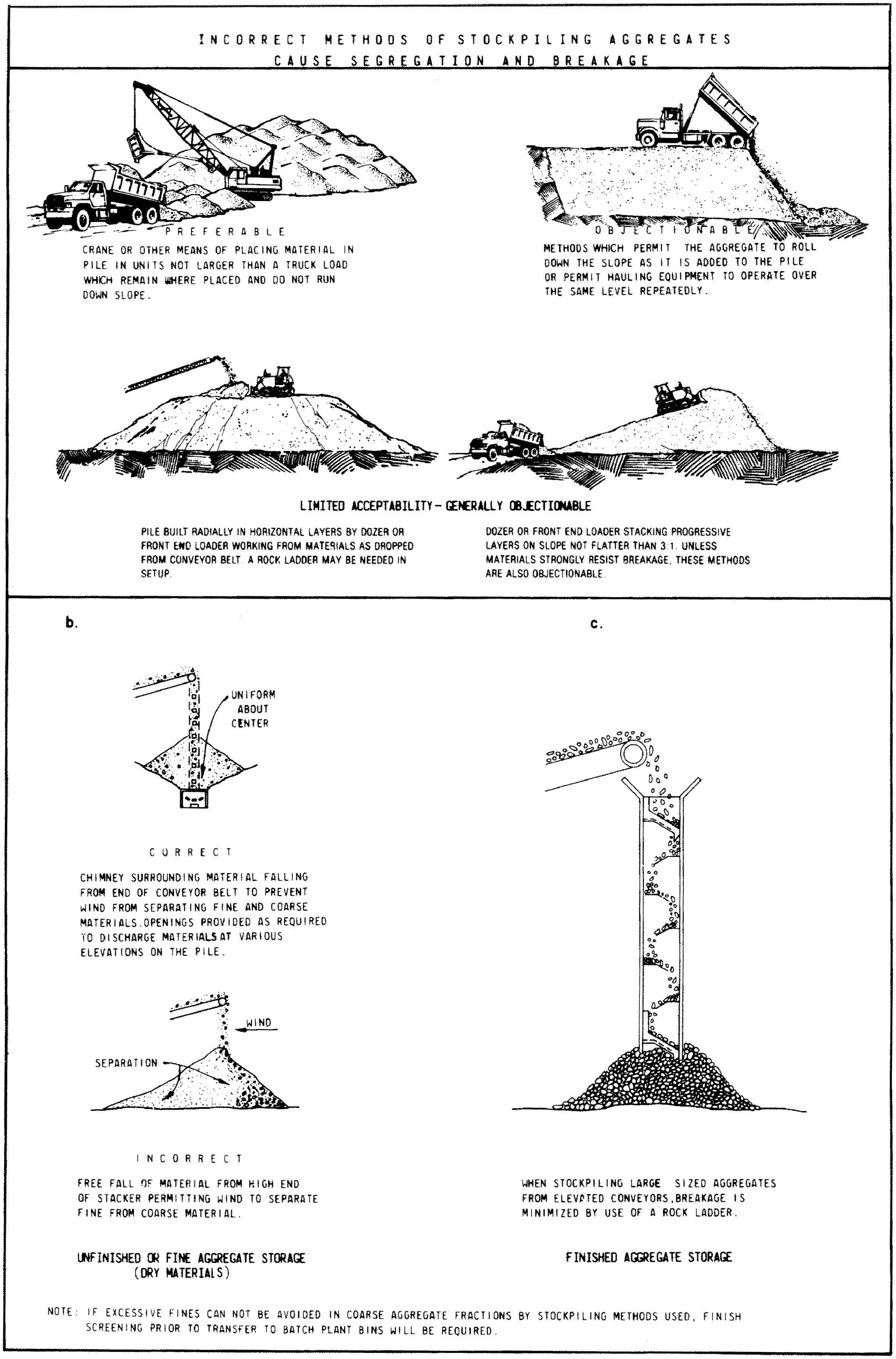

Fig. 4.1—Correct and incorrect methods of handling and storing aggregates

crusher that must be removed by screening or water classification. The costs of installation and operation of crushers for this purpose may be high and may involve the loss of some sound material, and removal of the degraded fractions may be difficult or expensive. On the other hand, where a marginal quality deposit is the only one available within a reasonable haul distance, selective crushing may be the only process available to make the material suitable for use.

4.3.2 *Other separation devices*—In many deposits, deleterious fractions such as lignite and chert are significantly lower in density than the better quality material within the deposit. Advantage may be taken of this characteristic in the beneficiation process. Density separation systems include high velocity water or air devices, jigs, and heavy media separation systems. Still others include elastic rebound fractionation and magnetic separation.

More sophisticated systems of this nature are economically feasible only when the beneficiated product is of greater value than the marginal concrete aggregate. In some cases, such devices are used to separate two or more constituents, all of which have value. An example includes ore-bearing rock with the richer particles further processed to refine the ore while the less valuable tailings may be processed as aggregate. Further, the fines from a crushed limestone plant may be passed through an air separator to produce fine aggregate for concrete and either mineral filler or agricultural limestone.

The art of processing continues to evolve, and current articles in the trade press keep abreast of improvements. Basic information on many of these processes may be found in the *Handbook of Mineral Dressing* (Taggart, 1945). There are a number of other texts on production and manufacture of aggregates (*Rock Products*, 1977; *Pit and Quarry*, 1977; and *National Stone Association*, 1991).

4.4—Control of particle shape

The particle shape of crushed aggregates is largely dependent on the crushing equipment used. Experience has shown that equipment that produces acceptable particle shape with one type of rock will not necessarily produce acceptable shape with another type. Particle shape can often be improved by the insertion of an additional crusher in the line between the primary crusher and the final crusher. It is generally conceded that the reduction ratio—the ratio between the mean size of the feed to a crusher and the mean size of the crusher product—should not be too great, particularly in the case of jaw crushers or others of the compression type. Impact type crushers generally produce a more nearly cubical particle shape, but when choke fed, specially designed flat-angle cone-type crushers generally produce favorable particle shape when used in processing a wider variety of rock types than can be accommodated by impact crushers.

Particle shape is a difficult property to define and specify. In the case of fine aggregate, there are test methods in use based on the void content of all or certain fractions of the material in a loose condition. Coarse aggregate shape is sometimes specified in terms of allowable percentages by weight of flat or elongated particles, defined in terms of length, width, and thickness of a circumscribing rectangular prism. ASTM D 3398 established an index of particle shape and texture. In specifications the use of ambiguous terms like “free” or “reasonably free from flat or elongated particles” should be discouraged.

4.5—Handling of aggregates

The most careful control of the manufacture of aggregates at the plant can be negated quickly through abuse in handling, storage, loading out, transporting to the job site, charging into storage bins, and batching. Even with effective quality control at the processing plant there will always be a degree of variability between units of volume, or lots, and within lots as well. To define and correct any excessive variability in the material as shipped, a statistically sound sampling program should be followed. Randomly selected batches or sublots should be sampled according to ASTM D 75 at various stages of the production process and all the way through to the final batching into the mixer.

Faulty or excessive handling of processed aggregate may result in one or all three principal problems that may affect the properties of concrete mixtures. The first is segregation, which destroys the grading uniformity. The second is contamination, or inadvertent inclusion of deleterious material. A third problem, lack of successful maintenance of uniform and stable moisture content in the aggregates as batched, further complicates the production of uniform concrete. Degradation of the material, which produces more fines and has a detrimental effect on the properties of the concrete, is a fourth problem.

Procedures for maintaining grading uniformity and moisture content are discussed in ACI 304R, Chapter 2. The principal recommendations from this report and from similar publications on the subject are summarized here in abbreviated form.

1. Segregation may be minimized when the aggregates are separated into individual sizes and batched separately.

2. Undersize material smaller than the designated minimum size in each fraction should be held to a practical minimum; where significant degradation may have occurred, rescreening of the coarse aggregate at the batch plant may be required to eliminate objectionable variation in the amounts of undersize materials.

3. Fine aggregate must be controlled to minimize variations in grading and moisture content. The ratio of fine to coarse aggregate as proportioned in the concrete mixture is governed by the fineness modulus of the fine aggregate, and excessive variation in the quantities of minus 75 µm (No. 200) sieve has a major effect on the mixing water requirement, rate of slump loss, strength, and drying shrinkage. Where blending of fine aggregates from two separate sources is necessary, the two fine aggregates should be stored separately and a positive method of control employed to insure a uniform blend.

4. Stockpiles, where necessary, should be built in horizontal or gently sloping layers. Conical stockpiles or any unloading procedure involving the dumping of aggregates down sloping sides of piles should be avoided. Trucks, bulldozers, and wheel loaders should be kept off stockpiles because they can cause degradation and contamination.

5. Every effort should be made to obtain a stable moisture content in aggregates, particularly fine aggregate. The stable moisture content is dependent on the grading, particle shape, surface texture, and aggregate drainage storage practices. Therefore, all aggregates produced or handled by hydraulic methods and washed aggregate should be stockpiled or binned for drainage prior to batching into concrete. Well-graded, round, and smooth particles that have had good draining storage practices may obtain a stable moisture content when drained at least 12 hours. Conversely, poorly graded, flat, and angular particles with poor drainage stockpiling may take as long as a week or more to obtain a stable moisture content. Fluctuations in the stable moisture content caused by weather can be compensated for by the use of moisture meters to indicate minor variations in moisture as aggregates are batched. The use of aggregate compensators for rapid adjustments can minimize the influence of moisture variation on such properties as slump, shrinkage, water-cement ratio, and strength.

6. Storage bins should be kept as full as practical to minimize breakage and changes in grading as the materials are withdrawn.

7. Aggregates should be sampled at random intervals as closely as possible to the point of their introduction into the concrete. In addition to a check on the grading, this will facilitate detection of contamination of aggregates that may occur during transportation and handling. It is good practice to maintain a running average on from 5 to 10 previous grading tests, dropping the results of the oldest and adding the most recent to the total on which this average is calculated. These averages can then be used to make necessary adjustments to mix proportions.

Fig. 4.1, reproduced from ACI 304R, is provided here to illustrate correct and incorrect methods for handling aggregates.

4.6—Environmental concerns

Some jurisdictions have strict environmental regulations for dust control. Care must be taken to satisfy these regulations; however, quality aggregates still must be produced. The dust collection equipment, designed to reduce pollution, removes some of the fine materials that are sometimes produced while processing aggregates. Some of this equipment will also reintroduce the collected dust back onto the material belt at the final drop location at a controlled rate. When this type of equipment is used, quality assurance testing must be performed after this point to maintain proper grading and cleanliness for the intended specifications.

CHAPTER 5—QUALITY ASSURANCE

5.1—General

Aggregate quality assurance is the overall system of quality control-quality acceptance to assure that the required level of aggregate quality is obtained. The operations generally associated with quality assurance include routine visual inspections and quality control tests, as the aggregate is produced and handled, and acceptance testing at the time it is purchased or used in concrete.

The purpose of aggregate quality control is to monitor and regulate the production process to assure uniform materials, consistently meeting the various specification requirements, at the time these materials are used in concrete. Once the source of aggregate has been sampled and tested and found to be suitable for use in concrete, quality control parameters are then applied to properties of the aggregate that may be affected by the processing and may be expected to vary. These properties normally include grading, moisture content, particle shape, and cleanliness. However, it is also prudent to periodically check other properties such as mineral composition, chloride ion content, specific gravity and absorption, abrasion resistance, and amount of deleterious material, particularly to determine if changes occur within the source.

Accordingly, with effective quality control, aggregates will have the least effect on batch-to-batch or day-to-day variation in properties of the concrete mixture. Quality control work includes routine inspection of the material source and of the aggregate processing plant and handling system, all the way through to the point of batching; routine sampling and testing of production and at various points during handling; and prompt corrective action when necessary.

Routine inspections and control tests should be performed at such frequencies that production adjustments can be promptly made, resulting in the least variation of the finished products. Deviation from the previous uniformity of routine test results may indicate changes in plant feed or conditions and require appropriate inspection and adjustment and/or other corrective action.

Acceptance testing should be performed on randomly selected samples taken each day or shift during concrete production to confirm compliance with aggregate specification requirements. Acceptance testing may also be performed on aggregate that is purchased from stockpiles at the production plant or elsewhere. Thereafter it is the user's responsibility to transport, stockpile, and handle these materials in a manner that results in the least amount of degradation, contamination, or segregation, and insures that the furnished aggregate conforms with specifications when used in concrete.

All sampling, whether for quality control tests or for acceptance tests, must be in accordance with ASTM D 75. Standard methods of sampling are essential to assure that samples show the true nature and condition of the material that they represent.

Table 5.1— Suggested quality control program routine control tests*

Test	Test method	Minimum test frequency†
Aggregate plant samples		
Coarse aggregate (each size group)		
Grading	ASTM C 136	Once per day
Cleanliness	ASTM C 117	Once per day
Particle shape	CRD-C 119	As required
Crushed particle content	Count percentage of particles	As required
Fine aggregate		
Grading	ASTM C 136	Twice per day
Cleanliness	ASTM C 117	Once per day
Sand equivalent	ASTM D 2419	Once per week
Organic impurities	ASTM C 40	As required
Batch plant samples		
Coarse aggregate (each size group)	ASTM C 566	Once per day
Moisture content		
Fine aggregate		
Moisture content	ASTM C 70 or C 566	As required to adjust for variation

*The requirements are generally applied to typical aggregate production. Additional requirements and higher frequency of testing may be used for more demanding jobs or marginal quality aggregates.

†During the early stages of aggregate and concrete production from new sources or new plants, the sampling and testing should be more frequent. The purpose of increased early stage sampling and testing is to establish quickly a history or uniformity so that any problem areas affecting uniformity can be corrected before the production demands override effective correction. Once consistent results are maintained, the testing frequency may be reduced.

These frequencies can be substituted with frequencies based on amount produced. Normally a combination is desirable and requires one test per specified amount but not less than one per day/week/month, etc.

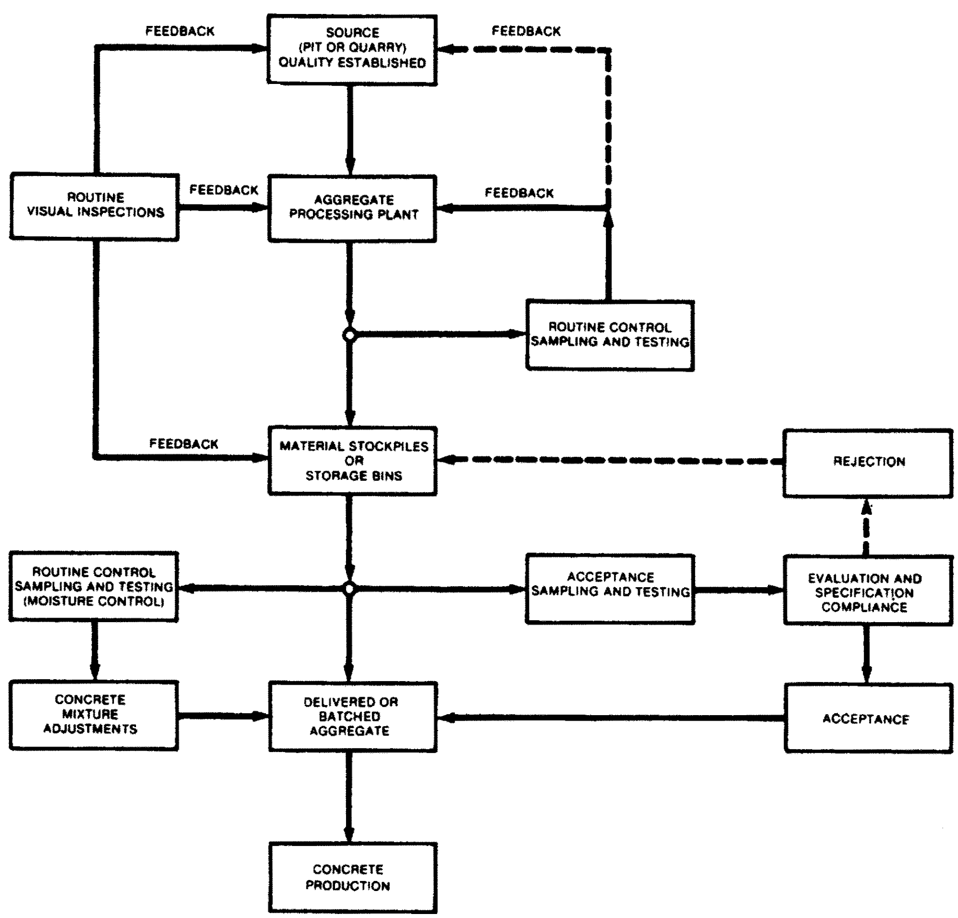

Fig. 5.1—Typical aggregate quality assurance scheme

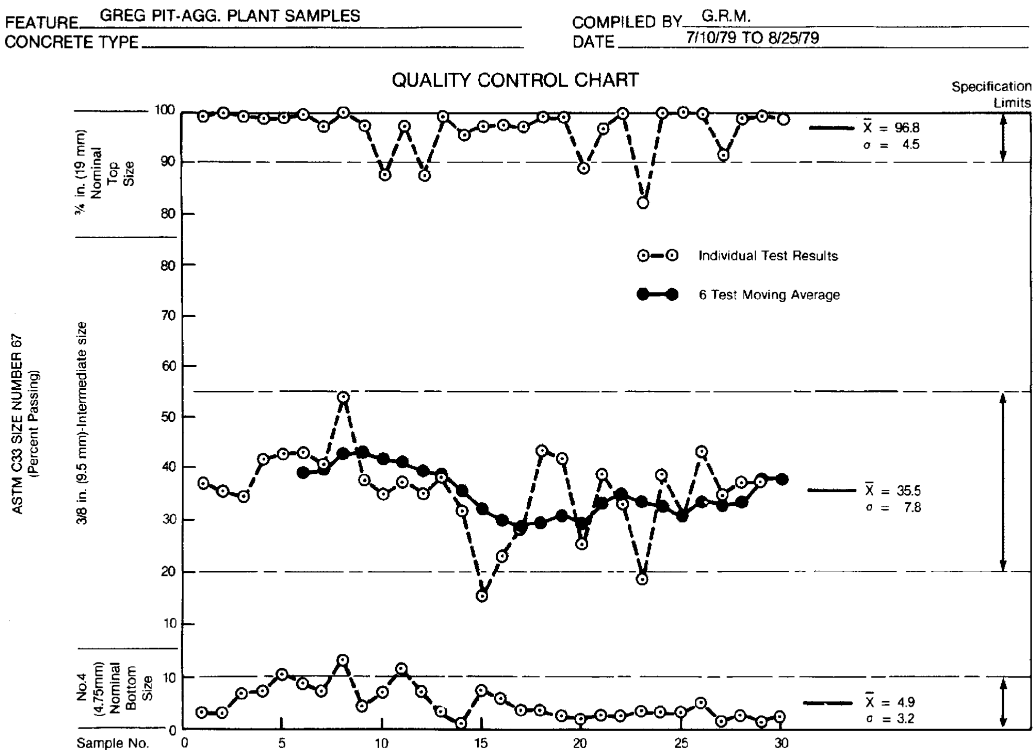

Fig. 5.2—Typical quality control chart

Statistical methods can be used to evaluate the results of quality control and acceptance tests as described in Chapter 2 of ACI 311.1R. Such an evaluation can provide a quantitative value on the variation in material characteristics or degree of control maintained and can also indicate trends in the data.

A typical aggregate quality assurance scheme is shown in Fig. 5.1.

5.2—Routine visual inspection

General—Routine visual inspections are intended to identify conditions that may influence plant operation and products. Inspections should be made on a daily basis by the plant supervisor or designated quality control engineer or technician. Plant personnel also should be alert at all times to detect material changes or plant mechanical problems. Daily reports or inspection reports should be used to document items requiring maintenance or modification and operational changes. Items normally checked during inspection are as follows:

5.2.1—Source

Contamination of raw material from overburden, clay, or organic matter

Depth of weathering

Zones of soft, weak, or poor quality rock

Coarse and fine lenses

Local lithology

Quarry rock-fragment size distribution and shape

Excavation methods and procedures, blending and mixing various strata

5.2.2—*Aggregate plant*

Raw feed stockpiles—material uniformity, segregation, and contamination

Plant feed method and rate

Crusher feed rate and material distribution

Crusher condition and operation

Moisture condition of crusher feed

Screening efficiency—material distribution and bed load

Screen sizes

Worn, broken, or blinded screens

Water spray bar pressure and distribution

Fine aggregate washing and sizing equipment and feed rate

Plant chutes and waste disposal system

Aggregate transfer points

Conveyor belt wipers

Stockpiling conveyors, and discharge control—bin dividers, rock ladders

Plant products in stockpile—grading, cleanliness, contamination, degradation, segregation, and moisture condition

Plant production quantities

General housekeeping

5.2.3—*Aggregate handling system*

Reclaim system—discharge openings, drainage, and contamination

Stockpile base, loader operator practice—contamination

Chute and bin liners

Particle breakage at transfer points

5.3—Routine control testing

Routine control testing is used to monitor the aggregate characteristics or properties during production. Routine control testing is intended only to alert the producer of potential problems. Types of testing, as shown in Tables 1.1 and 5.1, may be included as routine control tests.

Coarse aggregate samples for routine control tests generally are taken from the conveyor belt as the materials are going into stockpiles. This sampling location is preferred, and thorough removal of material on a section of the belt will assure a representative sample. The belt should be sampled at several intervals and these individual samples combined. For fine aggregate, samples are generally obtained from partially drained stockpiles using a suitable sampling tube inserted at several locations around the coned pile. An exception to these sampling locations is made for routine moisture control samples required for aggregate moisture adjustment of concrete batch weights. Samples for moisture content usually are taken at the aggregate weigh hopper. It is important that suitable working platforms and sampling devices, trays, and containers are provided to perform all sampling conveniently and safely (Bedick, et al., 1980).

Typical frequency of sampling and testing for routine control of concrete aggregates is listed in Table 5.1.

5.4—Acceptance testing

Acceptance tests are made on randomly selected samples and are intended to determine acceptance of the product or compliance with specification requirements. Accurate sampling for test purposes cannot be too strongly emphasized. Statistical evaluation can be applied to test data to show product variability and process control. Often, aggregate grading is the characteristic most frequently evaluated in acceptance testing. However, where other characteristics are of concern in producing uniform concrete, acceptance tests to control these characteristics should be made.

For grading control, tests normally are made for each shift of concrete batch plant operation on samples taken from the batch plant weigh hoppers. Accordingly, these tests represent “as batched” conditions that most accurately define the grading uniformity of aggregate in the concrete produced and the degree to which processing, stockpiling, handling, and storage were controlled—effectively.

Where aggregates are purchased, the purchaser should require that tests be made at a selected rate on material as loaded out of the producer’s stockpiles for evaluation of process quality control. The purchaser then assumes responsibility for grading variations generated between the point of material load-out and use in concrete.

It is important to note that, regardless of how well the processing is controlled, aggregate grading test results will vary and that uniformity is a relative term. Specifications must include tolerances for acceptance of occasional tests that may be outside grading limits such as one in five consecutive tests. Variability of test data may be inherent in the material or lack of process control or may be associated with errors in sampling and testing.

5.5—Record keeping and reports

Record keeping and reports should be maintained as simple as possible. Summary sheets and control charts are preferred (Nichols, 1978). Quality control tests have little value unless the data are analyzed on a periodic basis. Variability of the percent passing key sieve sizes can be computed using statistical concepts similar to those used for cylinder strength evaluation. Average value and standard deviation for the percent passing a specific sieve size will establish the location of the average value and degree of control with respect to the specification limits. This can be done on a cumulative or selected period basis. Control charts such as shown in Fig. 5.2 are valuable in visually presenting the data in a manner where variation can readily be seen.

A moving average of five to ten consecutive tests shows trends in the grading results not otherwise apparent. Such trends are useful in adjusting the aggregate plant to maintain a certain average value.

Statistical concepts also can be applied to other aggregate test data provided that the samples were taken on a random, and not select, basis. Evaluation of moisture control, particle shape, percent of deleterious material, cleanliness, or other properties may be important in control of concrete in certain work.

CHAPTER 6—MARGINAL AND RECYCLED AGGREGATES

6.1—Marginal aggregates

Due to depleted reserves and environmental pressures, the availability of “good” aggregates, particularly in many urban areas, has decreased (ASTM, 1976). Coupled with high transportation costs, this has focused increasing attention on the use of marginal or borderline aggregates.

Marginal aggregates are those that do not comply with all of the normal specification requirements and would usually be rejected. However, limited use of these aggregates may be allowed if the resulting concrete will meet the specific job requirements.

If present trends continue, it is inevitable that there will be more pressure to use marginal aggregates. Acceptable use of marginal aggregates is dependent upon good engineering judgement and quality evaluation. Continued advances in knowledge of the effects of individual aggregate material properties on the long-term behavior of concrete are needed to develop more definitive guidelines for users.

6.2—Use of marginal aggregates

Concretes are exposed to many different environments. The environment to which a particular concrete will be subjected can determine the necessary and pertinent ag-

Table 6.1—Beneficiation treatments and objective

Treatment	Objective
Crushing	Remove friable particles
Heavy media separation	Remove lightweight particles
Reverse air or water flow	Remove lightweight particles
Hydraulic jigging	Remove lightweight particles
Elastic fractionation (bounce)	Remove lightweight and soft particles
Washing and scrubbing	Remove coatings and fines
Blending	Control deleterious components
Screening	Control gradation

Table 7.2—Typical heavyweight aggregates

Material	Description	Specific gravity	Concrete unit wt lb/ft^3 (kg/m^3)
Limonite Goethite	Hydrous iron ores	3.4-3.8	180-195 (290-310)
Barite	Barium sulfate	4.0-4.4	205-225 (330-360)
Ilmenite Hematite Magnetite	Iron ores	4.2-5.0	215-240 (340-380)
Steel/iron	Shot, pellets, punchings, etc.	6.5-7.5	310-350 (500-560)

Note: Ferrophosphorus and ferrosilicon (heavyweight slags) materials should be used only after thorough investigation. Hydrogen gas evolution in heavyweight concrete containing these aggregates has been known to result from a reaction with the cement.

gregate properties to be specified. Aggregate characteristics that influence the properties of concrete are discussed in Chapters 2 and 3. Using marginal aggregates involves relaxing some of the normal aggregate specifications as conditions permit. In some cases this decision can be based on job requirements and expedient tests. In others a high level of judgement is required, weighing potential effects of decreased serviceability against savings from marginal material use.

Aggregates outside of normal specification criteria often can be used in concrete either because it will be exposed to less severe conditions or through the use of mixture proportioning changes made to compensate for the aggregate deficiency. Coarse aggregate that has a nonstandard grading can normally be used to make satisfactory concrete through proper proportioning adjustment or reprocessing the material (Section 4.3). Fine aggregate with grading deficiencies may be more difficult to use satisfactorily. However, a fine aggregate with a nonstandard grading often can be used after verification of concrete properties in trial batches. A deficiency of fines may require the use of additional cement, mineral admixtures, air-entraining admixture, or other admixtures to provide sufficient workability in lean or medium cement content mixtures. In high cement content mixtures, a fine aggregate lacking fines may be advantageous.

Aggregate degradation problems that affect water requirements and strength will have to be assessed under conditions similar to those proposed for use in the project. Changes in aggregate handling procedures and minimization of mixing and agitation times during concrete production may reduce degradation enough to produce satisfactory results. In special cases where the entire design team is involved, design may allow the use of a marginal aggregate; e.g., a higher shrinkage aggregate may be used if special attention is given to joint spacing and other design parameters that are directly affected by concrete shrinkage.

Using marginal aggregates in concrete should be decided on a case-by-case basis employing proven methods and good engineering judgement.

6.3—Beneficiation of marginal aggregates

It is sometimes possible to bring an unacceptable aggregate within allowable limits through beneficiation. Table 6.1 presents some of the beneficiation processes used to improve aggregate quality.

Although beneficiation can be used to manipulate various aggregate properties, it may be economically impractical compared to the cost of importing a higher quality material.

6.4—Economy of marginal aggregates

In areas where “good” aggregates are not available or are very costly, marginal aggregates may be an adequate and economical alternative for some applications. One should realize, however, that the associated evaluation, beneficiation, and risk have a negative impact on their economy. A detailed cost study will provide the first indication of whether use of a marginal aggregate is feasible. The cost of transporting “good” aggregate may be offset by the costs related to using a seemingly cheaper marginal aggregate.

6.5—Recycled aggregates and aggregates from waste products

Studies have been made to determine the suitability of recycled materials for use as aggregates in concrete (Halverson, 1981, and Buck, 1976). Such use is very desirable both economically and environmentally, but great caution must be used when considering recycled aggregate. Building rubble may contain deleterious amounts of brick, glass, and gypsum, and any recycled concrete may contain reactive or poor quality aggregates or high chloride contents. Aggregates made from municipal or industrial wastes (slags other than those from an iron blast furnace), recycled, or marginal materials may possess a number of undesirable physical and chemical qualities. Trial batches, extensive tests, chemical and petrographic analyses, and local performance records are of vital importance in the decisions regarding their use. In general, recycled materials should be specified and evaluated in accordance with ASTM C 33, except when the composition indicates the need for further specific requirements (Frondistou-Yannas, 1980).

CHAPTER 7—HEAVYWEIGHT AGGREGATES

7.1—Introduction

Heavyweight or high-density aggregates are essential when concrete of higher than normal density is required, usually for radiation shielding or an application where heavyweight concrete is needed for counter-balancing, ballasting, or stabilizing. Heavyweight concrete also may be useful in sound or vibration attenuation.

Heavy fine and coarse aggregates used in concrete generally range in specific gravity from about 3.5 (the mineral goethite, for example) to about 7.5 (steel punchings or shot) and produce concrete ranging in unit weight from about 180 to 350 lb/ft^3 (290 to 560 kg/m^3). Also, high density fine aggregate can be used to produce high density mortar or grout, when required (Kosmatka and Panarese, 1988; Sturrup, 1977; Wills, 1964; and NRMCA, 1965).

7.2—Heavyweight aggregate materials

Heavyweight aggregates generally consist of heavy natural minerals or rocks; or they consist of man-made materials, such as steel or iron. In many cases, the weight range or shielding properties desired will require the use of particular aggregate specific gravities or sources. Table A4.1.1 from ACI 211.1, Appendix 4, reproduced herein as Table 7.2, gives examples of typical heavy aggregates, their specific gravities, and resulting concrete unit weights.

Many of the types of materials used as heavyweight aggregates, their properties, and in some cases their sources are enumerated in more detail in the references given in this chapter and in the references provided in those citations. Also, the National Aggregates Association and National Ready-Mixed Concrete Association (NAA/NRMCA) (1989) maintains a listing of known active sources of heavyweight aggregates.

7.3—Properties and specifications for heavyweight aggregates

7.3.1 *General*—ASTM C 637 for Aggregates for Radiation-Shielding covers special aggregates where composition or high specific gravity, or both, are of prime consideration. Also, ASTM C 638 gives Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete. The following is from the scope of ASTM C 638:

This nomenclature is intended to give accurate descriptions of some common or important naturally occurring and synthetic constituents of aggregates for radiation-shielding concrete, that, at the same time, are not common or important constituents of concrete aggregates in general use. While most of the minerals and rocks discussed in C 638 may occur in small quantities in aggregates in general use, they are not major constituents of such aggregates. The synthetic aggregates included are ferrophosphorus and boron frit.

As far as the concrete-making properties of heavyweight aggregates are concerned, it is desirable, just as it is with normal weight concrete, to have fine and coarse aggregates that are clean, strong, inert, and relatively free of deleterious materials that may increase mixing water requirements or impair strengths. This ideal may not be met by some of the heavy ores, minerals, or synthetic materials used because of their high specific gravity. Some of these materials tend to degrade or powder during handling and batching operations. These properties may present special challenges in specifications, testing, and concrete production operations. Freezing and thawing resistance or other durability criteria may or may not be required depending on anticipated service environment of the concrete.

ASTM C 637 is useful for many of these special aggregates and ASTM C 33 also may be applicable to many heavyweight aggregates, and it is referenced in C 637. Specification C 637 classifies Aggregates for Radiation-Shielding Concrete as follows:

Natural mineral aggregates of either high density or high fixed water content, or both. These include aggregates that contain or consist predominately of materials such as barite, magnetite, hematite, ilmenite, and serpentine.

Synthetic aggregates such as iron, steel, ferrophosphorus, and boron frit.

Fine aggregate consisting of natural or manufactured sand including high-density minerals. Coarse aggregate may consist of crushed ore, crushed stone, or synthetic products, or combinations or mixtures thereof.

7.3.2 *Specific gravity*—Because density is normally of primary importance in these applications, ASTM C 637 contains a provision for uniformity of specific gravity of successive shipments of aggregate not to differ by more than three percent from that submitted for source approval, and the average specific gravity of the total shipment must be equal to or greater than the required minimum. For certain shielding applications, a minimum fixed water content of hydrous ores may be required as well.

7.3.3 *Grading*—ASTM C 637 indicates that fine and coarse aggregates should meet the conventional concrete aggregate gradings in ASTM C 33, except that provision is made for the acceptance of additional fine material, if the purchaser approves. In that case for the fine aggregate as much as 20 percent may pass the 150 µm (No. 100) sieve and 10 percent may pass the 75 µm (No. 200) sieve if it is essentially free of clay or shale. Specification C 637 also contains grading requirements for fine and coarse aggregate used in preplaced-aggregate concrete.

Because of the friable nature of many heavyweight aggregates, special precautions may be required or gradings can be selected that are on the coarse side, assuming generation of fines during concrete production. Rescreening of friable aggregates prior to batching may be necessary.

7.3.4 *Other properties*—Other properties of heavyweight aggregates generally are referenced to those specified for normal weight concrete designed to serve in a similar service or environment. In some cases particular specified properties may have to be waived in order to get the high specific gravity needed. Then the specific performance or properties of the concrete must be shown to be satisfactory.

7.3.5 *Methods of sampling and testing*—Test methods are generally as cited in ASTM C 33, with some exceptions. Larger sample weights are needed in some tests in order to assure the required sample volume or number of particles. Specific gravity, for example, is performed using ASTM C 127 and C 128, except the weight of the test sample is to be increased by multiplying by the ratio (Sp. Gr.)/(2.65). This is also true for the sample weight to be used for sieve analysis in ASTM C 136. If a blend of aggregates with grossly different specific gravities is used in the aggregate, it may be well to test the components separately and then combine the results.

For radiation shielding concrete aggregates, where fixed water content may be important, ASTM C 637 contains a test for determining fixed water content. There is also a test for water soluble material in boron frit.

7.4—Proportioning heavyweight concrete

ACI 211.1 in Appendix 4 contains guidance on modifying the proportioning methods for normal weight concrete to accommodate heavyweight aggregates. ACI 304.3R contains additional guidance for measuring, mixing, transporting, and placing heavyweight concrete.

7.5—Aggregates for use in radiation-shielding concrete

In most cases, the exact chemical composition of heavyweight aggregates is not critical as long as the required density is met (Volkman, 1994, and Davis, 1967). However, for some shielding applications, it may be necessary to limit the content of certain elements that may become highly radioactive in a neutron field. Another factor is the need in some cases to require an increased hydrogen content in concrete for a neutron shield. For this reason, hydrous ores or minerals may be required as aggregates. Some aggregates are hydrous iron ore (limonite, goethite), serpentine, or bauxite.

7.6—Heavyweight aggregate supply, storage, and batching

Usually heavyweight aggregates come from an active mining site where an ore is being mined or processed. It may be an advantage if the operation has screening equipment, sink-float operations, or other equipment that can separate the dense, lump ore from mine-run material. In other instances, operators may have to selectively mine the material in order to comply with density requirements. In some cases, satisfactory material may be available directly from the stockpile, and this may be less difficult than trying to obtain the required quality and quantity from the mine directly.

Transportation of heavyweight aggregates may be very expensive due to their weight. Allowed loads in trucks or rail cars may be less than full volume capacity. Also, the increased weight of the material on conveyors, bins, batches, mixers, etc. must be taken into account. Normally, truck mixers can only haul a fraction of their normal volume of concrete in cubic yards.

Because of the expense of heavyweight aggregates and the need to prevent intermingling with other materials, it may be necessary to use separate bins or storage areas for each type. Concrete pads under stockpiles may be installed to reduce waste. Steel punchings or shot may require covered areas to protect against oxidation. Also, all handling and batching equipment must be purged of normal weight materials prior to the production of heavyweight concrete. Segregation may be a problem because of the high density of coarse aggregate particles.

CHAPTER 8—REFERENCES

8.1—Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation. For the documents listed, the latest available version was used at the time this document was revised. Since some of these documents are revised frequently (although often in minor detail only) the user of this document should check directly with the sponsoring organization if reference to the latest version is desired.

American Association of State Highway and Transportation Officials

Guidelines for Design of Skid Resistant Pavements

T 103 Tests of Unconfined Aggregate in Freeze-Thaw

T 260 Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials

American Concrete Institute

116R Cement and Concrete Terminology (SP-19)

201.2R Guide to Durable Concrete

211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

216R Guide for Determining the Fire Endurance of Concrete Elements

304R Guide for Measuring, Mixing, Transporting, and Placing Concrete

304.3R Heavyweight Concrete: Measuring, Mixing, Transporting, and Placing

305R Hot Weather Concreting

306R Cold Weather Concreting

311.1R Manual of Concrete Inspection (SP-2)

318 Building Code Requirements for Reinforced Concrete

E1 Aggregates for Concrete

American Society for Testing and Materials (ASTM) Standards

C 29 Unit Weight and Voids in Aggregate

C 33 Concrete Aggregates

C 40 Organic Impurities in Fine Aggregates for Concrete

C 87 Effect of Organic Impurities in Fine Aggregate on Strength of Mortar

C 88 Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate

C 117 Material Finer Than 75-m (No. 200) Sieve in Mineral Aggregates by Washing

C 123 Lightweight Pieces in Aggregate

C 125 Terminology Relating to Concrete and Concrete Aggregates

C 127	Specific Gravity and Absorption of Coarse Aggregate
C 128	Specific Gravity and Absorption of Fine Aggregate
C 131	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
C 136	Sieve Analysis of Fine and Coarse Aggregates
C 142	Clay Lumps and Friable Particles in Aggregates
C 227	Potential Alkali Reactivity of Cement-Aggregate-Combinations (Mortar-Bar Method)
C 289	Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)
C 295	Petrographic Examination of Aggregates for Concrete
C 418	Abrasion Resistance of Concrete by Sandblasting
C 441	Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to Alkali-Silica Reaction
C 535	Resistance to Degradation of Large-Size Coarse-Aggregate by Abrasion and Impact in the Los Angeles Machine
C 586	Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)
C 637	Aggregates for Radiation-Shielding Concrete
C 638	Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete
C 666	Resistance of Concrete to Rapid Freezing and Thawing
C 682	Evaluation of Frost Resistance of Coarse Aggregates in Air-Entrained Concrete by Critical Dilation Procedures
C 779	Abrasion Resistance of Horizontal Concrete Surfaces
C 944	Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method
C 1105	Length Change of Concrete Due to Alkali-Carbonate Rock Reaction
C 1137	Degradation of Fine Aggregate Due to Attrition
C 1138	Abrasion Resistance of Concrete (Underwater Method)
C 1218	Standard Test Method for Water Soluble Chloride in Mortar and Concrete
C 1252	Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface, Texture, and Grading)
D 75	Sampling Aggregates
D 1411	Standard Test Methods for Water Soluble Chlorides Present as Admixes in Graded Aggregate Road Mixes
D 2419	Sand Equivalent Value of Soils and Fine Aggregate
D 2936	Direct Tensile Strength of Intact Rock Core Specimens
D 2938	Unconfined Compressive Strength of Intact Rock Core Specimens
D 3042	Insoluble Residue in Carbonate Aggregates
D 3319	Accelerated Polishing of Aggregates Using the British Wheel
D 3398	Index of Aggregate Particle Shape and Texture
D 3744	Aggregate Durability Index
D 4791	Flat and Elongated Pieces in Coarse Aggregate

U.S. Army Corps of Engineers Handbook for Concrete and Cement

CRD-C-71	Ultimate Strain Capacity of Concrete
CRD-C-104	Calculation of the Fineness Modulus of Aggregate
CRD-C-114	Soundness of Aggregates by Freezing and Thawing of Concrete Specimens
CRD-C-120	Flat and Elongated Particles in Fine Aggregate
CRD-C-124	Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)
CRD-C-125	Coefficient of Linear Thermal Expansion of Coarse Aggregate (Strain-Gage Method)
CRD-C-141	Soft Constituents in Fine Aggregate

The above publications may be obtained from the following organizations:

American Association of State Highway and Transportation Officials
333 N. Capitol St. NW
Suite 225
Washington, D.C. 20001

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180

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