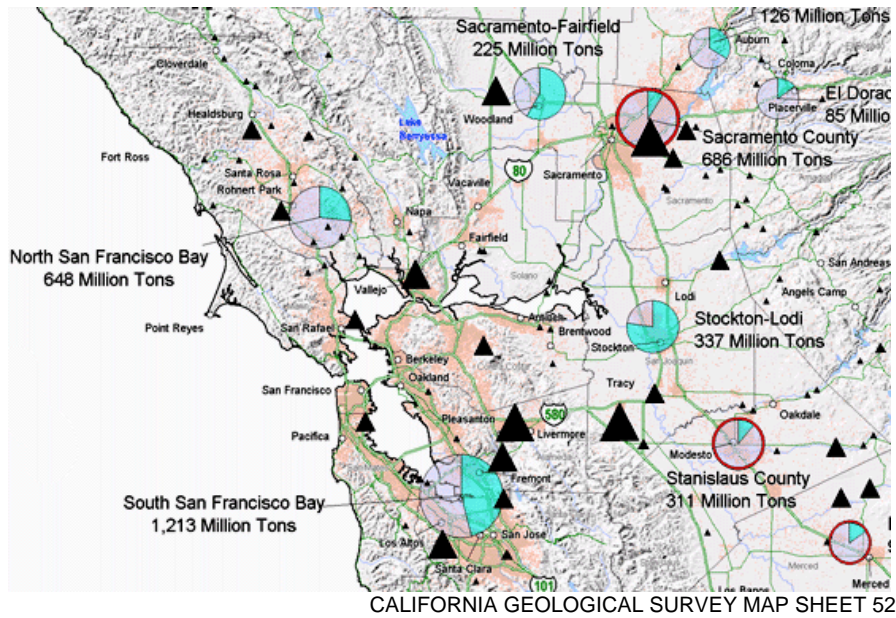


The San Francisco Bay Area Concrete Aggregate Report 2008



Prepared by

SEAONC Construction Quality Assurance Committee
June 2008



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The San Francisco Bay Area Concrete Aggregate Report - 2008

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THE SAN FRANCISCO BAY AREA CONCRETE AGGREGATE REPORT - 2008

SEAONC Construction Quality Assurance Committee

Introduction

Aggregate for concrete has, until recently, been an exclusively local issue. More than likely, if an engineer were not specific in specifying aggregate, the concrete would be made with aggregate from the closest and least expensive source that meets the relatively modest gradation, cleanness and durability requirements of ASTM C33. In fact, all Bay Area aggregate producers can meet this specification – until the pit runs out.

One of the largest aggregate production plants in the country, Hanson Aggregates' Radum Plant (formerly Kaiser) closed in 2001 after 75 years of operation. The first shipments of Canadian coarse aggregate began arriving in Bay Area ports at about the same time. Hanson's Windsor and Felton plants have also closed due to depleted resources.

The Construction Quality Assurance Committee has taken a closer look at local concrete aggregate producers and pits and put together this summary of the state of the industry, including a breakdown of characteristics, supply, and locations of the aggregate available to the structural engineer in the Bay Area. The focus is on coarse, naturally occurring aggregates, but fine aggregates and the use of recycled concrete are also discussed.

Aggregate Basics

Aggregates generally make up about 75% of the volume in a cubic yard of concrete. Of that 75%, approximately 60% is the coarse aggregate. The art and science of concrete mix design uses refinements in proportions, gradations, and aggregate surface characteristics to produce concrete with specific workability, finishability, and pumpability.

As engineers however, we are primarily interested in properties of the hardened concrete such as strength, durability, and resistance to shrinkage and cracking.

Coarse aggregates are either gravels (dug or dredged, then washed and graded) or crushed stones (produced by crushing quarry rocks or large gravels). The parent material consists of a mixture of rocks and minerals. Minerals, like quartz, feldspar and gypsum, have an orderly internal structure and a narrowly defined chemical composition. Rocks, like granite, limestone and chert, are generally composed of several minerals. Important engineering properties include hardness, durability, strength, and freedom from materials or chemicals that could negatively affect hydration or bond with the cement paste.

Since aggregates are typically quite strong (10 to 40 KSI compressive strength) compared to the cement paste, for concrete strengths up to 6000 psi or so, actual compressive strength of the aggregate does not have a large influence on concrete compressive strength.

Aggregate properties that can affect concrete quality are discussed below:

Gradation: The specific blend of particle sizes within an aggregate can affect workability, strength, density, shrinkage characteristics and cost of the concrete.

Soundness: Aggregates that are highly absorptive, porous, or prone to volume changes when saturated will produce unstable, weak concrete. Aggregates with a high soundness loss (i.e. poor soundness) may not perform well in a freeze-thaw environment.

Cleanness: Impurities in the aggregate, such as clays, silt, or organic material, will result in concrete with



reduced durability, poor paste-aggregate bond, potential for excess shrinkage, and unsatisfactory appearance.

Hardness: Aggregates with insufficient hardness and toughness will produce concrete with poor abrasion resistance and may not be appropriate for higher strength concrete.

Particle Shape: Angular aggregates, generally produced by crushing, can result in greater flexural strength compared to concrete made with rounded aggregates, but the mix becomes harsher, affecting workability and the ability of the concrete to fully encase congested reinforcement. Proper mix proportioning and/or the use of chemical admixtures can overcome these difficulties.

Reactivity: The alkali-silica reaction is the most common form of aggregate reactivity. Concrete made with such aggregate is damaged by the expansion of the cement paste around the aggregate. Substantial cracking along with general deterioration of the concrete results.

The Basic Standard – ASTM C 33

Bay Area aggregate producers put forth substantial effort to test and certify their aggregates in accordance with the requirements of several standards and many test methods. Specifying that concrete aggregates conform to ASTM C 33 will result in aggregates with material properties that conform to certain limits when tested in accordance with the following test methods:

Fine Aggregate

ASTM C 136 Method for Sieve Analysis of Fine and Coarse Aggregates.

ASTM C 117 Test Method for Materials Finer than 75- μm (No. 200) Sieve in Mineral Aggregates by Washing.

ASTM C 40 Test Method for Organic Impurities in Fine Aggregates.

ASTM C 88 Test Method for Soundness of Aggregates by use of Sodium Sulfate or Magnesium Sulfate.

Coarse Aggregate

ASTM C 136 Method for Sieve Analysis of Fine and Coarse Aggregates.

ASTM C 117 Test Method for Materials Finer than 75- μm (No. 200) Sieve in Mineral Aggregates by Washing.

ASTM C 142 Test Method for Clay Lumps and Friable Particles in Aggregates.

ASTM C 123 Test Method for Lightweight Particles in Aggregate (adjusted for coal, lignite and chert only.)

ASTM C 88 Test Method for Soundness of Aggregates by use of Sodium Sulfate or Magnesium Sulfate.

ASTM C 131 Test Method for Resistance of Degradation of Small-Size Aggregate by Abrasion and Impact in the Los Angeles Machine.

Although the predictive tests for alkali-silica reactivity of aggregates (ASTM C 289, ASTM C 1260, and ASTM C 1293) are in the non-mandatory Appendix to ASTM C 33, the text of the standard contains a requirement that both fine and coarse aggregates for use in concrete that will be exposed to wetting, humid atmosphere, or moist ground shall not contain materials that are deleteriously reactive with the alkalis in the cement. The reactivity tests referenced above can yield variable results. The Appendix suggests that actual experience with an aggregate source in service in concrete should take precedence over test results. Reactive aggregates can be used with low-alkali cement or with concrete made with supplementary cementitious materials such as fly ash and slag. Although no San Francisco Bay Area aggregates are known to be deleterious, Caltrans, for example, requires that all concrete contain a minimum amount of fly ash as a protection against potential aggregate reactivity.

It is not generally understood that the limits for deleterious substances and physical properties in ASTM C 33 vary according to the use of the concrete (location in structure) and the “weathering region” in which the structure is located. Figure 1 in ASTM C 33 indicates that the entire San Francisco Bay Area is in the negligible weathering region, while portions of the mountains and deserts are in the moderate to severe weathering region. Table 3 of



ASTM C33 defines the characteristics of the three weathering regions, identifies classes of aggregate based on the weathering region and the location and use of the concrete in the structure. For example, 5M is for exposed architectural concrete in the moderate weathering region, 2S is for interior floors without covering in the severe weathering region, and so on. Table 3 also lists the limits for the various coarse aggregate characteristics by class. Specifiers should consider identifying the weathering region and specifying coarse aggregate by class to ensure that the aggregate is appropriate for the usage.

Recycled concrete is referenced in ASTM C 33 as an acceptable coarse aggregate, subject to the requirements of the standard, but caution is advised in its use for structural concrete, due to porosity and the wide variability of the quality of the material.

ASTM C 33 does not limit the salt content of aggregates. However, water-soluble chloride ions in the reinforced concrete itself are limited by ACI 318 as a function of the exposure, and whether or not the concrete is prestressed or post-tensioned. Although dredged sands, such as the local Angel Island Washed Sand produced by Hanson Aggregates, are generally washed to remove chlorides, significant chlorides can remain. Since the mix water, admixtures, and cementitious materials can also contribute chlorides, it may be wise to specify that the concrete supplier certify that the chloride content of the concrete itself remains within the ACI 318 limit set for the specific usage.

It should be noted that, while the grading ranges of ASTM C 33 are quite wide, and the cleanness and physical property requirements are not particularly strict, concrete made with aggregates conforming to ASTM C 33 can generally be expected to perform adequately in most cases. *If it is desired to control other specific aggregate characteristics, such as aggregate particle shape or texture, the project specification must be augmented.*

Caltrans Standards and Test Methods

San Francisco Bay Area aggregates are also produced to meet Caltrans specifications and are tested in accordance with various California Test Methods, many of which test for the same characteristics as the ASTM standards referenced above. Table 1 shows the common test

methods used by Caltrans and those required by ASTM C 33 along with typical specification limits.

Bay Area Aggregate History

Two factors have influenced the evolution of aggregate supplies and suppliers in the San Francisco Bay Area over the last 35 to 40 years: (1) urban development around the sources, and (2) the focus on, or the demand for, improving performance issues such as strength, durability, creep, and shrinkage resistance.

Unlike many of the areas of the state, (especially southern California) we are fortunate in the San Francisco Bay Area to have had very high quality aggregate sources available locally. However, population pressures have made it all but impossible to obtain new or extended permits for aggregate mining and processing in the greater San Francisco Bay Area. As the existing pits run out, and as permitting new sources becomes more difficult, other sources (such as imports) have become more prevalent.

Concrete performance issues, particularly creep and shrinkage, came into the forefront locally in the 1960s as a result of excessive deflection exhibited in the flexural members of several newly-designed San Francisco Bay Area structures. Refinements in design procedures and higher strength reinforcement had resulted in the use of shallower members and longer spans. In some cases however, deflections were greater than calculated, leading to the suspicion that creep and/or shrinkage in the concrete was the cause.

A 1965 SEAOC study, supplemented in 1974 (Appendix II) discussed causes and effects of creep and shrinkage in concrete. Aggregates that effectively aid in restraining shrinkage of the cement paste are the stronger, more durable and chemically stable materials such as quartz, feldspar, limestone, dolomite and granite. The study pointed out that other variables, such as aggregate size (larger aggregate, less shrinkage), gradation (to reduce paste volume), and cement source (shrinkage can vary by a factor of 2 for different cements) have the potential for even greater effects on creep and shrinkage.

San Francisco Bay Area aggregates include limestone and granite, along with other hard and durable rocks such as basalt and diabase. The SEAOC study led to the



conclusions that several local aggregates contributed to low-shrinkage in the concrete:

Graniterock Company, A.R. Wilson Quarry, Aromas, a granite material.

Hanson Aggregates, Cupertino, “Permanente limestone”.

Felton/Olympia, Santa Cruz, several suppliers, fine aggregate, now much depleted.

RMC Pacific’s (now Cemex), and Hanson’s Clayton plants, a diabase material

Engineers needing concrete with good shrinkage performance were able to specify aggregates from these sources with a reasonable expectation that the aggregate’s contribution to limited shrinkage would be maximized.

Lightweight Aggregates

Lightweight aggregates are no longer produced locally. The expanded shale aggregates typically used as coarse aggregate in structural lightweight concrete are produced in accordance with ASTM C330, and shipped to concrete suppliers in the San Francisco Bay Area from places such as Colorado and Texas. Recent experience suggests that it is difficult to achieve the 110 pcf concrete required for fire rating of steel deck assemblies with the aggregates currently available. Thus, care should be taken to ensure that load-carrying capacity of structural members are adequate to support lightweight concrete with an equilibrium dry density of 115 pcf and a wet weight of 125 pcf.

San Francisco Bay Area Aggregate Producers

San Francisco Bay Area aggregate producers provide aggregates for many uses other than concrete, including asphaltic concrete, road bases, and subbases. The aggregate production business in the San Francisco Bay Area has been subject to the same consolidation stresses affecting most industries, blurring the lines between concrete supplier and aggregate producer. Most companies in the aggregate business are also supplying cement, ready-mix concrete, or producing asphalt concrete. Recent changes in the industry include the acquisition of RMC Pacific and Rinker (ready-mix suppliers and aggregate producers) by CEMEX, an

international cement, ready-mix and aggregate producer founded in Mexico; Hanson Aggregates’ purchase of Mission Valley Rock, including the Sunol Plant; and most recently, Hanson’s acquisition by Heidelberg Cement Group.

Table 2 presents the major aggregate producers, their quarries and products, and the specifications and test methods the products represent. For a narrative discussion of each producer, including description of the output of each quarry or plant, see Appendix 1.

Specifying Concrete Aggregates

In general, specifications should focus upon performance objectives such as strength, exposure and durability requirements, and water-cementitious ratio. Overly prescriptive specifications can limit creativity and increase costs. Consider allowing the concrete producer to select the aggregate sources and mix proportions that satisfy the engineering properties desired while taking advantage of the most economical combinations of materials. This could help maximize opportunities to utilize lower quality or recycled (not necessarily lower quality) materials when high performance is not required.

As discussed, it is generally adequate to specify that concrete aggregates meet the requirements of ASTM C33, and to require that the producer either certify that the aggregate does not produce deleterious expansion or provide appropriate reactivity test results. The specification should also include the maximum aggregate size, with consideration for member thickness and reinforcement congestion.

For higher performance concrete, such as concrete with strengths higher than 6000 psi or low shrinkage requirements (less than 0.040% when tested in accordance with ASTM C-157) it is recommended to specify the British Columbia imports Sechelt or Orca, limestone from Hanson’s Cupertino quarry, diabase from Hanson’s Clayton quarry, or granite from Graniterock’s A. R. Wilson Quarry. There are also shrinkage reducing admixtures that can be effective.

When considering specifying to control shrinkage, it is important to specify that trial batch testing using the actual materials and proportions be performed sufficiently in advance so that mix adjustments can be made and retested



if needed before construction. It is also important to understand that actual shrinkage of the concrete in service and in field-cured tests will not necessarily correlate closely with the trial batch test results.

Aggregate Costs

Shipping costs are critical to the total costs of aggregates. While there are differences in production costs associated with the type of deposit, the cost of getting the product to the ready mix plant or job site is likely to control the overall cost.

Shipment by water is generally less expensive than shipment by rail, which is less expensive than shipment by truck. Ultimately trucking is generally required to get the material to the ready-mix plant.

Hourly rates for eighteen cubic yard “end-dumps” or 20 yard “belly-dumps” are currently in the range of \$85 to \$95 per hour. An additional hour in round trip time from the plant or quarry to the ready mix plant will thus add about \$5 per cubic yard to the cost of the aggregate which will contribute about \$3.50 to the cost of a cubic yard of concrete.

Rail is generally used to ship lightweight aggregate from sources outside of California.

Imported aggregates, such as those coming from Sechelt, and Orca Sand and Gravel in British Columbia are competitive only because the source is on the water, appropriate deepwater port facilities were constructed at the source, and off-loading facilities for bulk aggregate carriers are available in the population centers where the aggregate is needed most (San Francisco’s Pier 94,

Redwood City and the recently opened facility in Richmond). Ship-borne aggregates are also “lightered” off to barges capable of delivering aggregates to shallow water facilities at Oakland, Petaluma and Stockton.

Aggregate Supply

The California Department of Conservation, California Geological Survey, monitors construction aggregate supply, reserves and permitting activities in the various regions of the state. Map Sheet 52, “Aggregate Availability in California” shows existing permitted aggregate reserves in the Bay Area as being substantially less than the demand for the next 50 years. The Sacramento area is indicated to have less than 10 years supply at permitted sources.

Until the recent slump in the housing market, fine aggregate supply in the San Francisco Bay Area had been particularly critical. Concrete suppliers have been blending sands from different sources and documents accompanying mix-design submittals will often state that the fine aggregate used will meet ASTM C33 but will not identify specific sources.

Imported aggregates and new or expanded sources can help to fill the gaps in supply. However, while some producing plants have ample reserves, the availability of specific aggregate characteristics is limited, mostly by transportation costs. The engineer needs to be sensitive to this fact and should contact local producers to verify availability and costs when specifying low shrinkage, high strength, or other types of high performance concrete. The engineer should also be sensitive to these issues if he or she plans to specify locally produced aggregate as part of claiming a LEED credit.



Table 1 - Common Aggregate Tests

	Testing Required by ASTM C 33		Acceptance Criteria	Testing Required by Caltrans Section 90	
Fine			ASTM / Caltrans	California Test Method	
Gradation	ASTM C 136	Method for Sieve Analysis of Fine and Coarse Aggregates		202	Sieve Analysis of Fine and Coarse Aggregates
Amount of fines	ASTM C 117	Test Method for Materials Finer than 75 -mm (No. 200) Sieve in Mineral Aggregates by Washing	5% / 8%-	202	Sieve Analysis of Fine and Coarse Aggregates
Organic impurities	ASTM C 40	Test Method for Organic Impurities in Fine Aggregates	Satisfactory	213	Organic Impurities in Concrete Sand
Soundness	ASTM C 88	Test Method for Soundness of Aggregates by use of Sodium Sulfate or Magnesium Sulfate	12% / 10% loss	214	Soundness of Aggregates by Use of Sodium Sulfate (May be waived if Durability Index is greater than 60)
			75 min	217	Sand Equivalent
			60 min	229	Durability Index
Coarse					
Gradation	ASTM C 136	Method for Sieve Analysis of Fine and Coarse Aggregates		202	Sieve Analysis of Fine and Coarse Aggregates
Amount of fines	ASTM C 117	Test Method for Materials Finer than 75-mm (No. 200) Sieve in Mineral Aggregates by Washing	1% max		
Impurities	ASTM C 142	Test Method for Clay Lumps and Friable Particles in Aggregates	2% max		
Impurities	ASTM C123	Test Method for Lightweight Particles in Aggregate (adjusted for coal, lignite and chert only)	3% max		
Soundness	ASTM C 88	Test Method for Soundness of Aggregates by use of Sodium Sulfate or Magnesium Sulfate	12% / 10% loss	214	Soundness of Aggregates by Use of Sodium Sulfate
Durability Hardness Toughness	ASTM C 131	Test Method for Resistance of Degradation of Small-Size Aggregate by Abrasion and Impact in the Los Angeles Machine	50% / 45% loss	211	Abrasion of Coarse Aggregate by Use of the Los Angeles Rattler Machine
Cleanliness			75 min	227	Evaluating Cleanness of Coarse Aggregate



Table 1 - Common Aggregate Tests (*continued*)

	Other Testing in ASTM C 33		Acceptance Criteria	Other Testing Required by Caltrans Section 90	
Alkali-Silica Reactivity	ASTM C 289	Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates	Innocuous		
Alkali -Silica Reactivity	ASTM C 1260 (A Rapid Test)	Potential Reactivity of Aggregates (Mortar Bar Method)	0.10% / 0.15%	ASTM C 1260	Potential Reactivity of Aggregates (Mortar Bar Method)
Alkali -Silica Reactivity	ASTM C 1293 (1 year Test)	Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reactivity	0.04% / 0.04%	ASTM C 1293	Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reactivity
Alkali -Silica Reactivity	ASTM C 1567	Standard Test Method for Determination of the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregates (Accelerated Mortar bar Method)	0.10%		
Chloride Content	ASTM D 512	Chloride Content	Not regulated (ACI 318 sets limits for concrete mix only)		



Table 2 – San Francisco Bay Area Aggregate Producers

Legend

Innoc. = Innocuous

The following information was provided by aggregate producers. Values shown represent results of aggregate tests current in Spring 2008. Consult with producers for the most current data.

Sat. = Satisfactory

Producer / Plant	Fine or Coarse	Size	Meets ASTM C 33	Meets Caltrans Section 90	C 117 Fineness	C 40 Organic Impurities	C88 Sulfate Soundness	C 142 Clay Lumps, etc.	C123 Lightweight Particles	C131 Abrasion by LA Rattler	C 289 Reactivity	C87 Mortar Strength	CT 217 Sand Equivalent	CT 206 and 207 Absorption	CT 229 Durability	CT 227 Cleanness	Specific Gravity	Fineness Modulus	C 295 Reactivity
Granite Construction Inc.																			
Metz Sand and Gravel Greenfield, CA	Fine	Sand	Yes	Yes	2	Clear	2	0					85	1.4	75		2.57	2.88	
	Coarse	1x#4	Yes	Yes	0.03		1	0		25				2.4	75	86	2.5		
Felton Quarry Santa Cruz, CA	Fine	Blend	No	Yes	6.2		5						68	2.2	57		2.61	2.96	
Freeman Quarry Gilroy, CA	Coarse	1x#4	Yes	Yes	0.4		4.7			19				1.2	56	86	2.84		
Granite Rock																			
Wilson Quarry, Aromas, CA	Coarse	3/4 to 1	Yes	Yes													2.8		
	Fine	Sand	Yes	Yes													2.71		
	Coarse	1/2 x #4	Yes	Yes													2.78		
	Coarse	3/4 x 1/2"	Yes	Yes													2.8		
Hanson																			
Angel Island Washed SF Yard	Fine	Sand	Yes	Yes		Clear	4.5	0.3	0		Innoc	115	94	0.7		94	2.65	2.9	Innoc
Angel Island Washed Oakland Yard	Fine	Sand	Yes	Yes	0.2	Sat.	4.5	0.3	0		Innoc	115	94	0.7		94	2.6	2.9	Innoc
Presidio Shoals Oak	Fine	Blend	No	No		Clear	5	0.4	0				86	0.6		93	2.6	1.7	Innoc
Presidio Shoals Martinez	Fine	Sand	No	No	1.4	Clear	5	0.4					84	0.6		86	2.6	1.7	Innoc
Clayton	Coarse	1 1/2 x 3/4	Yes	Yes	0.3		1.5	0.2	0	8.7	Innoc			0.6		85	2.84		Innoc
	Coarse	1 x #4	Yes	Yes	0.2		0.8	0.2	0	8.2	Innoc			0.6		91	2.84		Innoc
	Coarse	3/4 x #4	Yes	Yes	0.2		0.8	0.2	0	8.2	Innoc			0.6		91	2.84		Innoc
Permanente Limestone	Coarse	1 1/2 x 3/4	Yes	Yes	0.1		2.7	0.5	0	24	Innoc			0.6		83	2.68		Innoc
	Coarse	1 x #4	Yes	Yes			5	0.5	0	25	Innoc			0.6		92	2.68		Innoc
	Coarse	1/2 x #4	Yes	Yes			4.7	0.5	0	25	Innoc			0.8		86	2.68		Innoc
Sechelt (Import)	Coarse	1 x #4	Yes	Yes	0.1		0.2	0.1	0	25.4	Innoc	-		0.7	92	85	2.72		Innoc
	Coarse	1/2 x #8	Yes	Yes	0.1		0.3	0.2	0	23.6	Innoc			0.9	93	82	2.69		Innoc
	Fine	Sand	Yes	Yes	1.0	Clear	3.9	0.3	0	-	Innoc	140	89	0.9	86		2.65	2.78	Innoc
CEMEX (Formerly RMC)																			
Olympia Plant #125	Fine	Sand	Yes	Yes									90 +/-3	1.4	89 +/-5		2.6		
Clayton Plant #135	Coarse	1 1/2 x 3/4	Yes	Yes	<1.0		2			19	Innoc			1.0	67	79 +/-6	2.81		
	Coarse	1 x #4	Yes	Yes	<1.0		2			19	Innoc			1.0	67	89 +/-6	2.81		
	Coarse	1/2 x 1/4	Yes	Yes	<1.0		2			19	Innoc			1.0	67	89 +/-6	2.81		
Eliot #140	Coarse	1 1/2 x 3/4	Yes	Yes	<1.0		<10			28 +/-6	Innoc			1.5 +/-0.3		75 +/-6	2.68		
	Coarse	1 x #4	Yes	Yes	<1.0		<10			28 +/-6	Innoc			1.5 +/-0.3	66 +/-6	81 +/-6	2.68		
	Coarse	1/2 x 1/4	Yes	Yes	<1.0		<10			28 +/-6	Innoc			1.5 +/-0.3		83 +/-5	2.68		
	Fine	Sand	Yes	Yes	2 +/-1	Sat.	<10				Innoc	110	81 +/-6	1.8 +/-0.3	60 +/-2		2.67		
Sunol #120	Coarse	1 x #4	Yes	Yes	<1.0		<10			21	Innoc			1.7		65 +/-5	2.66		
	Coarse	3/8 x #4	Yes	Yes	<1.0		<10			20	Innoc			1.9			2.68		
	Fine	Sand	Yes	Yes	2 +/-1	Sat.					Innoc	110	81 +/-4	1.8		45 +/-5	2.63		
Orca (Import)	Coarse	1/2 x #4	Yes	Yes	<0.5		<1			5	Innoc. (ASTM C1260 0.01%)			0.5	90	>80	2.88		
	Fine	Sand	Yes	Yes	<2.0		<1				Innoc. (ASTM C 1260 0.01%)	110	85	0.5	80		2.78	2.65	
Syar																			
Lake Herman, CA	Coarse	1/2 x #4		Yes															
	Fine	Sand	Yes	Yes				2.97					83				2.7		
	Coarse	3/8	No	No															
	Fine	Sand	Yes	Yes				2.97					83				2.7		
Madison	Coarse	1/2 x #4	Yes	Yes													2.67		
	Fine	Sand	Yes	Yes							Clear		84				2.61		
	Coarse	3/8	Yes	No															
Vulcan Materials																			
Pleasanton	Coarse	1 x #4	Yes	Yes			5.2			22.5						95	2.68	3.12	
Reg. Top Sand @ Pleasanton	Fine	Sand	Yes	Yes									84	1.2			2.67		
Reg. Pea Gravel @ Pleasanton	Coarse	3/8 x #4		Yes			8.0			21.5						96			
Regular Pleasanton	Fine	Sand		Yes			5.3			20						93	2.69		
West Coast Aggregates																			
Pilarcitos	Fine	5/16	No	No														4.55	
	Fine	Sand	No	No									85					2.83	
Lexington	Fine	Sand	No	No									88					3.01	
	Coarse	3/8 x # 6	No	No															
	Coarse	1 x #4	No	No											75				



Appendix I

Aggregate Producers

CEMEX (Plants Formerly Owned by RMC Pacific Materials)

Clayton #135 is a quarry and crusher operation, producing an angular mineral aggregate called diabase. Diabase is a hard and durable mineral with good shrinkage characteristics suitable for high-strength concrete. Quarry total output is approximately 300,000 to 400,000 tons per year and the supply is estimated at about 30 years. The plant is located near the base of Mount Diablo in Contra Costa County.

The Eliot #104 plant is a sand and gravel operation producing aggregates of greywacke and sandstone suitable for normal strength concrete (3000 to 4000 psi). This is an inexpensive aggregate with only moderate shrinkage characteristics. Total output is up to 1.5 million tons per year, and supply is estimated at about 20 years. The plant is located in the Pleasanton/Livermore area.

The Sunol #120 plant is also sand and gravel operation producing aggregates of greywacke suitable for normal strength concrete (3000 to 4000 psi). This is an inexpensive aggregate with only moderate shrinkage characteristics. This is a small deposit, producing only 200,000 to 300,000 tons per year. The plant is located in the Sunol area.

Cemex has recently entered into a supply and distribution agreement with the Polaris Minerals Corporation for aggregate from the Orca Quarry on Vancouver Island, Canada. This is a high-quality sand and gravel deposit with at least a 25 year life. The aggregate has a higher than usual specific gravity, which can result in hardened concrete weighing more than 150 lbs per cubic yard, and the weight of the wet concrete can limit the cubic yardage carried by a ready-mix truck. This aggregate is being used for the east span of the San Francisco-Oakland Bay Bridge. The Orca Quarry and the Richmond, California port terminal were developed specifically by Polaris Minerals to target the California market. The first shipments arrived at the Richmond terminal on October 9, 2007. A second quarry, Eagle Rock, also on Vancouver Island is in development. This will be a quarry and crusher operation producing crushed granite aggregates.

The Vulcan Materials Company

The Vulcan Materials Company was started in Birmingham, Alabama. The company entered into the western market with the purchase of CalMat in 1999. Aside from the Pleasanton quarry discussed below, the company also operates quarries for concrete aggregates in Sacramento, Fresno, Los Banos, Bakersfield, and Sanger.

The Pleasanton plant is located at an alluvial deposit, and produces fine and coarse aggregates for concrete and asphaltic concrete. The material is composed of various rocks and minerals, and is generally rounded. Larger rocks are run through a crusher operation, but then typically used for asphalt. Aggregates for concrete meet ASTM C33 requirements and are considered not to have any special characteristics with respect to concrete shrinkage. The plant produces approximately 3.5 million tons per year (all aggregate products) and the site is permitted for 25 years.

Hanson Aggregates

Hanson Aggregates is the largest aggregates producer in the world, the second largest aggregate producer in California, and the largest producer of cement in Northern California. Hanson purchased Kaiser Sand & Gravel (established in 1923) in 1992, and Kaiser Cement (established 1939) in 1981. They have the following sources for aggregates in the Bay Area:



Permanente Limestone, from the Cupertino quarry, is very high quality low shrinkage crushed rock. Hanson would not divulge quarry output and supply, but noted that, while reserves are ample, annual production is affected by permit limitations.

Clayton, Concord-Walnut Creek quarry, produces Diabase, which is a high quality, low- to moderate-shrinkage rock.

Sunol, recently acquired from Mission Valley Rock, is a sand and gravel operation on an alluvial deposit producing coarse and fine aggregates for concrete. The coarse aggregate contains a fraction of crushed rock from oversize material that is crushed and then blended.

Sechelt, imported from Canada at the Ports of San Francisco, Redwood City, Oakland, Richmond, and Stockton, is a combination round and crushed glacial deposit rock. It is very high quality aggregate with very low shrinkage, low water demand and high strength. They are using this aggregate in the high strength concrete on the new Bay Bridge.

Syar Industries

Syar has been a family owned business since the 1940s and is currently run by James Syar, the son of the founder. Three pits around the San Francisco Bay Area produce concrete aggregates:

Madison, California is an alluvial deposit with a mixture of many types of rocks and minerals, obtained by screening the alluvial river deposits. Quarry total output is approx 1 million tons per year, and supply is estimated at about 27 years.

Lake Herman, Vallejo is a quarry producing 100% crushed basalt rock. This is currently mostly used for asphalt and aggregate base, since thus far it has been uneconomical to use for concrete aggregates. Quarry total output is approximately 2 million tons per year, and supply is estimated at 50 years, although the quarry is up for re-permitting soon.

Healdsburg is also an alluvial deposit, with a total annual output of 1.5 million tons of screened alluvial gravel. The future of the site is uncertain at this time. They are currently trying to obtain permits to continue and are running up against noise complaints from the residential encroachment in the area.

Graniterock

Graniterock's operations are located in the far south bay, from Hollister to as far west as Santa Cruz. The plants in the Santa Cruz area produce a sand which is generally too fine for concrete aggregate and will not be discussed here. Graniterock is a privately-held company and will not provide data on output and supply.

The A.R. Wilson quarry is Graniterock's main source of coarse aggregate for concrete. The material is granite, processed by mining and then crushing. This material can produce high-strength concrete and concrete with low shrinkage characteristics.

The Southside Quarry in Hollister is a river deposit. The sand and gravel operation produces pea gravel, $\frac{3}{4}$ inch round rock and concrete sand. The materials are variable, but meet the requirements of ASTM C 33.

West Coast Aggregates

West Coast Aggregates, Inc. is a California Corporation which started business in February 1989. Its only business at this time is construction aggregates. The company's quarry and sand and gravel operations are located in the San Francisco Bay Area and the San Joaquin Valley.

The Pilarcitos Quarry in Half Moon Bay produces concrete sand. The material is granite.



The Lexington Quarry in Los Gatos is a sand and gravel operation producing both fine and coarse aggregates for concrete. The material is greywacke.

Other quarries including Green Pit, Crows Landing (near Patterson) and Valley Rock in Tracy do not currently produce concrete aggregates, although the company has plans to produce concrete aggregates in the near future at Valley Rock.

Granite Construction Company Incorporated

Granite Construction Company has processed rock for over 80 years. The nationwide company, headquartered in Watsonville, produces aggregates, ready mix, and hot mix asphalt at over 60 locations in the western United States. The materials operations were started as a small complement to the heavy civil construction that was Granite's main business, but are now a major component of the company that provide materials to outside customers as well as their own construction jobs and plants.

Felton Quarry near Santa Cruz is one of the main sources for construction materials in Santa Cruz County. A granite deposit, the Felton Quarry produces a blend sand for use in concrete as well as other aggregate products.

Metz Sand and Gravel is located in the Salinas Valley near Greenfield. Material is mined from a dry streambed, which produces a very clean, high-quality concrete sand along with coarse concrete aggregate and other sands.

The Freeman Quarry in Gilroy is a quarry and crushing operation that supplies various sizes of crushed basalt suitable for coarse concrete aggregate. Concrete aggregates are only approximately one-third of the total production at this quarry.

Teichert

Teichert is one of the oldest construction companies in California. The aggregate materials business supplies construction aggregates from plants located mostly in the Sacramento area.



Appendix II

SEAOC Reports:

Control of Shrinkage of Concrete - 1965

Supplementary Recommendations for Control of Shrinkage of Concrete - 1976

CONTROL OF SHRINKAGE OF CONCRETE

REPORTED BY
THE COMMITTEE ON SHRINKAGE OF CONCRETE
STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA

May 1965

A. H. Brownfield
David L. Narver, Jr.

M. R. Neumann
M. V. Pregnoff, Chairman

I - INTRODUCTION

The SEAOC Committee on Shrinkage of Concrete was formed by the Structural Engineers Association of California as a result of the resolution passed by the members at the 1963 Annual Convention, SEAOC:

WHEREAS the State has requested this Association to form a committee to recommend realistic methods of controlling shrinkage of concrete,

WHEREAS the State has been studying the problem of shrinkage for several years and has sufficient data to show that some aggregates exhibit a high potential for shrinkage,

WHEREAS it is our duty to protect ourselves, our clients, the owner and the contractors when this information is available,

NOW THEREFORE BE IT RESOLVED that the Board of Directors is hereby requested that a Committee be assigned by the State Association to study the problem to recommend methods of control and to establish reasonable shrinkage factors consistent with sound engineering principles.

The resolution was prompted by many recent experiences with concrete buildings where excessive sagging, cracking and leaking have occurred.

II - THE PROBLEM OF CRACKING AND DISTORTIONS IN CONCRETE STRUCTURES

Cracking and sagging of concrete members is not a new problem. Since the beginning of the use of concrete, engineers, architects and builders occasionally have had unfortunate experiences with sagging floors or cracked, "leaky" walls, which caused anxiety to the owners and inconvenience to the occupants of buildings.

Lately the problem of distortions in concrete buildings has become worse because of an increasing demand for longer buildings and longer shallow depth members. The design of very shallow members is now possible because of the availability of high strength steels and concretes. Precast construction also demands light, shallow, thin members for ease of handling during erection.

It appears that the more advanced principles of design of concrete structures demand that the acceptability of the work should not be based solely on the ultimate strength and workability of concrete. Shrinkage and creep must also be given proper consideration; this is because the deformations due to creep and shrinkage may be two or more times greater than the elastic deformations.

Section 903 of the 1953 ACI Building Code requires that consideration shall be given to the effects of forces due to creep and shrinkage.

The panel on Plant Production of the Prestressed Concrete Institute² recommends that the quality control of concrete be so exercised as to insure that

"It must have low values of shrinkage and creep in order to minimize losses and member shortening which may cause jointing problems."

The above requirement is in addition to the usual criteria for strength, durability, etc.

Deflections and cracks in concrete structures may never be entirely eliminated, but they can be controlled and minimized by

- a. Proper selection and proportioning of concrete ingredients.
- b. Proper construction methods, such as mixing, placing, consolidating, curing, etc.
- c. Proper techniques in the design of concrete members and joints.

All the above items are of equal importance and the order in which they are given is immaterial.

Concrete cannot be used intelligently without taking into consideration its volumetric changes with time.

Concrete deforms elastically and creeps under sustained loads as time goes on. It shrinks and swells due to changes in moisture content under varying temperature-humidity environments. It contracts and expands due to changes in temperature. When some of these movements are restrained by the foundations, the steel reinforcement or by adjacent portions of the structure, tensile stresses in the concrete are induced. Cracks are formed in places where tensile strength and extensibility of concrete are overcome.

Creep and shrinkage of concrete are so intimately interconnected that one cannot be considered without the other. In fact, E. Freyssinet, the famous French Engineer, evolved a theory that shrinkage is a creep due to sustained capillary forces. Wei-Wen Yu and George Winter³ derived a coefficient which takes care of both shrinkage and creep in the computation of deflections of concrete beams.

In general, when the magnitude of the shrinkage of a concrete mix is controlled, the magnitude of its creep is also controlled to a certain extent because the undesirable factors that affect shrinkage seem to have a similar effect upon creep.

The tendency of concrete to crack under conditions of restraint is a time-dependent process. It depends upon the eventual movement due to temperature changes and shrinkage, on the tensile strength of concrete, its creep properties, effective modulus of elasticity, etc. Creep allows greater extensibility and thus offsets the tendency to crack. However, the higher shrinkage usually overcomes the relief offered by the creep.

In 1962 the State of California built eight similar concrete deck sections in the Webber Creek Bridge⁴. Concrete of four degrees of shrinkage was produced by using combinations of two cements and two aggregates. Shrinkage specimens were cast on the

job and tested in the laboratory in accordance with ASTM procedures. A year later one of the concrete decks with higher shrinkage characteristics (750×10^{-6} ; 3 in. by 3 in. bars, 28 days of drying) showed 69 soffit cracks with a total length of 245 feet, with 13 cracks leaking. One of the concrete decks with lower shrinkage characteristics (290×10^{-6} ; 3 in. by 3 in. bars, 28 days of drying) exhibited 7 soffit cracks with a total length of 29 feet, with 1 crack leaking.

III - AMOUNT OF SHRINKAGE

Most shrinkage is due to diffusion of moisture from the interior of the concrete toward its surface to replace that lost by evaporation. The process is exceedingly slow and complex. The surface of concrete dries more rapidly than its interior. This causes concrete to shrink non-uniformly because the shrinkage of outer fibers is restrained by the inner fibers. A complicated system of sustained stresses is created at which time creep enters into action and modifies the effect of shrinkage. Thus there is no such thing as "free" unrestrained shrinkage. This convenient term is used for total shortening of a laboratory specimen of plain concrete. In some tests, cracks either at the rock-paste interface or in the paste itself, are formed due to internal restraint. These cracks relieve the shrinkage stresses with the result that short-time measurements indicate low shrinkage⁴, not indicative of the true shrinkage potential.

Because drying commences at all exposed surfaces, the magnitude of progressing shrinkage varies considerably with the size and shape of the member and depending also upon how many surfaces are exposed to drying. Under ordinary climatic conditions the average shrinkage of structural members one foot or more in thickness probably would never approach that of small bars⁵. This phenomenon is due to the fact that concrete will absorb in one day as much moisture as it will release in two weeks. Thus periodic absorption of moisture by concrete in service prevents the indefinite continuation of drying as in a laboratory under a steady humidity-temperature environment. Tests lasting for 720 days showed that shrinkage in the field of 3 by 4 in. specimens was 0.3 to 0.5 of that of specimens under laboratory conditions²¹ for 720 days.

Tests of the California Division of Highways showed that outdoor shrinkage in Sacramento for 112 days of 14 by 20 in. beams was about 0.3 of that of 4 x 5 in. specimens⁸ dried under the same conditions.

Carlson¹¹ assumed that drying shrinkage is approximately proportional to the amount of moisture lost. On this basis he found that 50% of the ultimate shrinkage will take place in 1 month in a 3 in. slab; in 1.8 months in a 4 in. slab; in 4 months in a 6 in. slab, and in 16 months in a 12 in. slab; all drying from both faces at constant 50% relative humidity. The above shows the importance of consideration of the size, exposure and shape of a member in shrinkage studies. A 12 in. thick slab or wall exposed to natural weather may not reach 50% of ultimate shrinkage in 16 months because of periodic absorption of moisture during changes of weather.

For the study of cracking in a larger concrete member the distribution, as well as the average amount, of shrinkage is of importance. Carlson¹¹ gives an approximate distribution of shrinkage in slabs or walls of any thickness for any period of continuous drying at 50% relative humidity. A 12 in. wall at the end of 100 days drying from one face only will tend to shrink 48% of the ultimate at the first 0.1d (d = thickness) from the drying face, 18% at 0.2d, 7% at 0.3d, 2% at 0.4d, 1% at 0.5d. At 0.6d there will be no shrinkage at all. Under these conditions surface cracking is inevitable for concrete with an ultimate shrinkage of 900 millionths.

Several textbooks and publications treat the subject of warping of concrete due to shrinkage 15, 16, 17, 18, 19, 20, 25.

For practical purposes formulas are usually given in terms of the effective "free" ultimate concrete shrinkage S_u , which is the ultimate shrinkage of the concrete member in the structure, regardless of its cross section or mode of drying, expressed as a dimensionless ratio of the length of shrinkage divided by the length of member under consideration.

Miller¹⁸ gives 500, 600 and 700 millionths as commonly accepted ultimate values for low, medium and high shrinkage respectively.

For the purpose of this report the concretes having ultimate shrinkage of 400, 600 and 800 millionths will be classified as Class A, B and C respectively.

The effect of shrinkage upon deflections is greater than realized. In many cases the deflection due to shrinkage is just as large as immediate deflection due to dead load and in some cases the deflection due to shrinkage is greater than the deflection due to creep²⁰

The calculated deflections of a 5" thick canopy slab cantilevered 8' is:²²

0.43 in. immediate due to dead load
0.42 in. due to creep
0.59 in. due to shrinkage
1.44 in. total

The deflection of 0.59 in. due to shrinkage is based upon a low shrinkage concrete (400 millionths). For high shrinkage concrete (800 millionths) the shrinkage deflection will be 1.18 inches, which is nearly 3 times the immediate dead load deflection. With increased deflection due to the high shrinkage of the concrete, creep and the deflection due to it will also increase somewhat, so that the total deflection will be well over 2 inches.

When deflection and/or cracking are a major consideration it is not advisable to use high shrinkage concrete.

IV - CONTROL OF SHRINKAGE BY LABORATORY SPECIMENS

Compressive strength of a 6 x 12 in. cylinder admittedly does not represent the strength of the concrete in a structure, where the stress distribution differs greatly from that in a test cylinder. However, standard cylinder tests are of considerable value for practical purposes of strength control of concrete.

Similarly, the shrinkage of a laboratory specimen can be used to control and serve as an index of potential shrinkage of concrete to be used on a job.

Shrinkage test specimens are usually small concrete bars 3 x 3 in., 4 x 4 in., or 4 x 5 in. in cross-section. They are moist cured for 7 days. The shrinkage is measured on a 10 in. min. gage length. The specifications usually limit the amount of shrinkage after either 14, 21 or 28 days of drying, and sometimes at later ages.

Tremper and Spellman⁸ compared the results of laboratory specimens dried under standard conditions to those of field exposure of full-size or near full-size structures and pavements. There is substantial evidence that suitably designed laboratory tests can be used to predict the effect of the characteristics of the constituents of concrete and the conditions of its manufacture on its shrinkage in service.

The drying shrinkage of small laboratory specimens is approximately proportional to the surface-to-volume ratio. If the relative shrinkage of a 4 x 4 x 11 in. bar is taken as 1.0, the shrinkage of a 3 x 3 in. is 1.3; of a 4 x 5 in. is 0.9; of a 6 in. cylinder is 0.7.

G. E. Troxell⁹ made a series of short-time tests on concrete shrinkage. He concluded that the actual long-time shrinkage may be computed from the short-time shrinkage provided a proper conversion factor for the special test conditions has been determined previously. In his tests 28-day laboratory shrinkage tests predicted 200-day laboratory shrinkage with 13% max. and 2% min. error.

In order to arrive at a proper and reasonable shrinkage limit of a laboratory specimen, it is necessary to consider the overall phenomena of shrinkage of concrete including the resulting cracking.

We need the amount of ultimate shrinkage in a structure from all or any sources and the cracking potential it creates. It is difficult to estimate closely the weather conditions under which the concrete will be made in a structure, or to predict the effective temperature-humidity environments such as air conditioning, heating and ambient conditions to which the concrete in a structure will be subjected in different parts of the country. Therefore, it is best to allow for the most unfavorable possibilities.

The rate of shrinkage is rapid at first and then decreases asymptotically with time. Again, it is a function of the size and shape of the member. Shrinkage of 3 x 3 in. specimens dried at 50% R. H. and 75° F appears to approach its ultimate after about 32 weeks¹⁰. The 28-day drying shrinkage of 3 by 3 in. specimen may be taken equal to about 50 percent of its ultimate shrinkage. The shrinkage of a 4 x 4 in. specimen approaches its ultimate in about 64 weeks; its 28-day shrinkage may be taken about 40 percent of the ultimate. The 28-day shrinkage of 6 in. cylinder specimens may be taken about 35 percent of the ultimate. These are average values taken from various tests.

Troxell, Raphael and Davis¹⁰ tested fifty-six 4 in. cylinder specimens; max. aggregate size 3/4 in. and 1.5 in.; several types of aggregates; cement types I and IV; relative humidity 50 and 70%. The rate of shrinkage was as follows:

- 14 to 34% of the ultimate shrinkage occurred in 2 weeks.
- 20 to 50% of the ultimate shrinkage occurred in 4 weeks.
- 40 to 80% of the ultimate shrinkage occurred in 3 months.
- 66 to 85% of the ultimate shrinkage occurred in 1 year.

The above values can be used in estimating approximate long-time shrinkage of small laboratory specimens from their short-time shrinkage. These values do not apply to larger members.

Assume that the ultimate "free" concrete shrinkage will be controlled by the laboratory shrinkage of a 4 by 4 in. test specimen, moist cured for 7 days and then dried for 28 or 21 days under 50% ± R. H. and 73.4° ± F (A. S. T. M. Designation C 157-64). Designate 28-day drying shrinkage of laboratory specimen by S. As mentioned before, assume that the 28-day shrinkage is 0.4 of its laboratory ultimate S'. Then

$S' = S \div 0.4 = 2.5S$. Assume that due to variation in humidity, temperature, sizes of members, etc., the effective "free" ultimate shrinkage in a structure will be 0.5 of that of the laboratory specimen. Then the effective average "free" shrinkage in the structure will be $S_{11} = 2.5S(0.5) = 1.25S$.

Thus the 28 day laboratory shrinkage of 4 x 4 in. specimens dried for 28 days should be:

$400 \div 1.25 = 320$ millionths for Class A concrete.
 $600 \div 1.25 = 480$ millionths for Class B concrete.
 $800 \div 1.25 = 640$ millionths for Class C concrete.

Due to considerable spread in the properties of concrete of the same nominal strength, a variation of 15 percent can be allowed in the above values.

If specimen is dried for 21 days multiply the above values by 0.83.

These values may be specified as shrinkage limits of test specimens in order to control the shrinkage of concrete for a project. See Appendix I for sample specification.

It should be borne in mind that no laboratory test of small specimens can be expected to predict exactly the shrinkage of concrete members in a structure under all kinds of conditions. Future tests on the correlation between laboratory and field shrinkage may show that the above given values should be decreased or increased.

V - SELECTION AND PROPORTIONING OF CONCRETE INGREDIENTS FOR LEAST CREEP AND SHRINKAGE

The shrinkage of concrete depends on the properties and relative amounts of both the cement paste and the aggregate.

The main ingredient of a concrete mix is the aggregate. It is not an inert material introduced only for economic reasons. It is a building material connected into a cohesive whole by means of the cement paste⁵. The aggregate, which occupies 75% of the total volume of concrete, is normally stronger and more durable than the cement paste. Its physical, thermal and chemical properties have a large influence on the overall performance of concrete. Neat cement paste shrinks as much as 2700 millionths of its length, which is equal to 3.24 inches per 100 feet (1000 millionths of length equal 1.2 inches per 100 feet). Good aggregate shrinks very little. It restrains the shrinkage induced by the cement paste. Not all aggregates are equally effective in restraining the shrinkage of the cement paste. Small 4 to 6 in. laboratory concrete specimens made of such aggregates as quartz, feldspar, good grades of limestone, dolomite and granite ultimately shrink 350 to 550 millionths of their length under constant humidity-temperature environment of 50% ± R. H. and 70° ± F. Concrete specimens made of certain siliceous and/or calcareous mixed gravels, sandstone, marble, slate or low grades of granite ultimately shrink 600 to 1100 millionths of their length under the same constant humidity-temperature environment. The effect of the mineralogical character of aggregates must be given consideration in the control of the magnitude of the shrinkage of concrete, or actual shrinkage data obtained by tests.

Pollivka^{13, 14} concluded that "the nature of the aggregate is one of the major factors influencing the shrinkage and cracking characteristics of concrete."

Excessive amounts of clay in the aggregate increase the shrinkage up to 25%. Limits of clay content of the aggregate should be specified. See Test Method No. Calif. 217E (Materials Manual, Testing and Control Procedures - Materials and Research Department, State of California, Sacramento, California).

Laboratory tests⁶ show that there is a range as much as 2 to 1 in the relative shrinkage exhibited by different cements with the same aggregate. Shrinkage characteristics of a cement cannot be predicted reliably from the ordinary chemical analysis. Type I (low alkali) cement normally exhibits low shrinkage, but there can be a difference of 100% between the Type II cements of different manufacturers.

Tests have shown that for the same water content per cubic yard of concrete the shrinkage remains the same for a wide range of cement contents. For example, concrete mixes with either 6, 7 or 8 sacks per cubic yard, but with 35 gallons of water per cubic yard gave about the same shrinkage of 500 millionths of the length⁷. Mixes with larger maximum size aggregates demand less water. Thus shrinkage can be decreased by about 20% by using 1½ in. maximum size aggregate instead of ¾ in. maximum. Reduction of water content by the use of proper admixtures should reduce shrinkage. The ideal mix to minimize shrinkage for a given set of materials is one containing in a cubic yard the least amount of water, the largest maximum size aggregate and the lowest possible percentage of sand consistent with good workability. The slump should be the least at which the concrete can be consolidated by intelligent use of modern vibrators. 0" to 2" slump concrete is being used in some fabricating plants and 3" and 4" slump concrete is being placed in field.

VI - TECHNIQUES IN DESIGN OF CONCRETE BUILDINGS TO MINIMIZE THE EFFECT OF SHRINKAGE

It should be kept in mind that most portions of a concrete building, during construction and at service, are constantly in motion due to variations in temperature and humidity. When the movements of adjacent portions are unequal the tensile strength and extensibility of concrete may be overcome and cracks will ensue. The undesirable effect of cracking upon the serviceability of a building may be reduced by trying to provide details and shapes that will minimize the differential movements of adjacent elements.

It can be assumed that the propagation of an average shrinkage with time in a wall is inversely proportional to the square of its thickness¹¹. For example, a 12 in. thick wall will tend to shrink in a given time $(8/12)^2 = 0.44$ as much as an 8 in. thick wall. Discontinuities or changes in thickness and horizontal dimensions should be avoided. A fenestration with wide wall panels at the ends of a building and narrow intermediate piers joined by relatively thin spandrels will surely result in cracks in the spandrels at the corners of windows due to restraining action of end walls. A building front with narrow piers throughout, uniformly spaced, is better. If large end wall panels are functionally or esthetically necessary, specially designed contraction joints can be introduced at the points of dimensional or volumetric discontinuity. A wall front with thick and wide piers (say 16 by 48 in.) joined by thin spandrels will result in cracks in the spandrels, because they dry out much faster (inversely to square of a thickness) than the thick piers in between.

Since the rate of the advancing shrinkage front diminishes as a square of a depth from the drying surface, the thick wall may never dry out and reach its ultimate shrinkage because during the changes of seasons it will be absorbing moisture, while the thin wall will dry out and crack before the change in season arrives. However, the thick wall drying from one face only may crack at the outer face due to internal restraint, but the

cracks most likely will be shallow and will not reach the inner face. A building with exterior columns and 8 in. thick walls with openings will have more "leaky" cracks than a building with 12 in. thick bearing walls with similar openings.

Observations show that in buildings with basements or large heavy foundations under walls the most numerous cracks are in the first story walls due to the restraining action of the portions of the building below the ground where the shrinkage is the least. The building with columns only in the first story of exterior front will crack less because the columns will accommodate the movements due to differential shrinkage²⁷.

Observations show that the building fronts having about 60 percent or more of openings crack least, but solid blank walls and walls with relatively small openings (say 25 percent of gross area) present trouble. Cracks are developed at about 10 to 16 feet on centers. The greater the spacing of cracks the wider the cracks. Owners of buildings are faced with the problem of water leakage through cracks. If walls are sprayed with asphaltic compound on the inner face and furred the penetration of moisture will not be as troublesome.

Since shrinkage of concrete walls may never be eliminated, an attempt can be made to distribute the movements due to shrinkage in as many smaller (not "leaky") cracks as possible. "V" or "U" grooves can be used in the hope that the cracks will open within these grooves. The grooves should be located opposite to each other in both faces of wall. Using vertical grooves at about 6 feet on centers and providing vertical and horizontal grooves at extensions of heads, jambs and sills of openings will increase the number of smaller cracks and channel them within the grooves. Wider spacing of grooves decreases the chance of cracks being smaller and occurring within the grooves.

Inspection of existing buildings revealed that concrete walls whose surfaces were coated with oil paint cracked less than those having only a cement wash. The vinyl paints that breathe are best for this purpose. The least cracking was noticed in buildings where walls were covered with stucco, and particularly in those which were painted in addition. Thus, protection of the surfaces of concrete from rapid moisture changes will decrease its cracking tendency.

Precast concrete members, such as wall panels, precast slabs, precast frames should not be joined too soon. If a waiting period of about 3 weeks or more is allowed for drying, much cracking will be eliminated. When a series of precast elements are interconnected, or connected to steel columns, the details of the connections should allow for movements due to shrinkage and temperature changes. A generous use of thokol, or equal, is recommended at all exposed joints.

Shortening of a reinforced concrete beam and slab due to shrinkage is resisted by the reinforcing steel and by adjacent members. When the reinforcing steel is unsymmetrical with respect to the center of gravity of the cross-section warping takes place. An introduction of compressive steel will reduce the warping due to shrinkage appreciably, particularly in cantilevers. The references 3, 15, 16, 17, 18, 19 and 20 give methods of computing deflections due to shrinkage warping.

Since the deflections due to creep and shrinkage are dependent on time, it is advisable to give consideration to controlling the time of installation of non-structural fragile elements under or over concrete beams. For instance, a certain concrete beam may deflect 0.25 in. immediately after removal of the shores. Eventually it will deflect an additional 0.50 in. due to creep and shrinkage³. However, about half of the above added deflection will take place during the first three months after removal of the shores³. Thus only 0.25 in. of deflection will be left to hurt the non-structural fragile elements, if they are installed three months after removal of the shores.

VII - CONSTRUCTION METHODS IN FIELD

Strict enforcement of good standards of construction in the field, such as mixing, cooling, placing, consolidating, curing, etc., will reduce drying shrinkage of concrete in the structure.

Concrete which is allowed to dry immediately after it is placed is only 50 percent as strong at 6 months as concrete which has been cured for 14 days before being exposed to dry air. When properly cured, concrete develops tensile strength and resists cracking. In general, the ultimate shrinkage of concrete is not reduced by the prolonged curing, but the number of cracks is appreciably reduced due to the higher tensile strength of concrete as a result of additional curing. Wall forms should be kept in place for at least 10 days and be continuously moist including Saturdays and Sundays. If a concrete wall is allowed to dry rapidly it will be weak in tension with the result of more extensive cracking. Concrete floor slabs should be cured by covering them with curing paper and kept wet for at least 10 days. The ability of sprayed curing liquids to cure concrete should be carefully investigated before being used. The sprayed layer should not be too thin. Curing of concrete is generally inadequate and very often is applied too late to be of benefit. It should begin as soon as the slab has stiffened enough to support the paper. Curing procedures should be strictly enforced if one wants to minimize the number of cracks in the structure.

Hot weather requires special attention in the manufacture, placement and curing of concrete²³. The temperature of equipment and all ingredients should be maintained at such a level that the temperature of the concrete at the forms is not over 75° F. Adequate personnel, both as to number and skill, are necessary. Delays in placement contribute to slump loss and lead too often to the use of additional water in the field to offset this loss. This practice should be avoided.

Harmful effects of additional water are two-fold: it increases the shrinkage by about 10 to 15 percent and it decreases the tensile strength of concrete which is needed to resist cracking due to shrinkage.

Hot weather also leads to the so-called plastic shrinkage cracks. The plastic shrinkage cracks are the result of very rapid evaporation of water from the surface of concrete while it is still plastic and very weak. The severity of plastic cracking depends upon the rate of evaporation of water, which in turn depends upon temperature, relative humidity and wind velocity. Under average conditions and mild wind, as much as 1/8 lb. of water per sq. ft. of surface per hour could evaporate. For extreme conditions (90° F., dry, high wind) the loss of water observed was 3/4 lb. per sq. ft. of surface per hour²⁴. The disappearance of the sheen from the surface of concrete indicates that the evaporation at the surface is faster than the rate of rising water. At that moment the plastic shrinkage cracks will begin to occur.

Plastic shrinkage cracking can be eliminated by providing proper humidity environment using a fog mist. The fog mist should be started after first floating of the concrete and continued until curing paper is applied to the slab. Concrete poured late in the afternoon with a falling temperature will have less plastic shrinkage cracking.

Cracking, checking and crazing of concrete floor slabs often result from improper finishing operations. The concrete slab is "manipulated to death." This procedure brings the fast shrinking fines and water upwards, thus making the top layer of the slab weak in tension. Davis and Troxell²⁵ investigated the floor slab of a government building. Measurements showed that drying shrinkage of the top inch of the floor was approximately five times as great as that of the bottom inch. Overtroweling or too early troweling should not be allowed.

VIII - CUMULATIVE EFFECT OF ADVERSE FACTORS ON SHRINKAGE

The cumulative effect of adverse factors on shrinkage of concrete due to the departure from the use of best materials and workmanship is alarming. The shrinkage may increase as much as 500 percent of normal^a. Combination of such unfavorable factors as addition of water in the field necessitated by the high temperature of concrete at discharge and prolonged haul in transit mixers, using large slump, using 3/4 in. maximum size of aggregate instead of 1 1/2 in. may increase the shrinkage to about 160 percent of normal. The remaining increase of 340 percent may be due to lack of control of quality of constituent materials, such as use of cement of relatively high shrinkage characteristics, allowing excessive "dirt" in aggregate, use of weak compressible aggregates and use of unfavorable chemical admixtures.

The above shows that a concrete of minimum shrinkage requires all around control: proper materials, proper design of mix, proper mixing and transporting, and proper placing and curing.

The concrete usually is one of the first items manufactured and placed into a structure. Almost invariably at the outset haste develops. The General Contractor is primarily interested in placing concrete as fast as possible and getting the other trades into the building. In some cases he has to do this because the contract documents do not provide ample time. The time often is so limited that the Contractor must resort to doubtful expedients to get the work out. On account of haste, frequently, the well-intentioned project specifications are relaxed and the man responsible for enforcement must comply tacitly and accept the change as inevitable.

Haste is evident on many jobs:

1. There is a tendency to overload transit mixers in order to get as much concrete to the job as fast as possible, such that the concrete is improperly mixed before it is placed.
2. Sometimes concrete delivered to the job is so stiff that water is added indiscriminately to remedy the situation.
3. The placing (pouring) schedule is rushed such that the vertical lifts are too high and inadequate time lag is allowed between the placement of successive lifts.
4. There is a tendency to use undesirable sloppy wet mixes. Concrete ingredients are flying instead of flowing, resulting in a separation of larger aggregates from concrete. Low slump, drier mixes, producing better concrete, are not favored because it takes more personnel and extra effort to consolidate such concrete thoroughly.
5. Concrete is often placed under adverse weather conditions of temperature, humidity and wind.
6. The advantage of modern vibrators is not fully utilized. The batch is merely flattened and not properly consolidated. Lack of current is frequently responsible for improper consolidation of concrete.
7. Curing operations are delayed and not carried out to completion, or are eliminated entirely.
8. The weight of subsequent pours is imposed upon recently cast "green" concrete, which resists the load but deflects and sags excessively. The excessive deflections are often blamed on shrinkage and creep, and poor design.

9. Slump is a rough measure of the degree of wetness of concrete. Often slump tests are omitted, even where specifications require them.

Concrete of good shrinkage characteristics requires careful step by step unhurried handling. Strict control of concreting operations and temperature is essential. Good drawings and specifications have no meaning, unless they are enforced. Job inspection by competent personnel should be such as to allow and insure enforcement.

The quality of all ingredients of a concrete mix, to satisfy the chosen shrinkage requirements of a project, can be controlled by making a trial batch of a mix using the proposed cement, aggregate and admixture, if any. A set of drying shrinkage specimens can be prepared and tested in a special room in a laboratory. Many testing laboratories in California are equipped to perform this service.

IX - CONCLUSION

Now that designs of concrete systems utilize long, slender, and shallow elements, consideration of shrinkage and creep can no longer be considered as negligible. As is shown in the preceding discussion, consideration of the concrete's strength alone is no longer a sufficient measure of serviceability. This does not imply that concrete is not a satisfactory material, but rather, points up the increased responsibility of the engineer and contractor.

In order to properly consider shrinkage and creep, the engineer needs more knowledge of the shrinkage and creep properties of concrete, particularly as regards local materials. The Committee, therefore, recommends that concrete producers initiate steps toward research on time-dependent shrinkage and creep properties of concrete made with local materials and on the effect these properties have upon concrete in service.

APPENDIX I

SAMPLE SPECIFICATIONS

For Shrinkage

(a) Prior to placing any concrete, a trial batch of each mix design of structural concrete shall be prepared using the aggregates, cement and admixture, if any, proposed for the project. From each trial batch at least three (3) specimens for determining the "Drying Shrinkage" shall be prepared in addition to six (6) compression test specimens.

(b) The "Drying Shrinkage" specimens shall be 4 by 4 by 14 in. prisms, fabricated, cured, dried and measured in the manner outlined in A.S.T.M. Designation C 157-64T. Measurements shall be made and reported separately for 7, 14, 21 and 28 days of drying after 7 days of moist curing. The effective gage length of the specimens shall be ten (10) inches.

Compression test specimens shall be fabricated, cured and tested in accordance with A.S.T.M. Designation C 192-59. Three (3) specimens shall be tested at an age of 7 days and three (3) at the age of 28 days.

(c) During construction "Drying Shrinkage" specimens of each class of concrete will be taken to insure continued compliance with these specifications. At least one (1) set of three (3) specimens will be taken from each 1000 cubic yards of concrete placed, but in no case less than three (3) sets of specimens will be taken for the project. Compression test specimens will be taken from the same concrete as used for preparing "Drying Shrinkage" specimens. These compression test specimens shall be considered as part of the normal requirements for tests in connection with this project.

(d) The average "Drying Shrinkage" of the test specimens after 28 days*) of drying shall not exceed 0.032**) percent. Considering the variations in concrete properties and in testing, a tolerance of 15 percent in the above figure will be allowed.

Notes to specification writer:

*) If 21 days drying is specified use 83% of the above values.

**) The figure of 0.032 percent = 320 millionths to be used if Class A concrete is desired. For Class B concrete the figure is 0.048 percent. For Class C concrete the figure is 0.064 percent.

The shrinkage limitations of concrete need not apply to foundations (below grade).

It is possible to require "Drying Shrinkage" test specimens of only one class of concrete with smallest maximum size aggregate, provided that the same materials and about the same or less water per cubic yard is used in other classes of concrete.

For Cleanliness of Aggregate

All aggregate shall have a minimum C.V. (cleanliness value) and S.E. (sand equivalent) of not less than 75. Three (3) samples shall be tested in each case and shall

bc taken from weigh hopper. The average of the results of the individual tests will be the accepted value in each case. These values shall be maintained throughout the course of the work and any indicated deviation therefrom will be cause for rejection of such material, pending additional tests. Test shall conform to Test Method No. Calif. 217E (Materials Manual, Testing and Control Procedures - Materials and Research Department, State of California, Sacramento, California).

SEE GUIDELINES
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SUPPLEMENTARY REPORT
PAGE 3

APPENDIX II

SHRINKAGE TEST DATA FOR CONCRETES USED ON SOME PROJECTS IN CALIFORNIA

Fig. 1 shows a plot of the 28-day shrinkage for concrete specimens tested in private and State of California laboratories under environment of approximately 70° F. and 50% relative humidity.

The tests were conducted for concretes actually specified for various projects during the years 1960 thru 1963. Different cements were used (Galaveras, Ideal, Permanente, Santa Cruz) in combinations with aggregates from various sources. Maximum size of aggregates varied from 3/4 to 1 1/2 in. Various admixtures (and no admixtures) were used.

The sizes of test specimens varied (3 by 3 in., 4 by 4 in., 5 by 6 in., etc.). The values of shrinkage plotted in Fig. 1 were converted to 4 by 4 in. specimen.

For this series of tests the total number of specimens was 214. It is seen that 115 specimens (about 53% of the total) met the requirements of $320 + 15\% 320 = 368$ millionths for Class "A" concrete; 185 specimens (about 86% of the total) met the requirements of $480 + 15\% 480 = 552$ millionths for Class "B" concrete; and 212 specimens (about 99% of the total) met the requirements of $640 + 15\% 640 = 736$ millionths for Class "C" concrete.

APPENDIX II

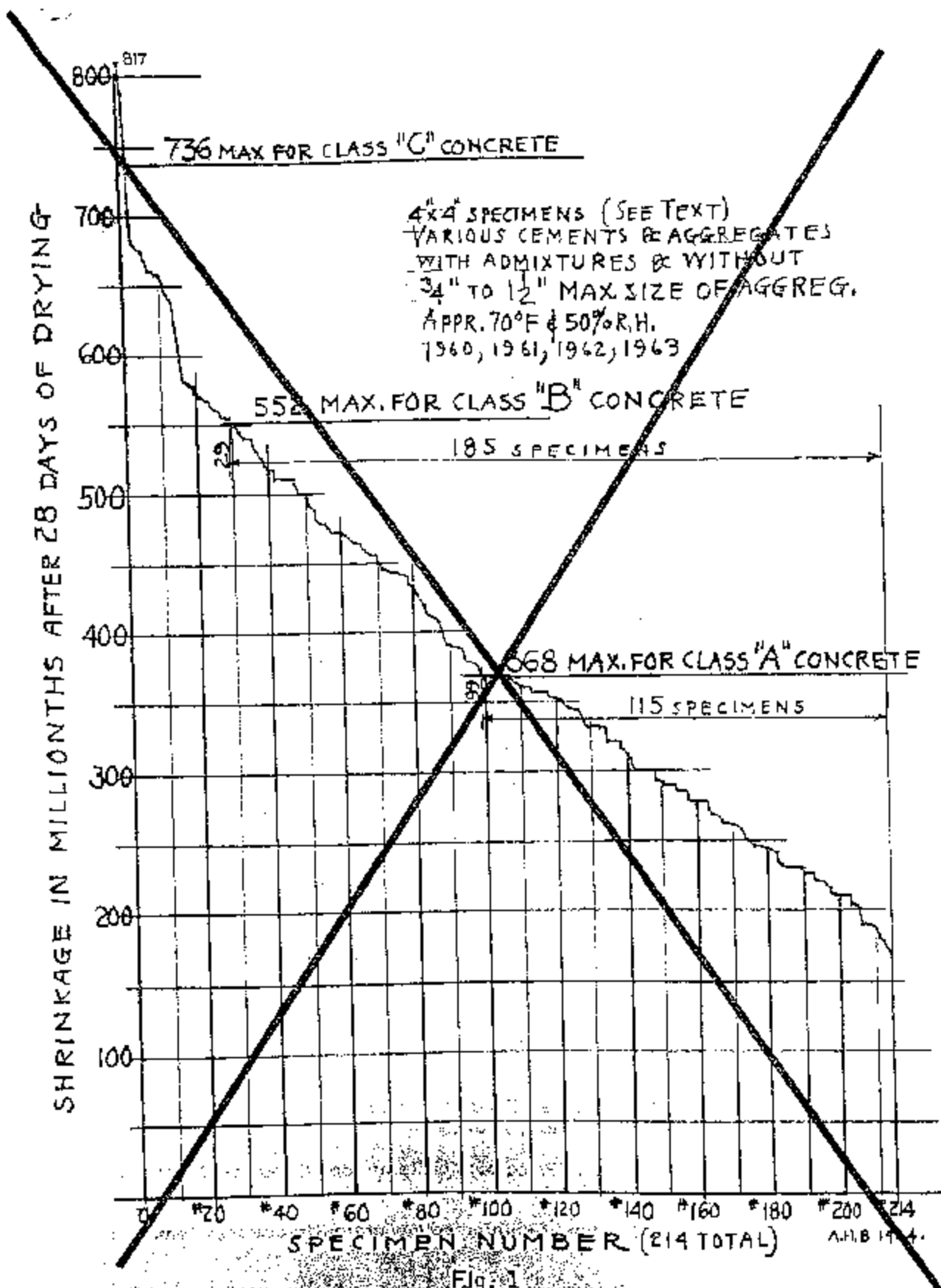


Fig. 1

SHRINKAGE TESTS DATA

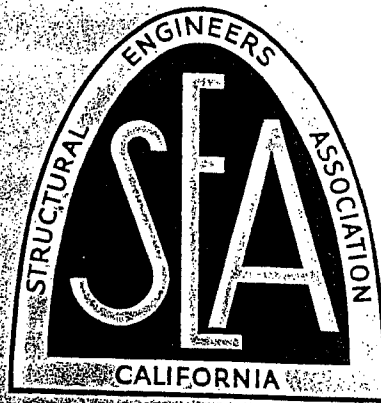
(see text)

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**SUPPLEMENTARY RECOMMENDATIONS
FOR
CONTROL OF SHRINKAGE
OF CONCRETE**



**STRUCTURAL ENGINEERS ASSOCIATION
OF CALIFORNIA**

SUPPLEMENTARY RECOMMENDATIONS
FOR CONTROL OF SHRINKAGE
OF CONCRETE

INTRODUCTION

In May, 1965, the Structural Engineers Association of California published a report by the Committee on Shrinkage of Concrete which included in the Appendix some sample specifications outlining how an engineer might place some controls on the quality of materials used on his project and thereby help to minimize the adverse effects of drying shrinkage.

During the intervening years since the publication of that report, the outline specifications contained therein have appeared in one form or another in thousands of project specifications throughout the state, particularly in the immediate San Francisco Bay Area. The document has been cited as a reference in many publications throughout the country and internationally, wherever engineers have encountered excessive cracked or deflected structures.

Although the overall effect has been to upgrade the quality of concrete used, there have arisen some problems which the authors could not foresee when the report was written. However, one of the purposes of the report was achieved; that is, to stimulate more research and to collect factual data on which to base limiting values.

Studies were soon available which pointed out wide variations in shrinkage data obtained between different laboratories, between different brands of cement and between laboratory and field-cured specimens of the same concrete.

A special task force subcommittee of the research committee of the SEAONC was established in January, 1971, to review available data and to make recommendations for revisions to the outline specification shown in Appendix I of the original report. The task force was made up of representatives from cement manufacturers, aggregate suppliers, ready-mix companies, testing laboratories and structural engineers.

The task force of SEAONC completed its task in July, 1974, when it submitted its recommendation to the SEAONC board. A minority report also was prepared by the 1975 SEAONC Research Committee. Both reports were referred to the State Research Committee for review in 1976. This final revised report was prepared by a special Ad Hoc Committee of SEAOC.

The recommended guide contained herein is written in outline form and contains certain suggestions and commentary. It is not intended that this be copied directly into project specifications. Rather it is to be used merely as a guide in preparing them. The purpose is to stimulate engineers to consider all the factors that help to control shrinkage and to select the methods best suited for his project within the limitations of the local environment and economics involved.

Prior to preparing specifications the engineer should review again the discussion of the drying shrinkage problem as presented in the 1965 report on Control of Shrinkage Concrete by SEAOC. The practical recommendations contained therein are still valid today. This supplement should be considered as a clarification and extension of that report.

The design engineer must have knowledge of the characteristics of the materials which are available for his project. Serious problems have developed when restrictive shrinkage requirements have been specified which were impossible to meet with locally available aggregates and cement.

It is recognized that by requiring drying shrinkage control, the engineer is merely attempting to establish a standard of quality for the concrete materials. Although absolute numbers are used, it should be clear that they are somewhat arbitrary and are used as guides in qualifying the materials proposed for use on a project.

Because there is considerable variation in results of drying shrinkage tests prepared in the field when compared to those prepared in the laboratory, it is unreasonable to require that field test results exactly duplicate the laboratory test results.

The initial qualifying laboratory tests must meet the specified requirements to comply with the level of quality desired. Once the materials have been accepted, shrinkage tests during construction may be desirable to provide a general evaluation of the quality of materials actually supplied. It may be equally as important to provide inspection of batching operations to check cleanliness of materials and to give reasonable assurance that the materials proposed are actually being used.

In summary, the engineer should remember that all of the following factors influence shrinkage:

- Cement - Type and Manufacturer
- Aggregates - Source and Gradation
- Admixtures - Type and Manufacturer
- Water/cement ratios
- Batching operations
- Placement methods
- Weather conditions
- Curing methods

In order to effectively control shrinkage, proper quality control procedures also must be followed throughout the entire operation.

As a final admonition, drying shrinkage limitations should not be specified unless: (1) the record of performance of at least some of the available materials have been reasonably established. (2) The entire concrete operation will have adequate quality control.

RECOMMENDED GUIDE FOR CONCRETE
SPECIFICATIONS CONTROLLING DRYING SHRINKAGE

a. Concrete Requiring Control of Drying Shrinkage

Where the different uses for concrete are listed, each specific class of concrete requiring special shrinkage control should be so designated. Seldom is drying shrinkage a factor for concrete placed below grade or where continuously exposed to moisture. However, some engineers prefer to use one class of concrete throughout the project to give less chance for error.

b. Acceptance of Materials

- (1) It is advisable to require that concrete mixes be designed, tested and, if necessary, adjusted in ample time before the first concrete is scheduled to be placed. Sometimes it may be advantageous to permit the placing of the shrinkage class of concrete in the first placement of footing concrete so that field testing can be performed well in advance of actual required use.
- (2) Laboratory or field trial batches for each shrinkage class should include the preparation of at least three specimens for determining drying shrinkage as outlined under "Test Procedures", in addition to six compression test specimens.
- (3) One of the following three classes of drying shrinkage limitations may be stipulated as a condition of acceptance. The maximum values indicated are based upon laboratory prepared specimens as outlined in the "Test Procedures" (Paragraph "e").

<u>Type or Class*</u>	<u>Laboratory Cast Specimens Maximum permissible drying shrinkage after 21 days of drying**</u>
M	.036% of length
N	.048% of length
O	.060% of length

*These types are comparable with the Classes A, B and C established in the 1965 Report of SEAOC Committee on Shrinkage of Concrete. They were arbitrarily chosen to divide the whole spectrum of shrinkage control into 3 divisions. Any value above 0.08% may be considered as uncontrolled.

**The laboratory shrinkage of small concrete specimens may be related to actual shrinkage in the building in the following manner:

Experiments show that shrinkage of 4"x4"x11" specimens approaches the ultimate in about 64 weeks of laboratory drying at 50% relative humidity. The shrinkage at 21 days of drying may be taken at about 35% of this ultimate. In real buildings exposed to variable environmental conditions, the concrete will usually not shrink as rapidly nor as much as the laboratory specimens because of larger member sizes with lower surface area to volume ratios and higher humidity. Consequently, the ultimate shrinkage of concrete in the building may be taken as about 40% of the ultimate shrinkage of the laboratory specimen after 21 days. The ultimate shrinkage in the building may be considered, therefore, to be $\frac{(.40)}{(.35)}$ times lab shrinkage, or 10 to 20% greater than the values at 21 days given in the above table.

- (4) As an alternative, trial batching to determine drying shrinkage may be waived by the structural engineer if a satisfactory prior record of compliance has been established on comparable concrete mixes. Previous mixes may be considered comparable if they contain the same materials, i.e., identical geologic sources of coarse and fine aggregates, same brand and type of cement and admixture. A satisfactory prior record of compliance could consist of three or more laboratory trial batches for concrete used, on 3 or more separate projects. The average shrinkage should be equal to or less than the specified maximum. Data is acceptable only from laboratories furnishing evidence that they have been surveyed by the Cement and Concrete Reference Laboratory of the National Bureau of Standards and meet requirements of ASTM E-329.

(c) Evaluation During Construction

- (1) During construction, drying shrinkage specimens should be prepared at the jobsite in a manner that closely follows the conditions required for laboratory prepared specimens. Utmost care should be used in curing and transporting these

specimens to minimize any adverse effects of weather. It is recommended that at least one set of three specimens be taken from each 1000 cubic yards placed, but at least 3 sets of three specimens be taken for the project. It is desirable that compression test specimens be taken from the same concrete as used for preparing drying shrinkage specimens. These compression test specimens may be considered as part of the normal requirements for tests on the project.

- (2) Considering the statistical variations in properties of field placed concrete, the following values are recommended for the maximum allowable average drying shrinkage after 21 days of drying of field sampled concrete.

<u>Type or Class</u>	<u>Field Cast Specimens Maximum permissible drying shrinkage after 21 days of drying</u>
M	.048%
N	.064%
O	.080%

d. Other Field Control Measures

(1) Cleanliness of Concrete Aggregates

Since cleanliness of aggregate as used at the batch plant is a significant contributing factor affecting shrinkage, it is mandatory that some sampling and testing program be specified.

All concrete coarse aggregate should have a minimum C.V. (Cleanliness Value of 75) and all fine aggregates should have a minimum S.E. (Sand Equivalent of 75). The sampling should take place as discharged from the weigh hopper or as close to the point of discharge into the mixer as possible.

Sampling should take place no more than 2 days prior to mixing concrete for the project so that corrections can be made to the equipment, bins or material in the event the material does not pass. A fair sampling rate during production might be once per 200 cubic yards of concrete placed, but not less than three times during construction. Tests shall conform to Test Method No. Calif. 217 for fine

aggregates and 227 for coarse aggregates. (Materials Manual, Testing and Control Procedures - Materials and Research Department, State of California-Sacramento.)

(2) Temperature of Concrete

Since one of the primary causes of concrete cracking in flatwork is sudden temperature drop during the first 24 hours, it is essential that some control be placed on the maximum temperature of concrete at the time of placement. It is recommended that this not exceed 75 or 80° F. Aggregates can be cooled by sprinkling. Concrete trucks can be cooled by wrapping with saturated blankets and, if necessary, chopped ice may be introduced in place of mixing water to keep the temperature low. It is also important to protect the concrete after placing, particularly so for thin flatwork subject to severe changes in temperature.

- (3) Since excess mixing water adversely affects drying shrinkage, it is essential that concrete be placed with as low slump as feasible and slump be carefully controlled and measured at the site. Concrete exceeding the maximum upper limit allowed by ACI should not be accepted for use.

e. Test Procedures, Laboratory or Field Cast Specimens

- (1) The "Drying Shrinkage" specimens shall be 4 by 4 by 11 in. prisms with an effective gage length of 10 in. fabricated, cured, dried and measured in the manner outlined in A.S.T.M. Designation C 157-69T and modified as follows: Specimens shall be removed from molds at an age of 23 ± 1 hours after trial batching, shall be placed immediately in water at $73^{\circ} \pm 3^{\circ}$ F. for at least 30 minutes, and shall be measured within 30 minutes thereafter to determine original length and then submerged in saturated lime water at 73° F. ± 3 . Measurement to determine expansion expressed as a percentage of original length shall be made at age 7 days. This length at age 7 days shall be the base length for drying shrinkage calculations. Specimens then shall be stored immediately in a humidity control room maintained at $73^{\circ} \pm 3^{\circ}$ F. and $50\% \pm 4\%$ relative humidity for the remainder of the test. Measurements to determine shrinkage expressed as percentage of base length shall be made and reported separately for 7, 14, and 21 days of drying after 7 days of moist curing.

- (2) *Although the Test Procedures (in paragraph e(1)) are completely detailed and written in specific language they are not intended to depart significantly from those spelled out in ASTM C-157-69T. Rather, they provide the necessary clarification for specimen size, time for removal of specimens and specific curing information that is needed in order to use C-157 properly. Only 2 major departures were taken, one is to shorten the initial storage period in water from 28 days to 7 days, the second is to use a 4x4x11" prism size rather than 3x3x11. Sufficient test data have been collected to demonstrate the adequacy of the 7 day initial curing period and practically all of the tests performed since 1965 (upon which these recommendations are based) were on 4x4x11" specimens water cured initially for 7 days before air drying. It would be futile for an engineer merely to specify that all tests be performed in exact conformance with ASTM-C-157 without clarification. The procedures given here should be followed exactly as written, otherwise different results would be obtained which could not be directly compared with the main body of information used to set the standards.*

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