Proportioning with Slag Cement

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Overview and History

ACI (American Concrete Institute) Concrete Terminology (ACI CT-23) defines slag cement as granulated blast-furnace slag that has been finely ground and that is hydraulic cement.

Slag cement can be used to replace Portland cement or Portland limestone cement at rates of 10 to 80 percent.

In the 1950's, granulated slag was used to produce blended Portland cements.

The first granulation facility in the U.S. was built in Sparrows Point, MD in the early 1980's.

An estimated 7.7 to 8.3 million tons of slag are used each year in the U.S. and over 200 million tons worldwide annually.

The use of slag cement in concrete as a replacement for OPC or PLC is estimated to reduce CO_2 emissions by 2.4 million metric tons annually, save 8.7 trillion BTU's of energy use, and conserve 3.8 million metric tons of virgin materials.

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Slag granules vs. Slag cement

Photo courtesy of Skyway Cement Co.

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Where to Start and Why?

- ACI 211.1-22 is the Guide to Selecting Proportions for Normal-Density and High-Density Concrete.
- Proportion from experience.
- Proportion for ASR or sulfate attack mitigation (prescriptive).
- Proportion to reduce embodied carbon.
- Proportion for increase durability.

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What Can't You Do?

CODE

Table 26.4.2.2(b)—Limits on cementitious materials for concrete assigned to Exposure Class F3

Supplementary cementitious materials	Maximum percent of total cementitious materials by mass
Fly ash or natural pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or natural pozzolans and silica fume	35
Total of fly ash or natural pozzolans, slag cement, and silica fume	50

- ACI 318-19(22) – only limits SCM's for F3 exposure class.

What Can You Do?

Typical replacement ranges by application.

Table 1

Concrete Application	Slag Cement
Concrete paving	25-50%
Exterior flatwork not exposed to deicer salts	25-50%
Exterior flatwork exposed to deicer salts with *w/cm* < 0.45	25-50%
Interior flatwork	25-50%
Basement floors	25-50%
Footings	30-65%
Walls and columns	25-50%
Tilt-up panels	25-50%
Pre-stressed concrete	20-50%
Pre-cast concrete	20-50%
Concrete blocks	20-50%
Concrete pavers	20-50%
High strength	25-50%
ASR mitigation	25-70%
Sulfate resistance Type II equivalence Type V equivalence	 25-50% 50-65%
Lower permeability	25-65%
Mass concrete	50-80%

SCA Information Sheet #2: Concrete Proportioning

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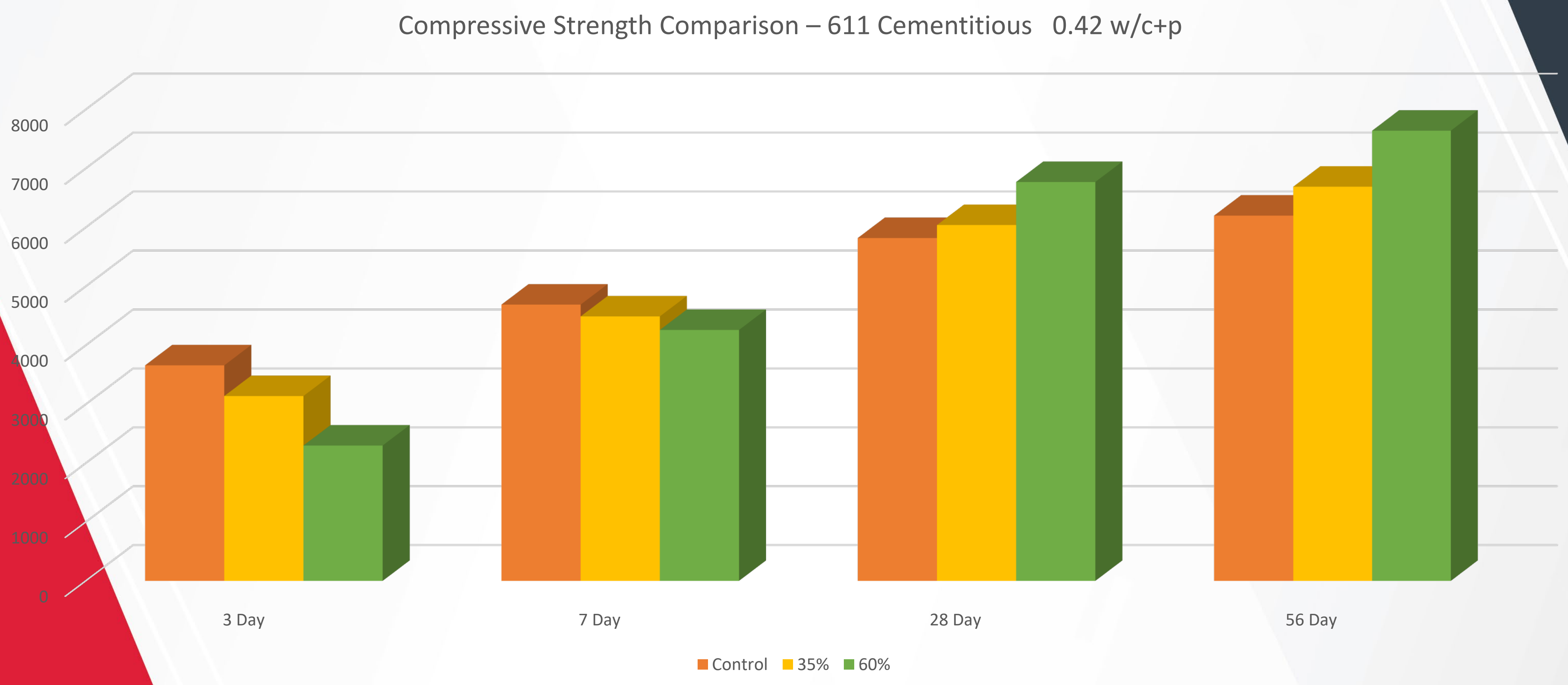
What to be Aware of?

- Tends to increase set time.
- Early age strength may be decreased.
- Water demand may increase.
- Mix will require re-proportioning due to lower specific gravity than cement.
- Mixtures with slag are affected by lower temperatures more than straight cement mixtures.

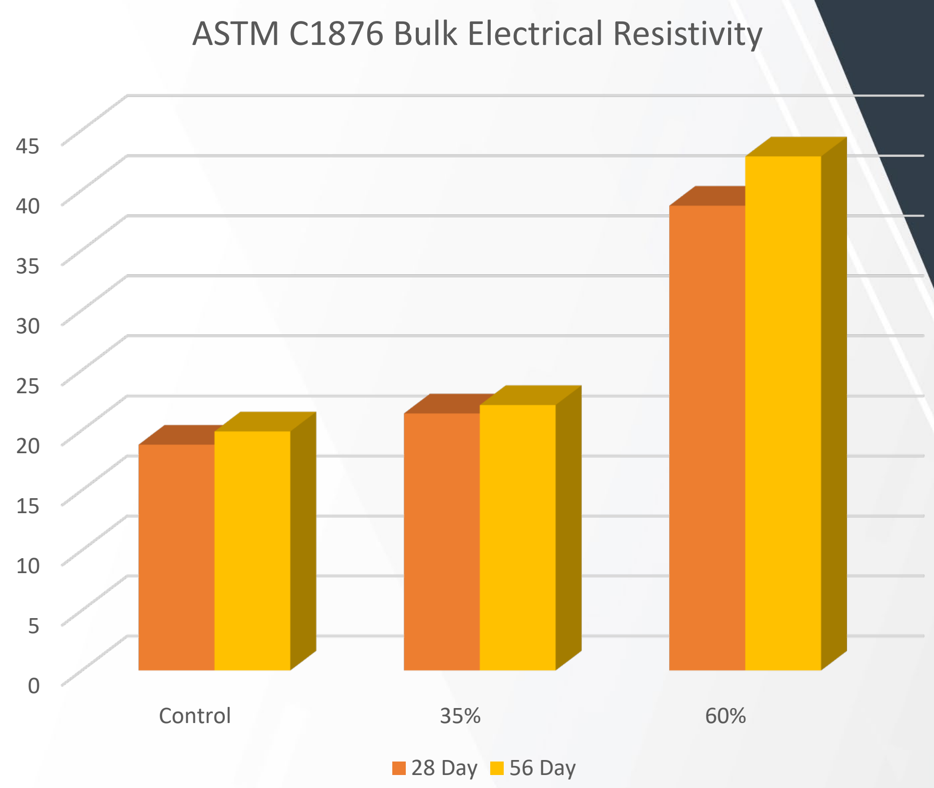
Proportioning with Slag to Improve Performance

Increased Strength – ASTM C39



Increased Durability

Chloride Penetration	56-Day Rapid Chloride Permeability Charge Passed as per ASTM C1202 (Coulombs)	28-Day Bulk Electrical Resistivity of Saturated Concrete (kΩ.cm)
High	>4,000	<5
Moderate	2,000-4,000	5-10
Low	1,000-2,000	10-20
Very Low	100-1,000	20-200
Negligible	<100	>200



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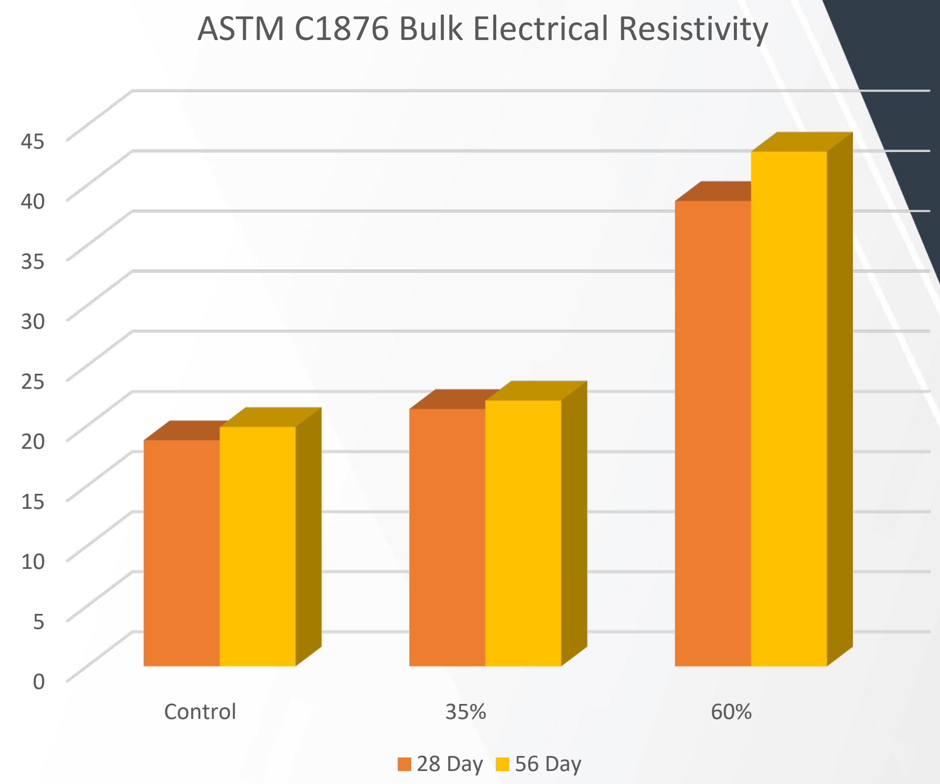

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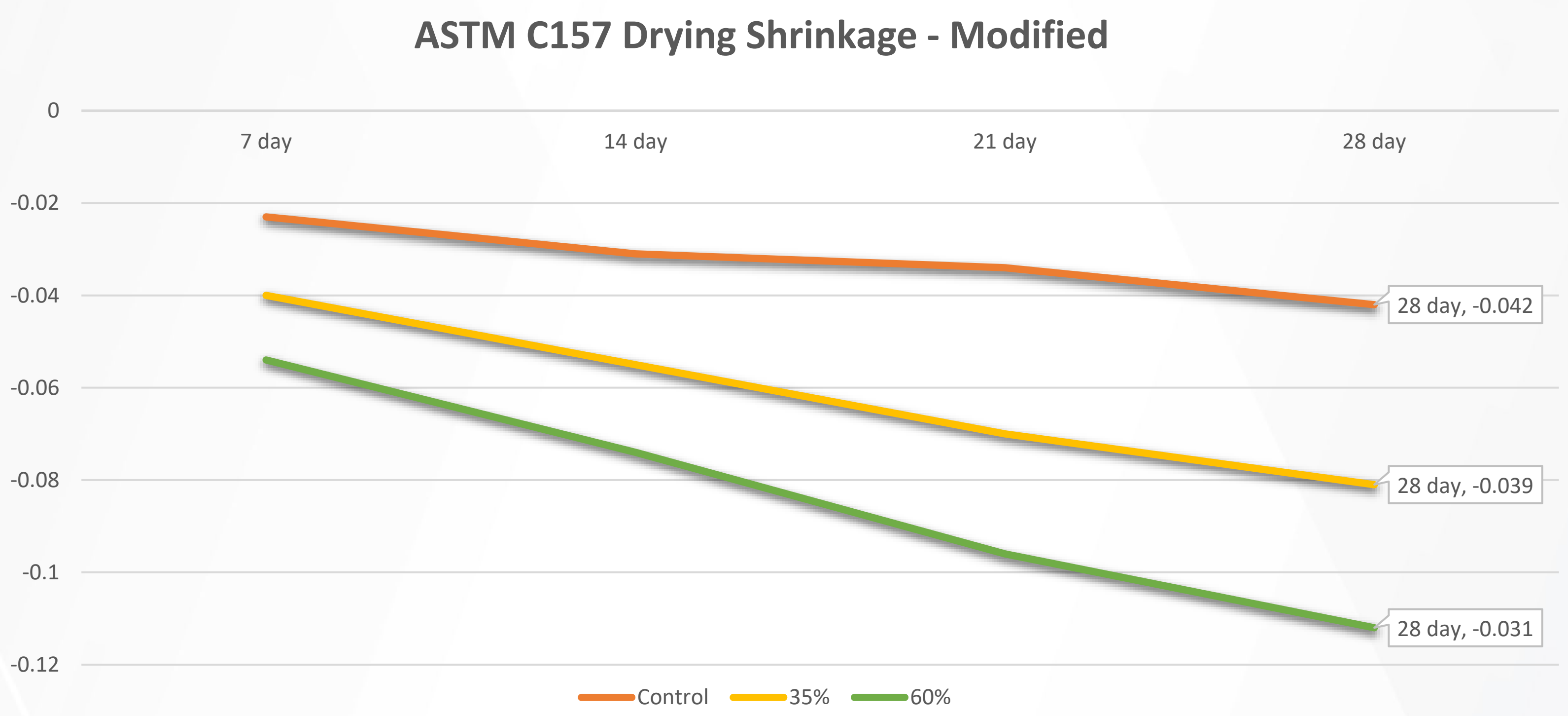
Reduced Drying Shrinkage



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Improving Resistance to Sulfate Attack

Table 2.5. Visual Ratings of 0.40 w/cm concretes in outdoor exposure for up to 54 months exposure (updated from Hooton, Ahani, and Fung, 2014)

Sulfate Type	15,000 mg/L Sodium Sulfate				15,000 mg/L Magnesium Sulfate			
Exposure Period (months)	12	24	36	54	12	24	36	54
PLC9	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Severe
PLC9 40% Slag	Undamaged	Minor	Minor	Minor	Minor	Minor	Minor	Minor
PLC9 50% Slag	Undamaged	Undamaged	Undamaged	Undamaged	Minor	Minor	Minor	Minor
PLC15	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Severe
PLC15 40% Slag	Undamaged	Undamaged	Undamaged	Minor	Minor	Minor	Minor	Minor

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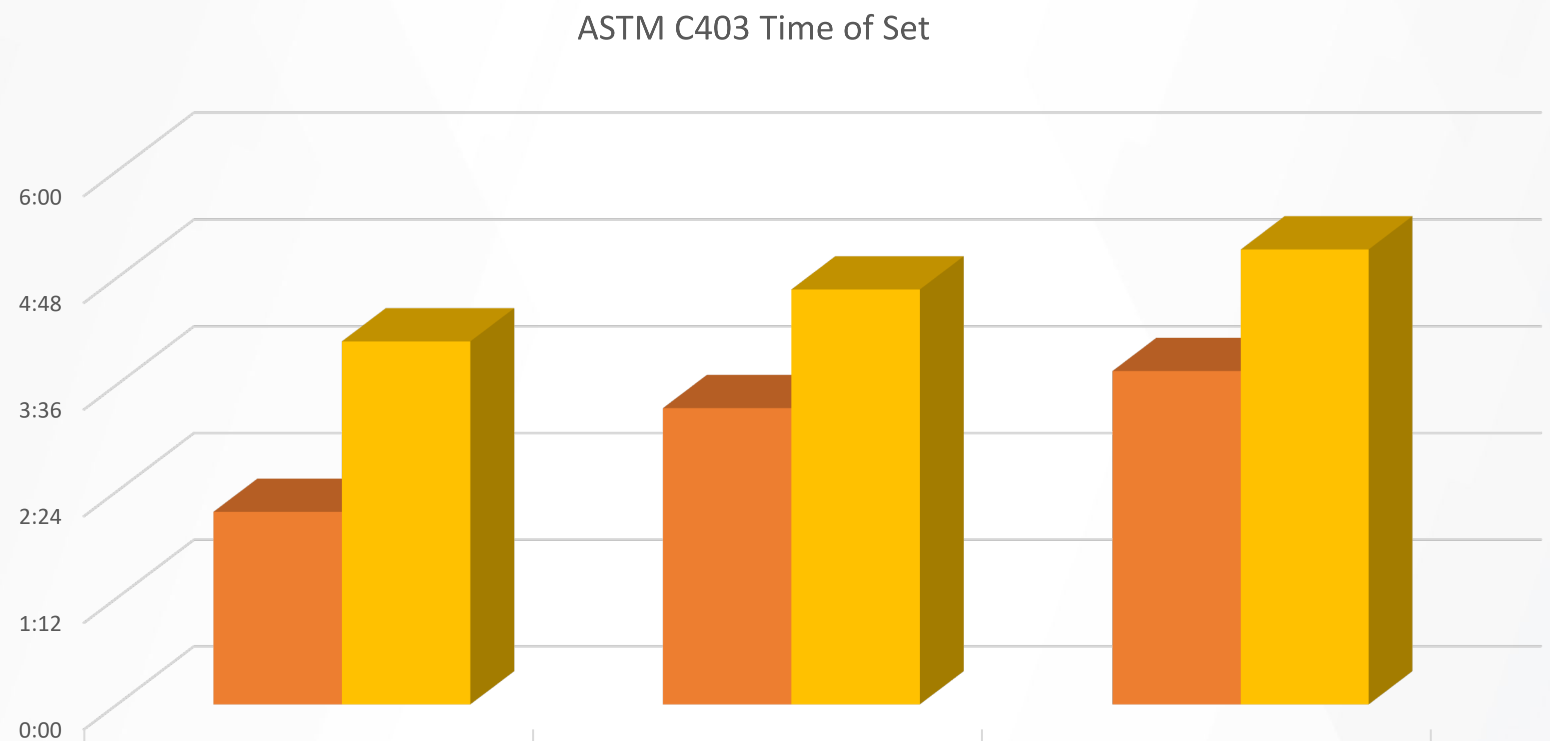
From Hooton, Ahani, and Fung, 2014 and PCA R&D SN3285a by R.D. Hooton and M.D.A. Thomas

Impact on Time of Set



	Control	35%	60%
Initial	2:10	3:20	3:45
Final	4:05	4:40	5:07

Initial Final

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Proportioning to Mitigate ASR

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Prescriptive Approach - IDOT

Aggregate Groups. Each combination of aggregates used in a mixture will be assigned to an aggregate group. The point at which the coarse aggregate and fine aggregate expansion values intersect in the following table will determine the group.

Aggregate Groups			
Coarse Aggregate or Coarse Aggregate Blend ASTM C 1260 Expansion	Fine Aggregate Or Fine Aggregate Blend ASTM C 1260 Expansion		
	≤0.16%	>0.16% - 0.27%	>0.27%
≤0.16%	Group I	Group II	Group III
>0.16% - 0.27%	Group II	Group II	Group III
>0.27%	Group III	Group III	Group IV

Mixture Options. Based upon the aggregate group, the following mixture options shall be used. However, the Department may prohibit a mixture option if field performance shows a deleterious alkali-silica reaction or Department testing indicates the mixture may experience a deleterious alkali-silica reaction.

Reduction of Risk for Deleterious Alkali-Silica Reaction					
Aggregate Groups	Mixture Options				
	Option 1	Option 2	Option 3	Option 4	Option 5
Group I	Mixture options are not applicable. Use any cement or finely divided mineral.				
Group II	X	X	X	X	X
Group III	X	Combine Option 2 with Option 3	Combine Option 2 with Option 3	X	X
Group IV	X	Combine Option 2 with Option 4	Invalid Option	Combine Option 2 with Option 4	X

"X" denotes valid mixture option for aggregate group.

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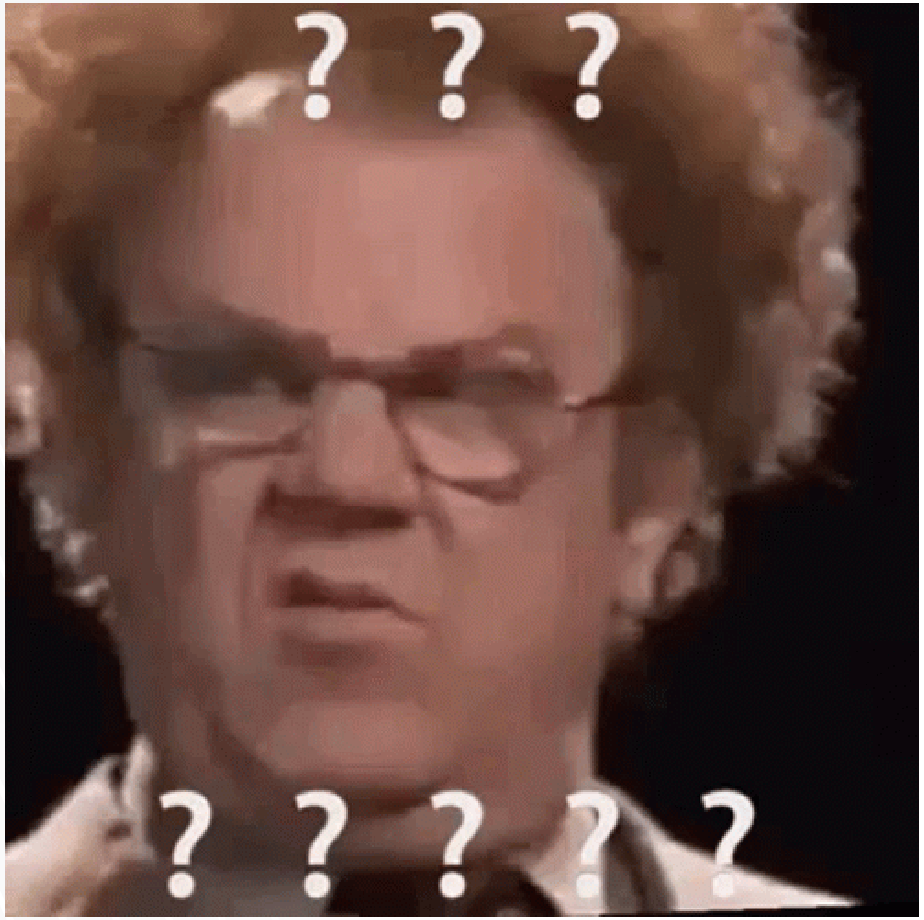
Prescriptive Approach – ASTM C1778



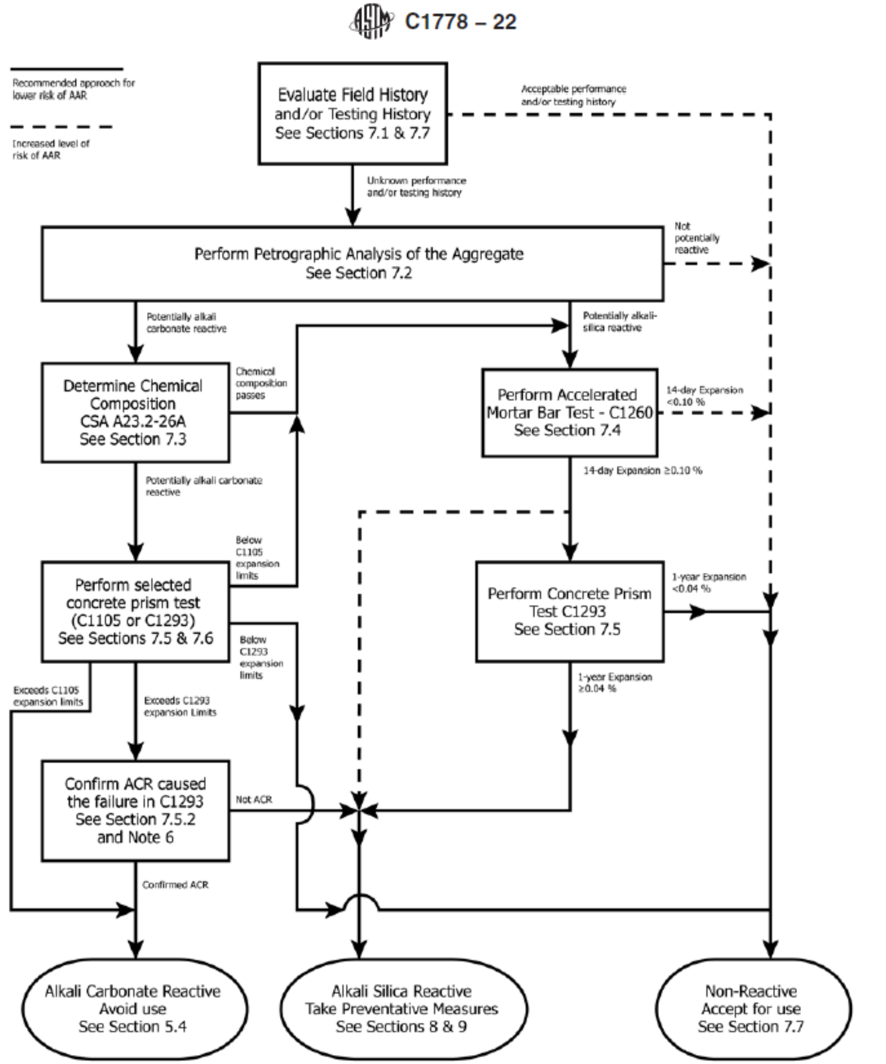


FIG. 1 Sequence of Laboratory Tests for Evaluating Aggregate Reactivity

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Determine Aggregate Reactivity Class and Level of ASR Risk

TABLE 1 Classification of Aggregate Reactivity

Aggregate-Reactivity Class	Description of Aggregate Reactivity	1-Year Expansion in Test Method C1293, %	14-Day Expansion in Test Method C1260, %
R0	Non-reactive	<0.04	<0.10
R1	Moderately reactive	≥0.04, <0.12	≥0.10, <0.30
R2	Highly reactive	≥0.12, <0.24	≥0.30, <0.45
R3	Very highly reactive	≥0.24	≥0.45

TABLE 2 Determining the Level of ASR Risk

Size and Exposure Conditions	Aggregate-Reactivity Class			
	R0	R1	R2	R3
Non-massive[A] concrete in a dry[B] environment	Level 1	Level 1	Level 2	Level 3
Massive[A] elements in a dry[B] environment	Level 1	Level 2	Level 3	Level 4
All concrete exposed to humid air, buried or immersed	Level 1	Level 3	Level 4	Level 5
All concrete exposed to alkalies in service[C]	Level 1	Level 4	Level 5	Level 6

[A] A massive element has a least dimension of greater than 0.9 m [3 ft].
[B] A dry environment corresponds to an average ambient relative humidity lower than 60 %, normally only found in the interior of buildings.
[C] Examples of structures exposed to alkalies in service include marine structures exposed to seawater and highway structures exposed to deicing salts (for example, NaCl) or anti-icing salts (for example, potassium acetate, sodium formate, and so forth).

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Determining Class by Consequence vs. Acceptablity of ASR.

TABLE 3 Structures Classified on Basis of the Severity of Consequences Should ASR[A] Occur (Modified for Highway Structures from RILEM TC 191-ARP)

Class	Consequence of ASR	Acceptability of ASR	Examples[B]
Class SC1	Safety, economic, or environmental consequences small or negligible	Some deterioration from ASR may be tolerated	Non-load-bearing elements inside buildings Concrete elements not exposed to moisture Temporary structures (service life < 5 years)
Class SC2	Some safety, economic, or environmental consequences if major deterioration	Moderate risk of ASR is acceptable	Sidewalks, curbs, and gutters Elements with service life < 40 years
Class SC3	Significant safety, economic, or environmental consequences if minor damage	Minor risk of ASR may be acceptable	Pavements Foundations elements Retaining walls Culverts Highway barriers Rural, low-volume roads Precast elements in which economic costs of replacement are severe Service life normally 40 to 74 years
Class SC4	Serious safety, economic, or environmental consequences if minor damage	ASR cannot be tolerated	Major bridges Power plants Dams Nuclear facilities Water treatment facilities Waste water treatment facilities Tunnels Critical elements that are very difficult to inspect or repair Service life normally ≥75 years

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Determining Level of Prevention and Calculating Alkali Loading

TABLE 4 Determining Level of Prevention

Level of ASR Risk (Table 2)	Classification of Structure (Table 3)			
	Class SC1	Class SC2	Class SC3	Class SC4
Risk Level 1	V	V	V	V
Risk Level 2	V	V	W	X
Risk Level 3	V	W	X	Y
Risk Level 4	W	X	Y	Z
Risk Level 5	X	Y	Z	ZZ
Risk Level 6	Y	Z	ZZ	[A]

[A] It may not be permitted to construct a Class SC4 structure (see Table 3) if the risk of ASR is Level 6. Measures should be taken to reduce the level of risk in these circumstances (9).

TABLE 5 Maximum Alkali Loadings to Provide Various Levels of Prevention

Prevention Level	Maximum Alkali Loading of Concrete	
	kg/m^3	lb/yd^3
V	No Limit	
W	3.0	5.0
X	2.4	4.0
Y	1.8	3.0
Z[A]	Table 8	
ZZ[A]		

[A] SCMs may be used in Prevention Levels Z and ZZ.

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Identification of Preventive Measures – Option 1

Cement Content: 658 lbs^3

Equivalent Alkali Content: 0.55%

658 x 0.0055 = 3.62 lbs. per cubic yard of equivalent alkalis

Identification of Preventive Measures – Option 1

Cement Content: 493 lbs^3

Slag Content: 165 lbs^3

Total Cementitious: 658 lbs^3

Equivalent Alkali Content of Cement: 0.55%

493 x 0.0055 = 2.71 lbs. per cubic yard of equivalent alkalis

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Identification of Preventive Measures – Option 2

TABLE 6 Minimum Levels of SCM to Provide Appropriate Level of Prevention

Type of SCM[A]	Alkali Content of SCM (% Na_2Oeq)	Minimum Replacement Level[D] (% by mass)				
		Level W	Level X	Level Y	Level Z	Level ZZ
Fly ash[B] (CaO ≤ 18 %)	<3.0	15	20	25	35	Table 8
	3.0 – 4.0	20	25	30	40	
Slag Cement	<1.0	25	35	50	65	
Silica Fume[C] (SiO_2 > 85 %)	<1.0	2.0 × KGA or 1.2 × LBA	2.5 × KGA or 1.5 × LBA	3.0 × KGA or 1.8 × LBA	4.0 × KGA or 2.5 × LBA	

[A] The SCM may be added directly to the concrete mixer or it may be a component of a blended cement. Fly ash should meet the requirements of Specification C618, slag cement should meet the specifications of C989/C989M, and silica fume should meet the requirements of Specification C1240. Blended cements should meet the requirements of Specification C595/C595M or C1157/C1157M.

[B] Fly ashes with greater than 18 % CaO can mitigate ASR. The efficacy of these higher calcium fly ashes should be evaluated using the performance-based testing outlined in 8.2 and 8.3.

[C] The minimum level of silica fume (as a percentage of cementing material) is calculated on the basis of the alkali loading of the concrete expressed in either units of kg/m^3 (KGA) or lb/yd^3 (LBA). Regardless of the calculated value, the minimum level of silica fume may not be less than 7 % when it is the only method of prevention.

[D] Note—the use of high levels of SCM in concrete may increase the risk of problems as a result of deicer salt scaling if the concrete is not properly proportioned, finished, and cured.

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Identification of Preventive Measures – Option 3

TABLE 7 Adjusting Minimum Level of SCM Based on Alkali Content of Portland Cement

Portland Cement Alkali Content (% Na_2Oeq)	Level of SCM
<0.70	Reduce the minimum amount of SCM given in Table 6 by one prevention level[A]
0.70 to 1.00	Use the minimum levels of SCM given in Table 6
>1.00 to 1.25	Increase the minimum amount of SCM given in Table 6 by one prevention level
>1.25	No guidance is given

[A] The replacement levels should not be below those given in Table 6 for prevention level, W, regardless of the alkali content of the portland cement.

TABLE 8 Using SCM and Limiting Alkali Loading of Concrete to Provide Highest Levels of Prevention

Prevention Level	SCM as Sole Prevention	Limiting concrete alkali loading plus SCM	
	Minimum SCM level	Maximum alkali loading, kg/m^3 [lb/yd^3]	Minimum SCM level
Z	SCM level shown for Level Z in Table 6	1.8 [3.0]	SCM level shown for Level Y in Table 6
ZZ	Not permitted	1.8 [3.0]	SCM level shown for Level Z in Table 6

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Proportioning with Slag for Massive Elements

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Using the Equivalent Cement Content Method

Equivalent Cement Content =

Cement + 0.5 F Ash +

0.8 C Ash +

1.2 Silica Fume and/or Metakaolin +

Slag Factor

Slag Factor

1.0 to 1.1 for 0 to 20% replacement

1.0 for 20 to 45% replacement

0.9 for 45 to 65% replacement

0.8 for 65 to 80% replacement

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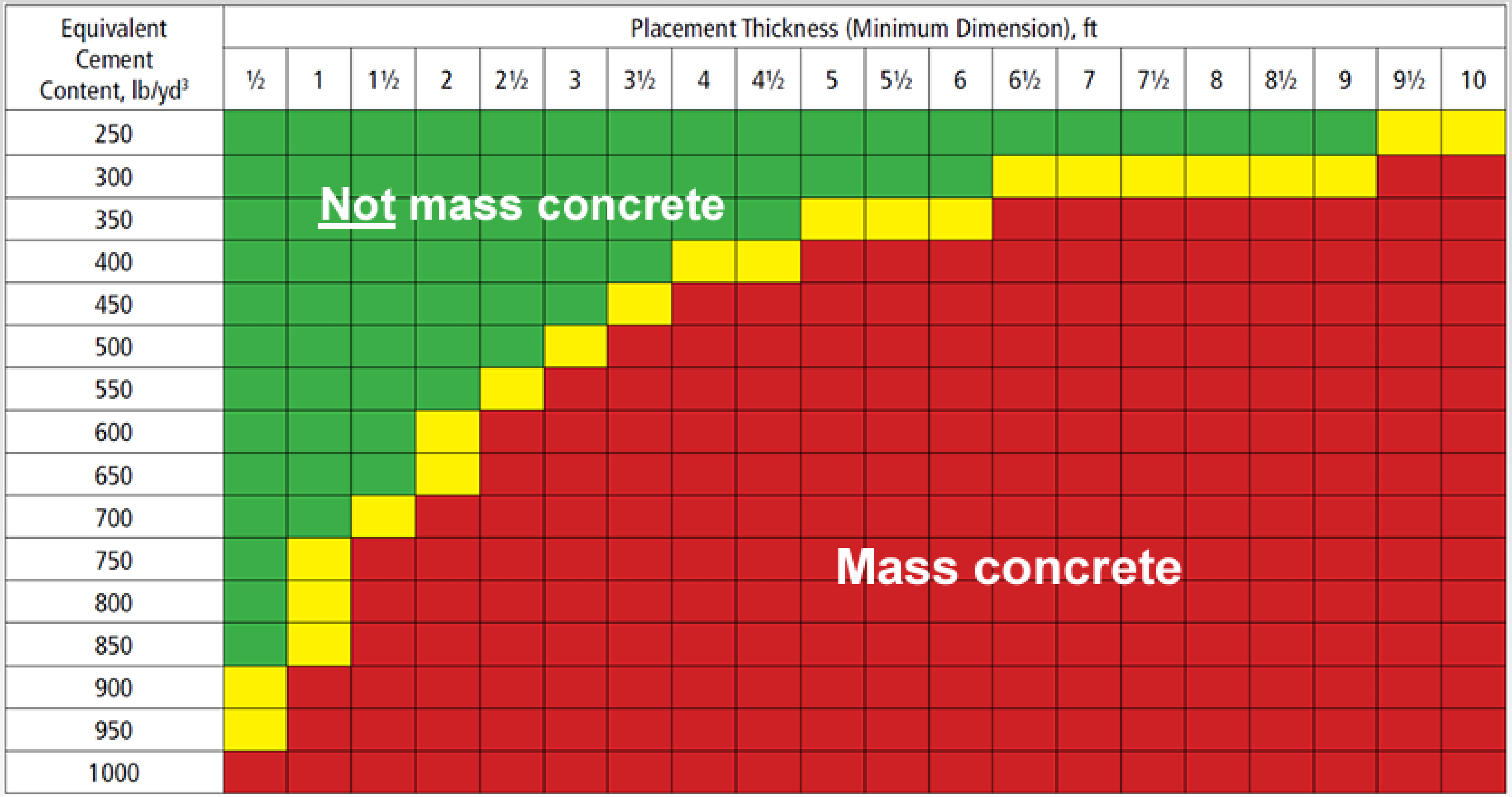
Gajda et al. 2018 and ACI PRC 207.1-22: Mass Concrete - Guide

Is it Mass Concrete?



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Gajda et al. 2018 and ACI PRC 207.1-22: Mass Concrete - Guide

Proportioning with Slag for Sustainability

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Slag Cement EPD – SCA

Production stage EPD Results for one metric ton of Slag Cement

Impact category and inventory indicators	Unit	A1, Extraction and upstream production	A2, Transport to factory	A3, Manufacturing	Total
Global warming potential, GWP 100[1)], AR5	kg CO_2 eq	1.8	62.7	82.6	**147.0**
Ozone depletion potential, ODP[2)]	kg CFC-11 eq	2.9E-07	1.4E-05	1.0E-05	**2.4E-05**
Smog formation potential, SFP[2)]	kg O_3 eq	0.19	33.1	4.28	**37.6**
Acidification potential, AP[2)]	kg SO_2 eq	8.7E-03	1.7	2.6E-01	**2.0**
Eutrophication potential, EP[2)]	kg N eq	2.9E-03	0.08	2.4E-01	**0.33**
Abiotic depletion potential for non-fossil mineral resources, ADP elements[3)]*	kg Sb eq	1.7E-06	2.4E-06	6.8E-05	**7.2E-05**

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OPC and PLC EPD – Portland Cement Association

Table 4. Production stage EPD results for portland cements.

Impact category and inventory indicators	Unit	Portland Cements 1 metric ton
Global warming potential, GWP 100, IPCC 2013	kg CO_2 eq	919

Table 4. Production stage EPD results for portland-limestone cement

Impact category and inventory indicators	Unit	PLC Cement 1 metric ton
Global warming potential, GWP 100, IPCC 2013	kg CO_2 eq	844

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EPD Comparison – 50 Percent Replacement

READY MIX CONCRETE PRODUCED BY:OZINGA

FACILITY:	Chicago Chinatown
STRENGTH:	4000 psi @ 28 days
MIX NAME:	1171

IMPACT INDICATOR		PER YD3	PER M3
Global Warming Potential	kg CO_2e	206.64	270.28

READY MIX CONCRETE PRODUCED BY:OZINGA

FACILITY:	Chicago Chinatown
STRENGTH:	4000 psi @ 28 days
MIX NAME:	1171

IMPACT INDICATOR		PER YD3	PER M3
Global Warming Potential	kg CO_2e	124.24	162.50

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Thank you

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