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PCA R&D SN3284

Chemical and Physical Characteristics of US Hydraulic Cements: 2014

by Paul D. Tennis

5420 Old Orchard Road
Skokie, Illinois 60077-1083
847.966.6200 Fax 847.966.9481
www.cement.org

KEYWORDS

AASHTO M 85, AASHTO M 240, ASTM C91, ASTM C150, ASTM C595, ASTM C1157, ASTM C1328, ASTM C1329, blended cement, chemical characteristics, compressive strength, fineness, hydraulic cement, masonry cement, mortar cement, stucco cement, performance, physical characteristics, plastic cement, portland cement, setting time, loss on ignition, insoluble residue, oxide analysis, phase composition, chloride content

ABSTRACT

This report summarizes responses to a survey on chemical and physical characteristics of hydraulic cements produced in the US. In the survey yearly average data for cements produced in 2014 was requested for cements manufactured under ASTM C150/AASHTO M 85 (portland cements), ASTM C595/AASHTO M 240 (blended hydraulic cements), ASTM C1157 (hydraulic cements), ASTM C91 (masonry cements), ASTM C1328 (plastic (stucco) cements), and ASTM C1329 (mortar cements). The properties of interest include those required to meet the chemical and physical requirements of the respective ASTM/AASHTO specifications.

Survey forms were distributed to 95 cement plants operating in the US and 68 plants responded–a return rate of about 72%, with data on 251 cements. Data for 134 ASTM C150/AASHTO M 85 portland cements was provided, and Type II cement is the most common portland cement type produced. For ASTM C91 masonry cements, data for a total of 66 cements were reported. Data was received for 28 blended cements produced under ASTM C595/AASHTO M 240 and 11 cements produced under C1157.

Survey results indicate that blended and ASTM C1157 cements have similar performance to portland cements in strength development and setting times.

REFERENCE

Tennis, Paul D., *Chemical and Physical Characteristics of US Cements: 2014*, R&D SN3284, Portland Cement Association, Skokie, Illinois, USA, 2016, 32 pages. www.cement.org/pdf_files/SN3284.pdf.

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by Paul D. Tennis*

INTRODUCTION

Overview

A survey was conducted in 2015 by the Portland Cement Association's Product Standards and Technology (PS&T) Committee to compile information on physical and chemical characteristics of cements commercially manufactured in the US in 2014, focusing on those characteristics referenced in specifications. In the survey, cement company staff were asked to provide chemical and physical properties of cements that were produced in 2014 including mean data for the year for each type of cement, as well as high and low values for the year, standard deviation, and number of analyses. This report focuses on mean values of those characteristics.

Historical Surveys

Data summarized here represents properties of cements produced in 2014. Other compilations of US cement properties have been developed by various authors and, although they have used different methodologies, those data are probably relatively representative of cement produced in those the time periods. Clifton and Mathey (1971) reported results of chemical and physical analyses by the National Bureau of Standards on 193 portland cements produced in the 1950s. Gebhardt (1995) collected data from a variety of sources for portland cements produced in 1994 for ASTM Committee C01 (see also PCA 1996 for a summary). The Portland Cement Association (PCA) also collected mill test report data in 1998 (Tennis 1999). In 2004, PCA also surveyed US and Canadian plants, requesting yearly average data (Bhatty and Tennis 2008), and included blended cements and masonry cements.

Although quantities of cements produced in each cement type are not part of this survey, the US Geological Survey (USGS) does provide summary data on volumes of cements produced by type (for example, van Oss, 2015), and has historical data available for many years. Data for 2014 were not available for the publication of this report; however in 2013, Type I and II cements were estimated at 61,000,000 metric tons, Type III cements at 2,670,000 metric tons, and Type V at 11,100,000 metric tons. Blended cements appear to be classified into Type IP (748,000 metric tons) and Type IS (519,000 metric tons), although those values appear to include C1157 cements in the totals. Data for Type IL and Type IT were not collected by USGS in 2013. Masonry cements (including mortar and plastic (stucco) cements) accounted for 2,127,000 metric tons in 2013 (van Oss 2015).

* Director, Product Standards and Technology, Portland Cement Association, 5420 Old Orchard Road, Skokie, IL, 60077-1083 USA, ptennis@cement.org, www.cement.org.

Methodology of Survey

Survey forms were sent via email on May 7, 2015, to PCA Product Standards and Technology Committee members as well as staff contacts (typically managers or chemists) at each cement plant. Yearly average chemical and physical data representing cements manufactured in 2014 under ASTM C150/AASHTO M 85 (portland cements), ASTM C595/AASHTO M 240 (blended hydraulic cements), and ASTM C1157 (hydraulic cements), ASTM C91 (masonry cements), ASTM C1328 (plastic (stucco) cements), and ASTM C1329 (mortar cements) were included. In addition, data for some optional tests that are not commonly reported was requested, if such data was readily available. Electronic data forms were distributed as Microsoft® Excel files or Microsoft® Word files, but all data was submitted using the Excel format. Data was collected by email and compiled and checked for data entry discrepancies and outliers and where problems were thought to exist, plants were contacted to verify or correct the data.

SURVEY RESPONSE

Of the 95 plants contacted, 68 responded for a response rate of 72%. Twenty two companies are represented in the survey. A summary of the 251 cements produced at those plants is given in Table 1.

Table 1. Cement Types Produced in the US, as Reported in the 2014 Survey.

ASTM C150/AASHTO M 85[a]				Total[a]
Type I	Type II	Type III	Type V	
12[b]	56[c]	47[d]	19[e]	134
ASTM C91				
Type N	Type S	Type M		
28	29	9[f]		66
ASTM C595/AASHTO M 240[a]				
Type IL	Type IP	IS(<70)		
12	8	8		28
ASTM C1157[a]				
Type GU	Type HE			
10	1			11
ASTM C1328				
Type S	Type M			
4	4			8
ASTM C1329				
Type N	Type S	Type M		
1	1	2		4

[a] No data were received for Types IV, IS(>70), IT, MS, HS, MH, or LH. Total reflects survey data received, which represent about 72% of cement plants in the US.
[b] Includes 1 white Type I cement and 1 Type IA cement, which are *excluded* from other tables of this report.
[c] Includes 37 cements marketed as Type I/II, 10 as Type II, 8 as Type I/II(MH), and 1 as Type II(MH). Four of the Type I/II cements and one of the Type II cements are marketed as LA (low-alkali).
[d] Includes 3 cements marketed as Type III LA.
[e] Includes 12 cements marketed as Type II/V, 6 as Type V, and 1 as Type I/II/V.
[f] Includes 2 cements marketed as a Type S/M.

Portland Cements (ASTM C150/AASHTO M 85)

The 68 plants that responded to the survey produce 134 portland cements. Included in this total are Types I (general use), II (moderate sulfate resistance), II(MH) (moderate sulfate resistance and moderate heat of hydration), III (high early strength), and V (high sulfate resistance). No data on any Type IV (low heat of hydration) cements was received; Type IV cements have not been commonly produced for a number of years.

In the total for Type II category are 37 cements, about two-thirds, marketed as Type I/II, indicating that those products meet requirements of both Type I and Type II. Only ten cements were marketed as Type II, and of those, 9 also meet requirements for Type I.

Nine cements are marketed as Type II(MH) (moderate heat of hydration and moderate sulfate resistance) and for consistency with previous surveys these cements are summarized with Type II cements, representing about 16% of this category. Of those nine Type II(MH) cements, eight are marketed at Type I/II(MH).

Four Type I/II cements are also marketed as Type I/II LA, indicating that the cements have low-alkali contents. This LA suffix does not a formal designation in ASTM C150 or AASHTO M 85, although low-alkali cements are defined in the specifications as having a maximum equivalent alkali content ($\%Na_2O + 0.658\%K_2O$) of 0.60% by mass. The Type III cements likewise include three marketed as Type III LA.

Of the 19 Type V cements, 11 (about 58%) are sold as Type II/V (indicating that they meet requirements for both Type II and Type V) and one as Type I/II/V (additionally meeting requirements for Type I).

Table 1 indicates that Type II cement, produced at 56 of the 68 plants responding, is the most common type produced in the US. The Type I/II designation is used by more than half the plants responding to the survey.

Masonry Cements (ASTM C91)

A little more than half (51%) of the cement plants responding to the survey reported producing masonry cements: 35 plants provided data on 66 masonry cements. Type N and Type S cements are most common, at 28 (80%) and 29 (83%) of those plants, respectively, while only nine plants (26%) reported producing Type M cements.

Blended Cements (ASTM C595/AASHTO M 240)

Blended cements are less commonly available in US cement plants: Only 22 plants reported producing blended cements. Produced by 12 plants, portland-limestone cements, Type IL, are the most common, followed by eight portland-pozzolan cements, Type IP, and eight portland blast-furnace slag cements, Type IS. Data was not received for any ternary blended cements, Type IT.

Type IL cements have only been defined in US specifications since August 2012, which appears to indicate relatively rapid acceptance for this new cement type.

ASTM C595 and AASHTO M 240 include options to designate cements as having special properties: A for air-entraining; MS and HS for moderate and high sulfate resistance, respectively; MH and LH for moderate and low heat of hydration respectively, and R for resistant to alkali-silica reactivity. Only one plant indicated that the blended cement it produces met requirements for a special designation: a Type IP meeting HS requirements.

Since the 2004 North American cement characteristics survey, blended cement designations in ASTM C595 and AASHTO M 240 have changed. Pozzolan-modified portland cement, Type I(PM), and slag-modified portland, Type I(SM), are no longer defined in ASTM C595 or AASHTO M 240. Those cements would now be included as Type IP and Type IS, respectively, with nomenclature that includes the nominal pozzolan or slag cement content in parentheses.

Hydraulic Cements (ASTM C1157)

Ten survey responses were received for hydraulic cement Type GU and one for Type HE.

Plastic (Stucco) Cements (ASTM C1328)

Data was provided for 8 plastic cements; these included 4 Type S and 4 Type M cements.

Mortar Cements (ASTM C1329)

Of the 4 responses received in the ASTM C1329 mortar cement category, 1 each was Type N and Type S, and 2 were Type M cements.

SURVEY TOPICAL QUESTIONS

In addition to collecting data on cement characteristics, a few questions related to standards development activities were included in the survey. Option R in ASTM C595 (AASHTO M 240) and ASTM C1157 is a requirement related to alkali-silica reactivity (ASR) resistance of a cement. Of the 29 plants that produced C595/M 240 or C1157 cements, only 1 reported that the material met Option R and no plants indicated requests from customers to meet that option. A possible explanation for this lack of use of Option R requirements in practice is that reactive aggregates are typically tested with a range of SCMs to determine whether expansion to ASR would be mitigated.

CHARACTERISTICS OF PORTLAND CEMENTS (ASTM C150/AASHTO M 85)

Chemical and Phase Composition

Chemical composition (as oxide analyses) and other chemical characteristics, such as loss on ignition, insoluble residue, free lime, and chloride content, are summarized in Table 2. Mean values are reported for each portland cement type, along with the standard deviation (SD) of those means, the maximum and minimum mean values reported, and the number of cements for which those values were reported (n). Mean Bogue phase composition, as determined using methods in ASTM C150/AASHTO M 85 are provided in Table 3.

Table 2. Oxide Composition and other Chemical Characteristics of US Portland Cements Reported for 2014, % by mass.

Cement type*	Statistic	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition	Insoluble residue	Na_2O	K_2O	Na_2O_{eq}	Mn_2O_3	TiO_2	P_2O_5	Free lime	Acid-soluble chloride
Type I	Mean	19.81	5.13	2.50	63.27	2.32	3.33	2.15	0.44	0.18	0.67	0.62	0.07	0.28	0.22	1.03	0.020
	SD	0.70	0.42	0.72	1.22	0.80	0.60	0.35	0.13	0.08	0.34	0.28	0.02	0.04	0.11	0.57	0.016
	Maximum	20.60	5.67	3.61	64.60	3.04	4.07	2.68	0.64	0.31	1.20	1.04	0.08	0.33	0.40	2.11	0.037
	Minimum	18.83	4.42	1.28	60.74	0.80	2.51	1.45	0.24	0.09	0.10	0.26	0.05	0.22	0.10	0.36	0.005
	n	10	10	10	10	10	10	10	10	10	10	10	3	9	6	9	3
	Spec limit	—	—	—	—	≤6.0	≤3.0/≤3.5**	≤3.0	≤0.75	—	—	≤0.60***	—	—	—	—	—
Type II	Mean	20.10	4.59	3.39	63.59	1.95	3.05	2.18	0.34	0.17	0.57	0.55	0.18	0.25	0.15	1.01	0.014
	SD	0.49	0.38	0.42	0.98	0.99	0.29	0.37	0.12	0.07	0.22	0.15	0.22	0.05	0.09	0.39	0.013
	Maximum	21.70	5.43	4.46	65.31	4.40	3.81	2.75	0.65	0.34	1.14	1.03	0.96	0.38	0.52	1.84	0.050
	Minimum	18.90	2.80	2.45	60.86	0.70	2.48	1.00	0.17	0.04	0.07	0.20	0.03	0.19	0.05	0.18	0.003
	n	56	56	56	56	56	56	56	53	56	56	56	23	34	32	56	20
	Spec limit	—	≤6.0	≤6.0	—	≤6.0	≤3.0**	≤3.0	≤0.75	—	—	≤0.60***	—	—	—	—	—
Type III	Mean	20.05	4.71	3.06	63.32	2.12	3.56	1.83	0.31	0.16	0.65	0.56	0.13	0.26	0.17	1.07	0.014
	SD	0.60	0.51	0.62	1.05	1.03	0.49	0.54	0.14	0.07	0.44	0.19	0.16	0.05	0.11	0.41	0.011
	Maximum	21.24	6.17	3.92	65.17	4.48	5.20	2.77	0.67	0.32	3.18	1.04	0.66	0.37	0.51	2.21	0.045
	Minimum	18.68	3.73	1.20	60.62	0.71	2.82	0.89	0.09	0.04	0.25	0.29	0.03	0.14	0.06	0.18	0.003
	n	47	47	47	47	47	47	47	44	47	47	47	14	31	27	46	12
	Spec limit	—	—	—	—	≤6.0	≤3.5/≤4.5**	≤3.0	≤0.75	—	—	≤0.60***	—	—	—	—	—
Type V	Mean	20.83	3.99	3.83	63.74	2.24	2.63	1.76	0.36	0.15	0.47	0.45	0.11	0.21	0.12	1.09	0.008
	SD	0.53	0.23	0.42	0.61	0.97	0.39	0.61	0.13	0.06	0.13	0.08	0.06	0.03	0.08	0.31	0.007
	Maximum	21.98	4.44	5.03	64.56	4.47	3.40	2.73	0.58	0.24	0.71	0.57	0.23	0.26	0.37	1.60	0.019
	Minimum	19.71	3.51	3.11	62.75	1.14	2.08	0.57	0.10	0.04	0.26	0.29	0.05	0.15	0.06	0.57	0.002
	n	19	19	19	19	19	19	19	19	19	19	19	7	13	12	17	5
	Spec limit	—	—	—	—	≤6.0	≤2.3**	≤3.0	≤0.75	—	—	≤0.60***	—	—	—	—	—

Key: SD=Standard deviation; n= number of values; "Spec limit" is specification limit in ASTM C150-12/AASHTO M 85-12; — = no limit.

* See Table 1 for groupings of cement types. Type I data excludes 1 white Type I cement and 1 Type IA cement.

** These default limits can be exceeded if C1038 data demonstrate that 14-day expansions do not exceed 0.020%. See the specifications for complete details. See also Table 7.

*** Optional limit.

Table 3. Estimated (Bogue) Phase Composition of Portland Cements Reported for 2014, % by mass.

Cement type*	Statistic	C_3S	C_2S	C_3A	C_4AF
I	Mean	57.5	13.0	9.3	7.6
	SD	3.58	2.44	1.41	2.19
	Maximum	62	16	11	11
	Minimum	49	9	7	4
	n	10	10	10	10
	Spec limit	—	—	—	—
II	Mean	59.1	12.7	6.4	10.3
	SD	3.98	3.01	1.30	1.26
	Maximum	68	20	8	13
	Minimum	51	7	0	7
	n	56	55	56	56
	Spec limit	—	—	≤8	—
III	Mean	58.0	13.6	7.3	9.2
	SD	3.66	2.58	2.04	2.05
	Maximum	66	20	14	12
	Minimum	49	7	4	4
	n	47	47	47	47
	Spec limit	—	—	≤15	—
V	Mean	59.2	14.6	4.1	11.6
	SD	2.81	3.68	0.66	1.30
	Maximum	63	22	5	15
	Minimum	52	8	2	9
	n	19	19	19	19
	Spec limit	—	—	≤5	—

Key: SD=Standard deviation; n= number of values; "Spec limit" is specification limit in ASTM C150-12/AASHTO M 85-12; — = no limit.

* See Table 1 for groupings of cement types. Type I data excludes 1 white Type I cement and 1 Type IA cement.

A summary of the range of mean alkali contents (equivalent alkalies) of the portland cements surveyed is shown in Table 4. In ASTM C150 and AASHTO M 85, cements with alkali contents of 0.60% or below are defined as low-alkali. Overall almost 80% of portland cements in the survey have low alkali contents. Again, it not clear that the optional low-alkali requirement is routinely specified for these materials: some raw materials may produce cements with low-alkali contents without special operations during manufacturing. Low-alkali content cements have historically been used to mitigate deleterious expansion with some alkali-silica reactive aggregates, although it is now understood that the alkali loading of the concrete is an important parameter (for example, ASTM C1778 or Farny and Kerkhoff, 2007). Use of supplementary cementitious materials (SCM) is probably the most common means of mitigating deleterious expansion due to ASR.

Table 4. Equivalent Alkali (Na_2Oeq)* Content of Portland Cements Reported for 2014.

Cement type**	≤ 0.60, % by mass	> 0.60, % by mass	Percent low alkali
I	7	3	70%
II	46	13	78%
III	37	10	79%
V	19	0	100%
Total	109	26	79%

*Per ASTM C150/AASHTO M 85: $\%Na_2Oeq = \%Na_2O + 0.658\ \%K_2O$.
**See Table 1 for cement type groupings.
.

Table 2 of ASTM C150/AASHTO M 85 provides optional requirements for Type III cements for C_3A content, as an indicator of sulfate resistance. Table 5 lists the number of cements in the survey meeting those requirements, although these may not be due to requirements by purchasers.

Table 5. Tricalcium Aluminate Content of Type III Portland Cements Reported for 2014.

C_3A content range	Number	Percentage
Less than or equal to 5%	5	10.6%
More than 5% and less than or equal to 8%	31	66.0%
More than 8%	11	23.4%

In 2004, ASTM C150 (and in 2007 AASHTO M 85) was revised to permit up to 5% limestone as an ingredient in portland cements. The use of limestone provides improved environmental characteristics with comparable performance. Data reported in the survey indicate that a majority of portland cements (about 66% overall) include limestone as an ingredient, although the percentage varies by cement type (see Table 6). For those cements including limestone as an ingredient, the average limestone content was 3.1% by mass, with a range of 1.2% and 4.5%.

Table 6. Use of Limestone in Portland Cements Reported for 2014.

Cement type*	Number of plants	Percentage
I	6	60%
II	50	89%
III	21	44%
V	12	63%

Note: Average limestone content was 3.1% for those cements including limestone as an ingredient.
*See Table 1 for cement type groupings.

Inorganic processing additions (IPA) are permitted ingredients in portland cements, but only five cements in the survey included IPA as an ingredient. All were Type II cements. The mean amount of IPA used in those cements was 3.1% by mass, with a range of 2.1% to 4.0%.

Default limits on sulfate content are included in portland cement specifications ASTM C150 and AASHTO M 85. However, it is recognized that cement or concrete properties can sometimes be improved by exceeding those limits, and provisions to exceed the default limits are included in the specifications: the cement, when tested via ASTM C1038, shall not exceed expansion of 0.020% at 14 days. Table 7 summarizes data on sulfate contents above or below the default table limits in C150/M 85.

Table 7. Sulfate Contents of Portland Cements Reported for 2014.

Cement type*	C_3A content	Default maximum SO_3 content limit**	Number		Mean ASTM C1038 expansion at 14 days, for cements exceeding table SO_3 limit %
			Below default limit	Above default limit	
I	8% or less	3.0	1	1	--
	More than 8%	3.5	4	4	0.008
II	All	3.0	29	27	0.006
III	8% or less	3.5	24	12	0.006
	More than 8%	4.5	9	2	0.008
V	All	2.3	6	13	0.008

*See Table 1 for cement Type groupings.
**See ASTM C150/AASHTO M 85 for complete details.

Two other requirement in ASTM C150 and AASHTO M 85 are the sum of C_3S and 4.75 times the C_3A content for Type II(MH) cements (the so-called "heat index," and a maximum 25% limit on the sum of the C_4AF content and twice the C_3A content for Type V cements. Table 8 provides simple statistics on those characteristics based on the survey.

Table 8. Miscellaneous Chemical Characteristics, % by mass.

Cement type and limit	Statistic	Value
Type II(MH) $C_3S+4.75\ C_3A$	Mean	85.8
	SD	8.99
	Maximum	95
	Minimum	63
	n	9
	Spec limit	≤100
Type V $C_4AF + 2\ C_3A$	Mean	19.8
	SD	1.20
	Maximum	22
	Minimum	17
	n	19
	Spec limit	≤25

Key: SD=Standard deviation; n= number of values; "Spec limit" is specification limit in ASTM C150/AASHTO M 85; — = no limit.

Physical Properties

Table 9 shows data on several physical properties, including autoclave expansion (ASTM C151), air content (ASTM C185), normal consistency (ASTM C187), paste early stiffening (ASTM C451), and mortar expansion (ASTM C1038). Table 10 shows summary statistics for various

physical properties listed in ASTM C150/AASHTO M 85, including the mortar cube compressive strengths (ASTM C109), Vicat setting times (ASTM C191), and fineness values by air permeability (Blaine, ASTM C204) and No. 325 (45-µm) sieve (ASTM C430). As with Tables 2 and 3, mean values are reported for each portland cement type, along with the standard deviation (*SD*) of those means, the maximum and minimum mean values, and the number of cements for which those values were reported (*n*).

The mean and range of mean values of ASTM C109 mortar cube compressive strengths reported in the 2014 survey are shown in Fig. 1. As expected, Type III cements have the highest strength development over the first 28 days. Type I and II have comparable strength development. Type V cements lag slightly behind Type I and II on average at 1 day, but have comparable strengths by 28 days.

Table 9. Select Physical Properties of Portland Cements Reported for 2014.

Cement type*	Statistic	Autoclave expansion, %	Air content of mortar, %	Normal consistency, %	Early stiffening, %	Mortar expansion, %
I	Mean	0.075	6.8	26.6	66.0	0.032
	SD	0.075	0.9	1.3	20.5	0.060
	Maximum	0.220	8.1	29.6	88.5	0.140
	Minimum	0.001	5.0	24.5	28.2	0.003
	n	10	10	10	6	5
	Spec limit	≤0.80	≤12	—	Optional, ≥50	≤0.020**
II	Mean	0.026	7.2	25.7	78.5	0.008
	SD	0.047	1.1	1.0	7.0	0.013
	Maximum	0.180	9.2	27.7	89.9	0.080
	Minimum	-0.040	5.0	21.6	63.0	-0.001
	n	55	55	56	39	35
	Spec limit	≤0.80	≤12	—	Optional, ≥50	≤0.020**
III	Mean	0.028	7.1	28.6	70.5	0.007
	SD	0.054	1.1	1.6	8.8	0.003
	Maximum	0.170	9.4	32.5	89.2	0.013
	Minimum	-0.050	4.0	25.5	52.0	0.002
	n	45	46	46	31	22
	Spec limit	≤0.80	≤12	—	Optional, ≥50	≤0.020**
V	Mean	0.030	6.8	25.4	84.1	0.008
	SD	0.053	1.0	1.3	6.4	0.003
	Maximum	0.178	8.8	28.0	91.5	0.013
	Minimum	-0.050	5.4	21.8	71.0	0.001
	n	19	19	17	14	12
	Spec limit	≤0.80	≤12	—	Optional, ≥50	≤0.020**

Key: SD=Standard deviation; n= number of values; — = no limit; "Spec limit" is the specification limit in ASTM C150/AASHTO M 85.

*See Table 1 for groupings of cement types.

**Mortar expansion limit only apply if sulfate content exceeds default table limits.

Table 10. Strength, Setting Time, and Fineness of Portland Cements Reported for 2014.

Cement type*	Statistic	Compressive strength, MPa (psi)				Setting time (Vicat), minutes		Fineness (Blaine), m^2/kg	Fineness 45-µm (No. 325) sieve, % passing
		1 day	3 days	7 days	28 days	Initial	Final		
I	Mean	16.0 (2320)	27.1 (3930)	34.0 (4930)	42.3 (6140)	121	229	397	95.1
	SD	3.23 (469)	2.08 (301)	2.10 (304)	3.29 (477)	21.6	23.9	20.4	2.2
	Maximum	20.6 (2980)	30.4 (4410)	38.3 (5560)	47.8 (6940)	163	252	440	97.9
	Minimum	11.7 (1700)	24.3 (3520)	31.1 (4500)	37.2 (5390)	90	190	375	91.2
	n	9	10	10	10	10	7	10	10
	Spec limit	—	≥12.0 (1740)	≥19.0 (2760)	—	≥45, ≤375	—	≥260	—
II	Mean	16.1 (2330)	26.8 (3890)	33.3 (4830)	42.7 (6200)	116	223	393	96.4
	SD	2.35 (341)	2.86 (415)	2.90 (420)	2.93 (425)	30.1	37.5	24.2	2.5
	Maximum	20.2 (2930)	31.8 (4610)	38.0 (5510)	48.6 (7050)	270	381	471	99.9
	Minimum	5.5 (800)	12.9 (1870)	19.7 (2850)	33.9 (4910)	74	178	305	85.7
	n	53	56	56	56	56	53	56	55
	Spec limit	—	≥10.0 (1450)	≥17.0 (2470)	—	≥45, ≤375	—	≥260	—
III	Mean	24.8 (3600)	34.9 (5060)	41.0 (5950)	48.8 (7080)	87	178	561	99.0
	SD	3.04 (441)	2.81 (408)	3.00 (436)	3.37 (488)	20.0	33.0	60.0	1.0
	Maximum	30.9 (4480)	40.9 (5930)	47.5 (6890)	54.1 (7850)	126	245	723	99.9
	Minimum	16.4 (2380)	26.7 (3870)	32.8 (4760)	41.0 (5950)	49	115	365	95.1
	n	45	46	45	45	46	39	45	45
	Spec limit	≥12.0 (1740)	≥24.0 (3480)	—	—	≥45, ≤375	—	—	—
V	Mean	14.3 (2080)	25.3 (3670)	32.0 (4640)	42.7 (6190)	126	224	401	95.9
	SD	3.24 (470)	4.68 (678)	4.95 (718)	4.32 (626)	30.7	37.2	54.1	5.0
	Maximum	21.9 (3180)	33.4 (4850)	39.6 (5750)	47.9 (6950)	176	280	551	99.8
	Minimum	8.6 (1250)	15.9 (2310)	21.6 (3140)	32.1 (4660)	70	161	302	81.0
	n	19	19	19	19	19	16	19	19
	Spec limit	—	≥8.0 (1160)	≥15.0 (2180)	≥21.0 (3050)	≥45, ≤375	—	≥260	—

Key: SD=Standard deviation; n= number of values; "Spec limit" is specification limit in ASTM C150/AASHTO M 85; — = no limit.
*See Table 1 for groupings of cement types.

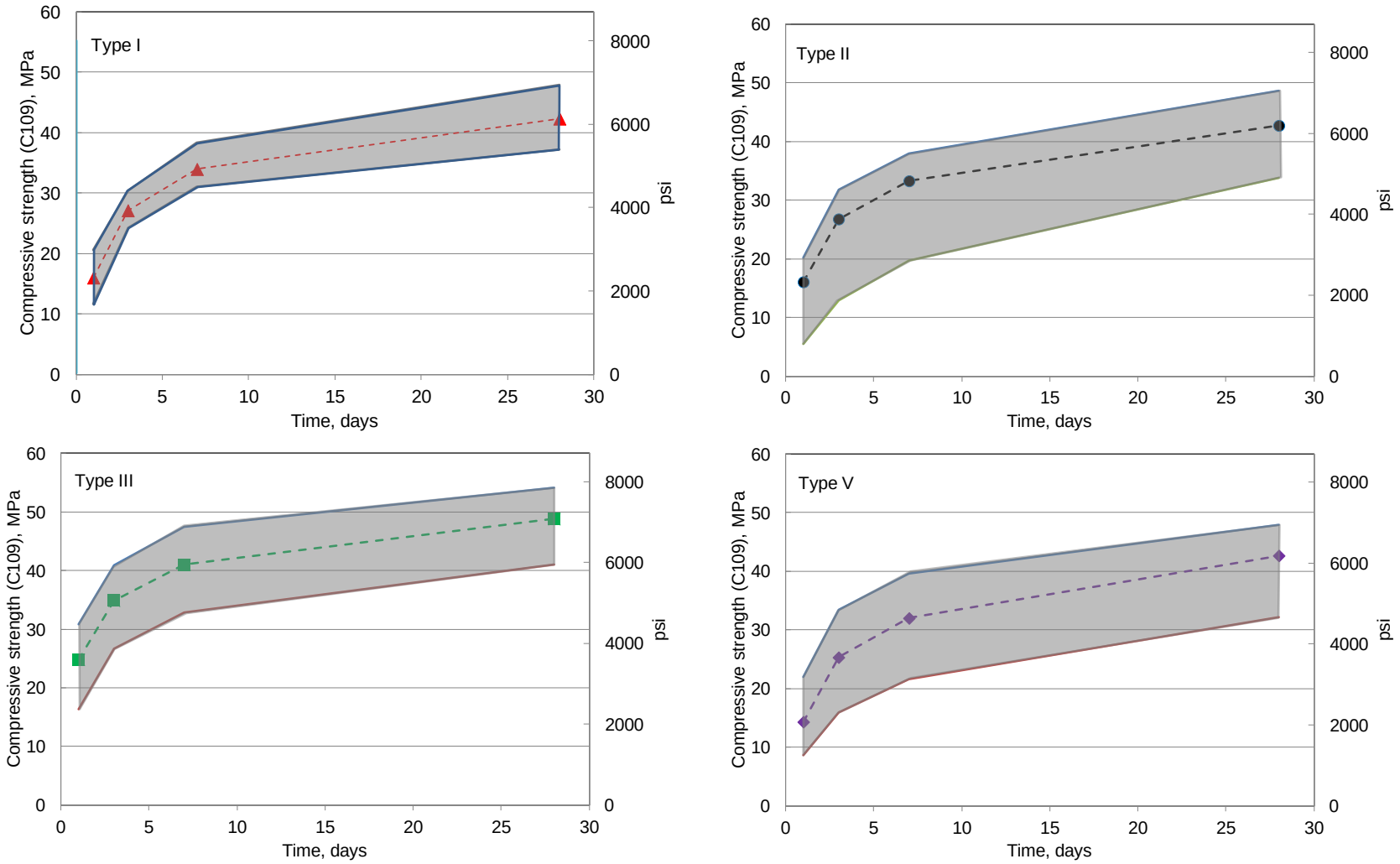

Figure 1. ASTM C109 compressive strengths of portland cements as reported for 2014. Mean values are connected by dashed lines and shaded areas represent ranges of values reported in the survey.

CHARACTERISTICS OF BLENDED CEMENTS (ASTM C595/AASHTO M 240)

Constituent Content and Chemical Characteristics

ASTM C595 and AASHTO M 240 include naming conventions that identify the nominal amount of limestone, slag cement or pozzolan in the cement. Mean values for cements produced in 2014 according to the survey are: limestone content of Type IL cements, about 11%; pozzolan content of Type IP cements, about 24%; and slag cement content of Type IS cements, about 30%. Table 11 provides summary statistics.

Table 11. Nominal Amount of Constituents in Blended Cements Reported for 2014, % by mass.

Constituent/ Cement type	Statistic	Content, % by mass
Limestone/ Type IL	Mean	11.1
	SD	1.70
	Maximum	14
	Minimum	10
	n	11
	Spec limit	>5 and ≤15
Pozzolan/ Type IP	Mean	23.5
	SD	7.64
	Maximum	32
	Minimum	9
	n	6
	Spec limit	≤40
Slag cement/ Type IS	Mean	30.3
	SD	8.98
	Maximum	40
	Minimum	20
	n	6
	Spec limit	<70; ≤95

Key: SD = Standard deviation; n = number of values; "Spec limit" = specification limit in ASTM C595/AASHTO M 240.

Table 12 shows chemical characteristics of ASTM C595/AASHTO M 240 blended cements reported for 2014. Data on mean, standard deviation, maximum, minimum, and number of cements represented are reported on the following cement properties (ASTM C114): MgO content, SO_3 content, and loss on ignition (LOI) and insoluble residue (IR).

Table 12. Select Chemical Characteristics Blended Cements Reported for 2014, % by mass.

Cement type	Statistic	MgO	SO_3*	Loss on ignition	Insoluble residue
IL	Mean	2.08	3.16	5.40	0.55
	SD	0.88	0.42	0.79	0.32
	Maximum	3.44	3.60	7.20	1.29
	Minimum	0.84	2.09	4.28	0.16
	n	12	12	12	9
	Spec limit	—	≤3.0*	≤10.0	—
IP	Mean	1.90	3.08	1.81	—
	SD	0.71	0.44	0.42	—
	Maximum	2.60	3.53	2.59	—
	Minimum	0.83	2.40	1.40	—
	n	8	8	8	—
	Spec limit	≤6.0	≤4.0*	≤5.0	—
IS	Mean	3.98	3.08	1.59	0.38
	SD	0.96	0.43	0.60	0.15
	Maximum	5.30	3.78	2.40	0.63
	Minimum	2.31	2.39	0.69	0.22
	n	8	8	8	8
	Spec limit	—	≤3.0*	≤3.0	≤1.0

Key: SD = Standard deviation; n= number of values; — = not enough data reported or no limit; "Spec limit" = specification limit in ASTM C595/AASHTO M 240.
*Table limit for SO_3 content may be exceeded if C1038 expansion does not exceed 0.020% at 14 days. See ASTM C595/AASHTO M 240 for complete details.

Limestone used as an ingredient in portland-limestone cements in 2014 was required to meet requirements for calcium oxide (CaO) content (minimum of 70% by mass), methylene blue index (maximum of 1.2g/100g) and total organic carbon content (maximum of 0.5% by mass). Table 13 provides values reported limestones used for Type IL cements produced in 2014.

Table 13. Additional Characteristics Reported for Limestone used in Type IL cements.

	$CaCO_3$ content % by mass	Total organic carbon content, % by mass	Methylene blue index, g/100 g
Mean	89.5	0.17	0.38
SD	7.20	0.12	0.19
Maximum	95.7	0.40	0.80
Minimum	72.0	0.02	0.17
n	11	9	9
Spec limit	≥70	≤0.50	≤1.2

Key: SD = Standard deviation; n= number of values; "Spec limit" = specification limit in ASTM C595-12/AASHTO M 240-12.

Physical Properties

Tables 14 and 15 provide physical data of ASTM C595/AASHTO M 240 blended cements received in the 2014 survey. The data on mean, standard deviation, maximum, minimum and number of cements represented are reported on the following cement properties:

- Compressive strength (ASTM C109)
- Setting time (Vicat, ASTM C191)
- Fineness (Blaine, ASTM C204, and No. 325 sieve, ASTM C430)
- Air content (ASTM C185)
- Autoclave expansion (ASTM C151), and
- Mortar expansion (ASTM C1038).

Figure 2 provides plots of mean C109 compressive strength data for the three blended cements at 3, 7 and 28 days, as well as the range of values received at those ages. These figures are plotted at the same scale as Fig. 1to facilitate comparison. In broad terms, these cements show comparable strength development to Type I portland cements.

Table 14. Compressive Strength and Setting Time of Blended Cements Reported for 2014.

Cement type	Statistic	Compressive strength, MPa (psi)			Setting time (Vicat), minutes	
		3 days	7 days	28 days	Initial	Final
IL	Mean	28.9 (4190)	34.8 (5050)	42.9 (6230)	117	218
	SD	2.88 (418)	3.43 (498)	3.85 (559)	19.3	30.3
	Maximum	31.7 (4600)	38.2 (5550)	47.8 (6930)	150	269
	Minimum	21.4 (3110)	26.2 (3800)	33.8 (4900)	80	178
	n	12	12	12	12	11
	Spec limit	≥13.0 (1890)	≥20.0 (2900)	≥25.0 (3620)	≥45, ≤420	—
IP	Mean	25.1 (3640)	31.4 (4560)	45.1 (6550)	135	251
	SD	3.66 (531)	4.12 (597)	5.21 (756)	35.7	39.0
	Maximum	29.7 (4310)	37.9 (5500)	54.6 (7920)	205	311
	Minimum	19.0 (2760)	24.5 (3550)	37.8 (5480)	87	196
	n	8	8	8	8	8
	Spec limit	≥13.0 (1890)	≥20.0 (2900)	≥25.0 (3620)	≥45, ≤420	—
IS	Mean	22.2 (3220)	31.1 (4520)	45.9 (6660)	132	223
	SD	2.88 (418)	2.69 (390)	4.11 (596)	30.7	71.5
	Maximum	28.6 (4140)	35.6 (5160)	51.0 (7400)	191	280
	Minimum	19.7 (2850)	27.5 (3990)	37.7 (5470)	90	143
	n	8	8	8	8	3
	Spec limit	≥13.0 (1890)	≥20.0 (2900)	≥25.0 (3620)	≥45, ≤420	—

Key: SD = Standard deviation; n= number of values; — = no limit; "Spec limit" = specification limit in ASTM C595/AASHTO M 240.

Table 15. Other Physical Characteristics of Blended Cements Reported for 2014.

Cement type	Statistic	Blaine fineness, m^2/kg	Fineness, 45-µm (No. 325) sieve, % passing	Air content, %	Autoclave expansion, %	Mortar expansion, %
IL	Mean	479	97.4	6.9	0.031	0.005
	SD	68.6	1.35	0.95	0.040	0.004
	Maximum	660	99.1	8.6	0.103	0.011
	Minimum	409	95.4	5.9	-0.007	-0.001
	n	12	12	12	12	8
	Spec limit	—	—	≤12	≥-0.02, ≤0.80	≤0.020*
IP	Mean	524	96.7	5.6	-0.031	0.007
	SD	155.5	2.64	1.99	0.045	0.001
	Maximum	850	98.6	8.2	0.020	0.008
	Minimum	397	91.3	3.0	-0.120	0.006
	n	8	7	8	8	2
	Spec limit	—	—	≤12	≥-0.02, ≤0.80	≤0.020*
IS	Mean	475	97.0	6.0	0.005	0.007
	SD	41.2	1.85	2.21	0.014	0.004
	Maximum	539	99.2	7.8	0.019	0.011
	Minimum	391	93.6	2.0	-0.020	0.003
	n	8	8	8	7	3
	Spec limit	—	—	≤12	≥-0.02, ≤0.80	≤0.020*

Key: SD = Standard deviation; n= number of values; — = not enough data reported or no limit; "Spec limit" = specification limit in ASTM C595/AASHTO M 240.
*Mortar expansion limits only apply if sulfate content exceeds default table limits.

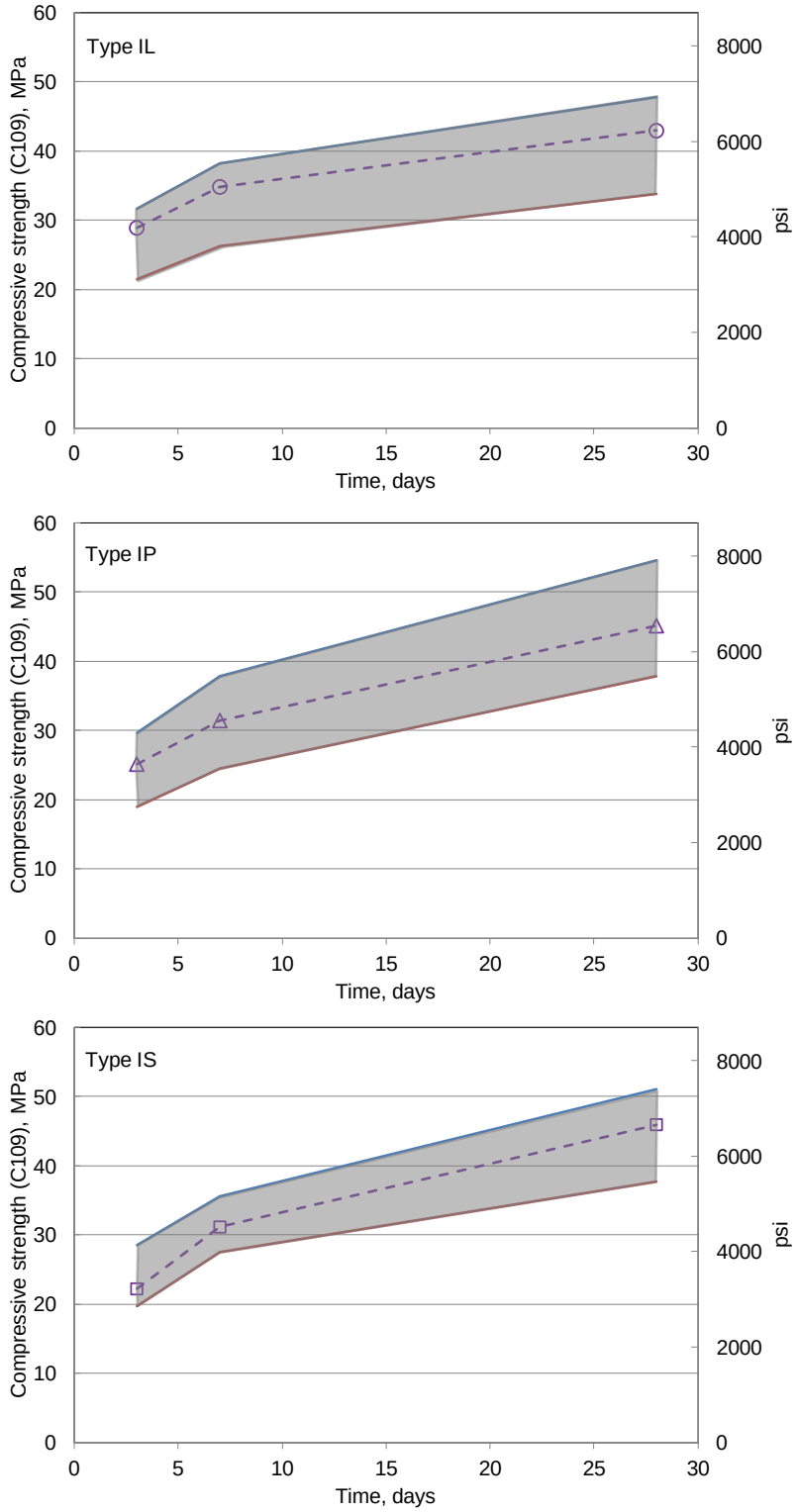

Figure 2. ASTM C109 compressive strengths for blended cements as reported for 2014. Mean values are connected by dashed lines and shaded areas represent ranges of values reported in the survey.

CHARACTERISTICS OF ASTM C1157 HYDRAULIC CEMENTS

Physical Properties

Tables 16 and 17 show physical data for ASTM C1157 Type GU hydraulic cements reported for 2014. The data include the mean, standard deviation, as well as the maximum and minimum for all data reported in the survey. The following properties are included:

- Compressive strength (ASTM C109)
- Vicat setting times (ASTM C191)
- Blaine fineness (ASTM C204)
- Air contents (ASTM C185)
- Autoclave expansion (ASTM C151), and
- Mortar expansion (ASTM C1038).

Figure 3 shows strength development curves (mean values) for 2014 Type GU cements as reported in the survey, along with the ranges of reported strengths at each age. At 1, 3, and 7 days, the mean strengths are 44%, 67% and 80% of the 28-d value.

Table 16. Compressive Strength and Setting Time of ASTM C1157 Type GU Hydraulic Cements Reported for 2014.

Cement type	Statistic	Compressive strength, MPa (psi)				Setting time (Vicat), minutes	
		1 day	3 days	7 days	28 days	Initial	Final
GU	Mean	19.1 (2780)	29.3 (4250)	34.9 (5070)	43.4 (6300)	106	199
	SD	3.71 (538)	4.16 (604)	3.76 (546)	3.35 (487)	19.9	39.7
	Maximum	25.9 (3760)	34.0 (4930)	39.1 (5680)	48.2 (6990)	122	262
	Minimum	13.0 (1880)	22.4 (3250)	28.9 (4190)	37.9 (5490)	59	131
	n	10	10	10	10	10	9
	Spec limit	—	≥13.0 (1890)	≥20.0 (2900)	≥28.0 (4060)	45 to 420	—

Key: SD = Standard deviation;, n= number of values; — = not enough data reported or no limit; “Spec limit” = specification limit in ASTM C1157.

Table 17. Other Physical Characteristics of ASTM C1157 Type GU Hydraulic Cements Reported for 2014.

Cement type	Statistic	Blaine fineness, m^2/kg	Fineness, No. 325 (45-µm) sieve, % passing	Air content, %	Autoclave expansion, %	Mortar expansion, %
GU	Mean	514	97.5	7.0	0.015	0.003
	SD	51.7	1.99	1.2	0.063	0.004
	Maximum	619	99.2	9.3	0.160	0.007
	Minimum	432	94.0	5.3	-0.040	-0.001
	n	10	10	10	10	6
	Spec limit*	—	—	≤12	≤0.80	≤0.020

Key: SD = Standard deviation; n= number of values; — = no limit; "Spec limit" = specification limit in ASTM C1157
*See ASTM C1157 for complete details.

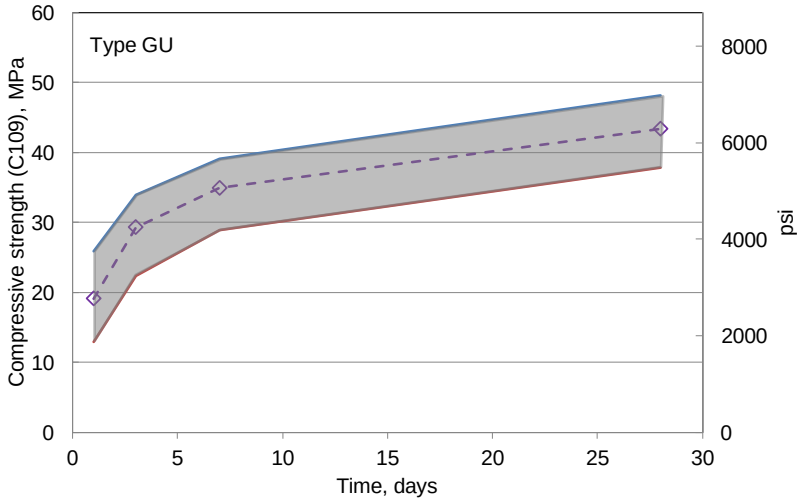

Figure 3. ASTM C109 compressive strengths for ASTM C1157 Type GU cements as reported for 2014. Mean values connected by dashed lines and shaded areas represent ranges of values reported in the survey.

COMPARISON OF HYDRAULIC CEMENTS FOR GENERAL CONCRETE CONSTRUCTION

Physical Properties

Figures 4 through 7 compare properties of hydraulic cements for general concrete construction in the US, as reported in the survey. Respectively these are setting time (Vicat), Blaine fineness, and compressive strength.

In Fig. 4, as might be expected, initial and final Vicat (ASTM C191) setting times for Type III cement are shorter than for other hydraulic cement types. Initial and final setting times

for other cements are comparable, although Type GU cements on average set a little sooner and Type IP cements set a little slower, on average. Generally, average initial setting times fall between 110 minutes and 140 minutes and final setting times fall between 200 minutes and 250 minutes.

Blaine fineness values for Type I, II, and V cements are relatively close, around 400 m^2/kg, whereas those for Type IL, IP, IS, and GU cements are higher on average, between 475 m^2/kg and 525 m^2/kg. Type III has the highest average at about 560 m^2/kg. Some Type III and Type IP cements have fineness over 700 m^2/kg, while some portland cements are closer to 300 m^2/kg.

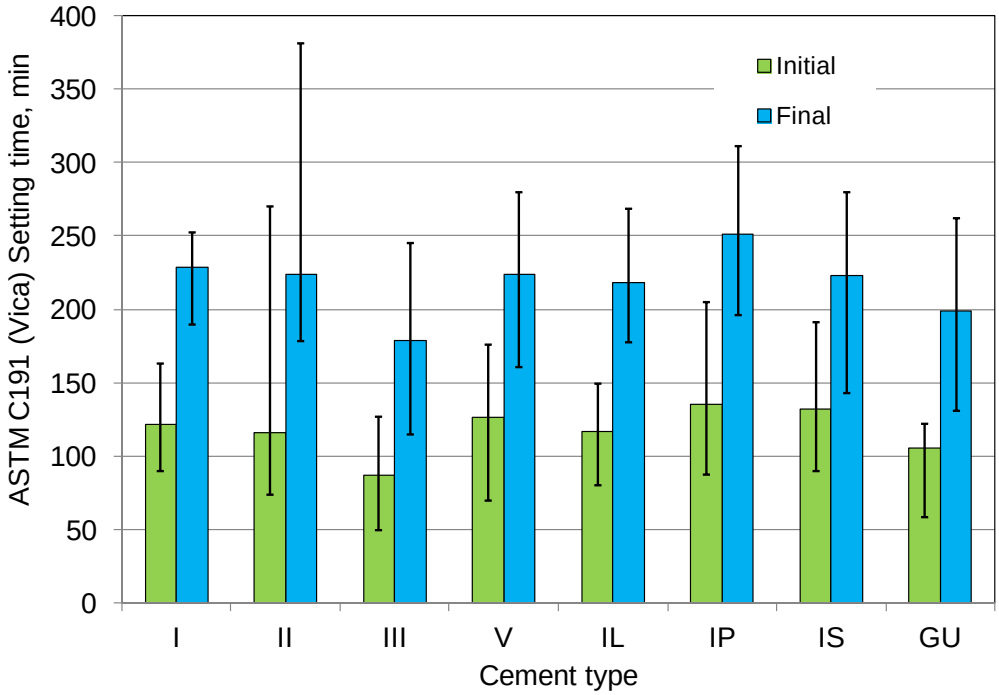

Figure 4. Mean ASTM C191 setting times (Vicat method) for hydraulic cements reported for 2014. Error bars indicate the range of reported values.

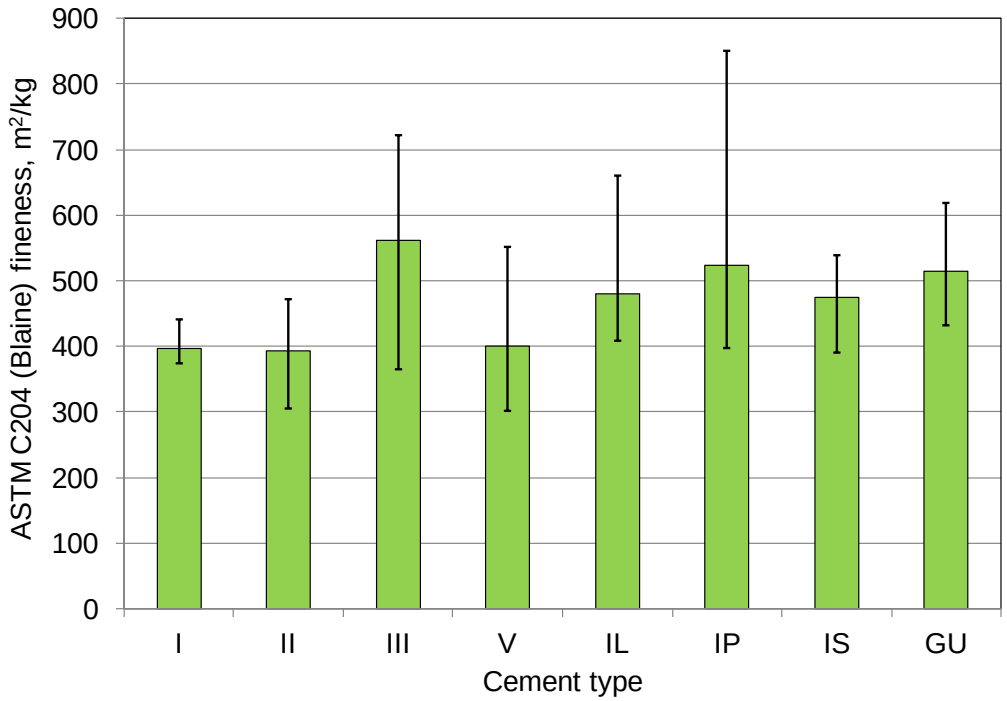

Figure 5. Mean ASTM C204 Blaine finenesses of hydraulic cements for general concrete construction. Error bars indicate the range of reported values.

Collected data indicate that compressive strength levels (See Fig. 6) for portland, blended and C1157 cements are generally comparable at 1, 3, 7, and 28 days, with the exception of those for Type III cement, which are higher than other cements through 28 days. All cement types average over 40 MPa (5800 psi) at 28 days. Figure 7 illustrates that Types IP and IS have steeper slopes for their strength vs. time curves between 7 days and 28 days, implying that their ultimate strengths will be higher than that of Type III with continued curing.

Comparable early strength development properties for the various cement types may not be surprising as these cements all compete for similar concrete applications. Also to be noted is that ASTM C109 specifies a mortar with a water:cement ratio 0.485 for portland cements and that water content of mortars made with non-portland cements produce a flow of 110±5 (via ASTM C1457), which may complicate direct strength comparisons.

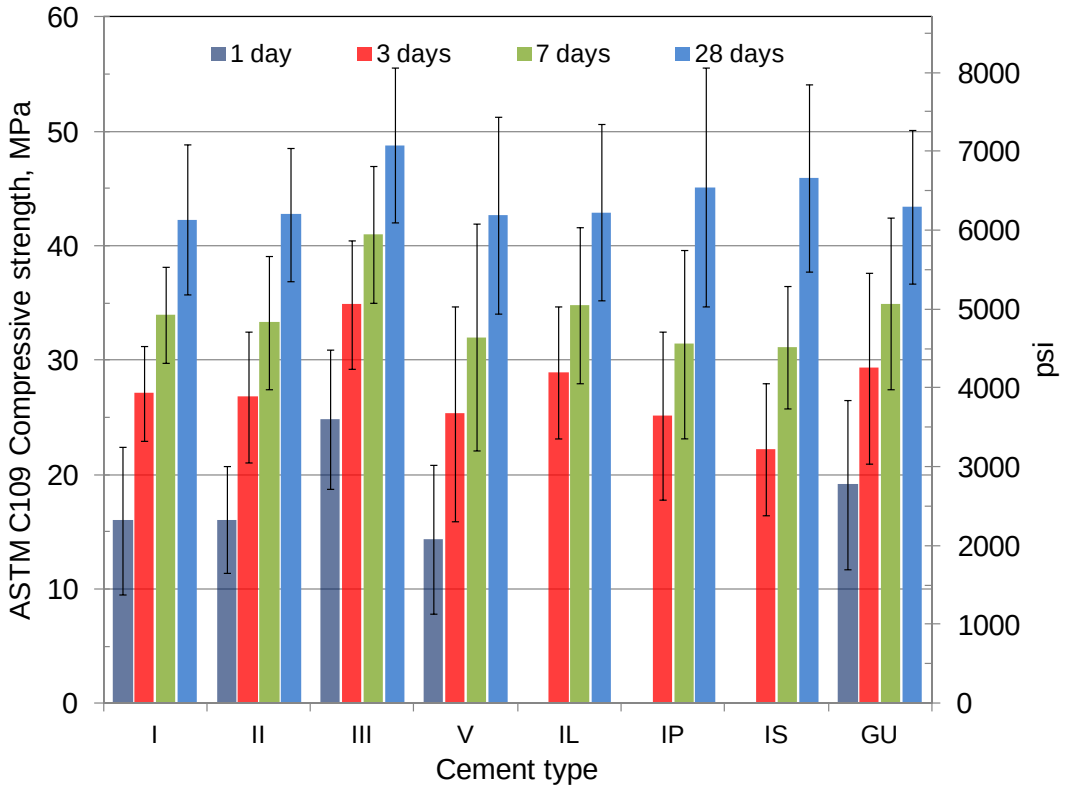

Figure 6. Mean ASTM C109 compressive strengths of hydraulic cements for general concrete construction as reported for cements produced in 2014. In this figure, error bars represent two standard deviations on either side of the mean.

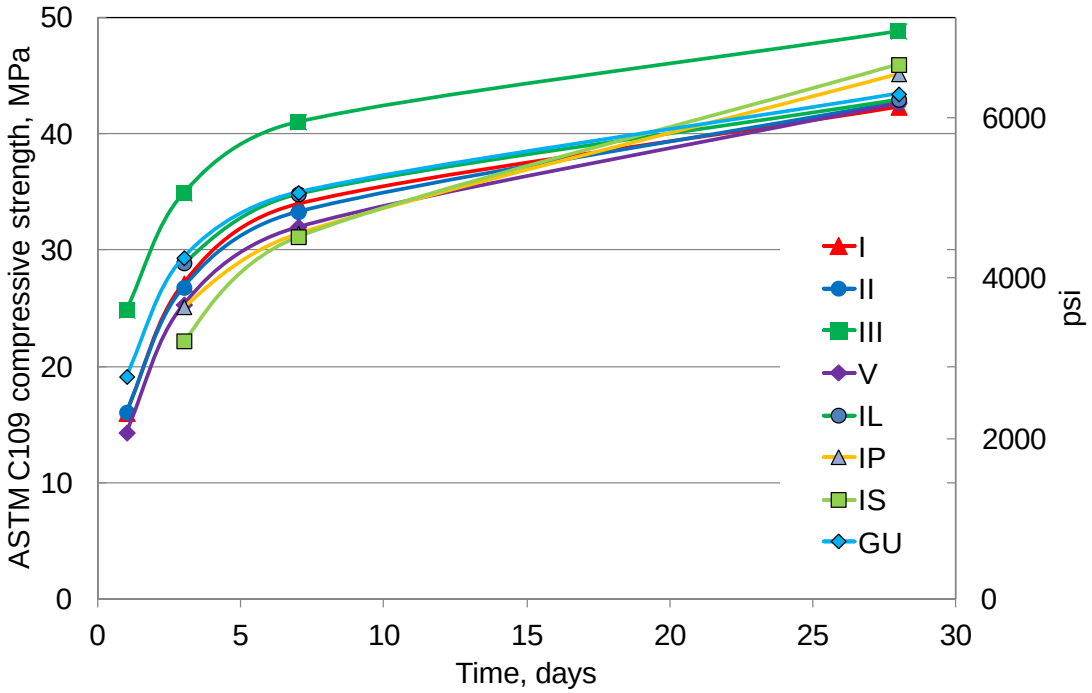

Figure 7. Mean ASTM C109 mortar cube compressive strengths for hydraulic cements for general concrete construction as reported for cements in 2014.

CHARACTERISTICS OF MASONRY CEMENTS (ASTM C91)

Physical Properties

Table 18 is a summary of physical data for ASTM C91 cements reported in the 2014 survey. The data are reported on the following properties of cements:

- Compressive strength (ASTM C109, using mortars defined in C91)
- Setting time (Gillmore, ASTM C266)
- Air content (ASTM C185)
- Water retention (ASTM C1506)
- Autoclave expansion (soundness) (ASTM C151), and
- Fineness by 45-µm (No. 325) sieve (ASTM C430).

Strengths of masonry cements, on average, follow the following progression: N < S < M, which follows the order of increasing strength requirements in ASTM C91. Mean 7-day strengths are approximately 80% of their 28-d values for all 3 cement types. Setting times mirror the trend for compressive strength, with Type N setting slowest on average, followed by Type S and Type M. However, it should be noted that there is a range of setting times for each cement Type that overlap the other types somewhat. Figures 8 and 9 provide a graphical summary of the strengths and setting times, respectively.

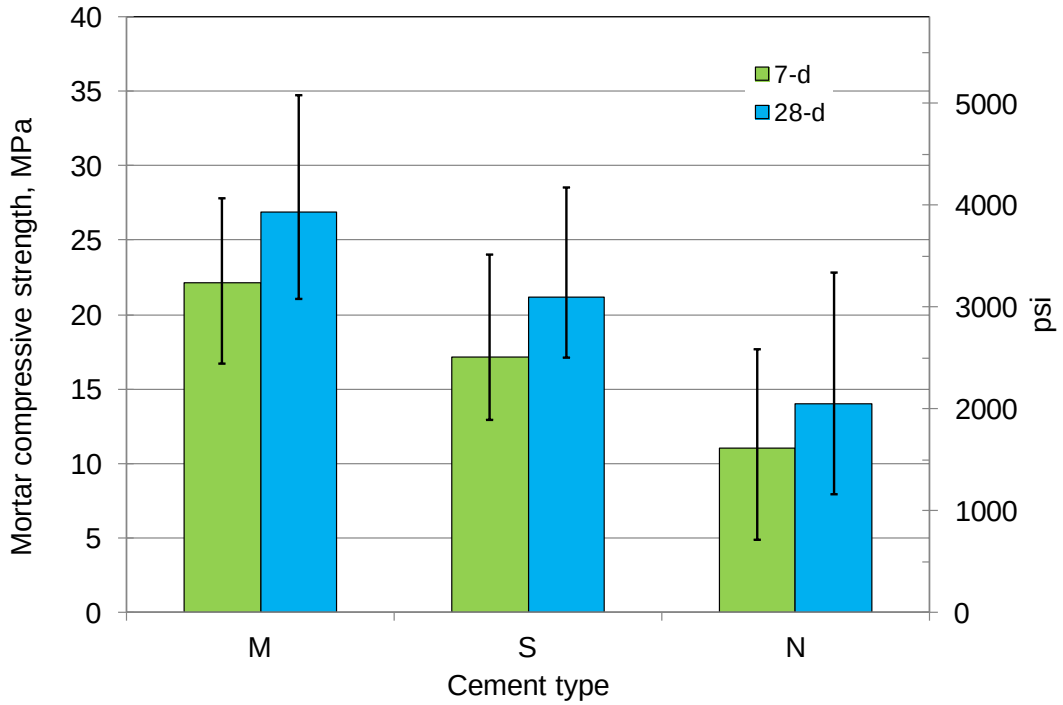

Figure 8. Strength development of ASTM C91 masonry cements as reported for 2014. Error bars indicate the range of values reported in the survey.

Table 18. Physical Data for ASTM C91 Masonry Cements Reported for 2014.

Cement type	Statistic	Compressive strength, MPa (psi)		(Gillmore) Setting time, min		Air content, %	Water retention, %	Autoclave expansion, %	Fineness, 45-µm (No. 325) sieve, % retained
		7-day	28-day	Initial	Final				
M	Mean	22.1 (3210)	26.9 (3900)	207	335	15.5	81.6	0.011	3.2
	SD	4.29 (623)	4.58 (664)	104	149	1.5	5.2	0.048	1.67
	Maximum	27.8 (4030)	34.7 (5040)	416	580	18.4	88.3	0.110	6.0
	Minimum	16.7 (2430)	21.1 (3060)	134	235	13.1	72.8	-0.050	0.6
	n	9	9	9	7	9	9	9	9
	Spec limit*	≥12.4 (1800)	≥20.0 (2900)	≥90, ≤1000	—	≥8, ≤19	≥70	≤1.0	≤24
S	Mean	17.2 (2490)	21.2 (3070)	220	358	15.8	82.4	0.039	3.6
	SD	2.70 (391)	2.88 (418)	63	105	1.6	3.5	0.062	3.07
	Maximum	24.0 (3480)	28.5 (4140)	393	638	19.0	92.6	0.270	12.2
	Minimum	12.9 (1870)	17.1 (2480)	149	219	12.9	77.2	-0.020	0.4
	n	29	29	29	22	29	28	27	29
	Spec limit*	≥9.0 (1300)	≥14.5 (2100)	≥90, ≤1000	—	≥8, ≤19	≥70	≤1.0	≤24
N	Mean	11.1 (1605)	14.0 (2035)	237	375	17.1	83.6	0.041	4.3
	SD	3.67 (533)	4.22 (612)	78	105	1.8	3.9	0.055	3.37
	Maximum	17.7 (2560)	22.8 (3310)	480	643	20.8	92.6	0.235	12.9
	Minimum	4.9 (710)	7.9 (1150)	134	238	13.4	77.0	-0.012	0.7
	n	28	28	28	19	28	25	26	28
	Spec limit*	≥3.4 (500)	≥6.2 (900)	≥120, ≤1000	—	≥8, ≤21	≥70	≤1.0	≤24

Key: SD = Standard deviation; n= number of values; — = no limit; "Spec limit" = specification limit.
*See ASTM C91 for complete details.

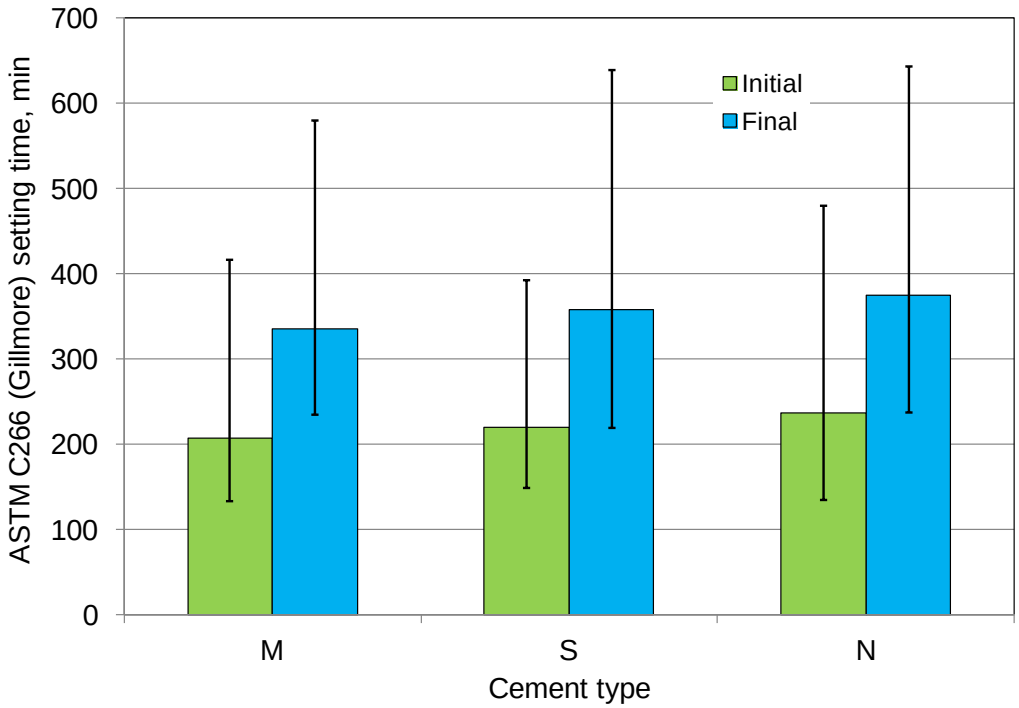

Figure 9. Gillmore setting times for ASTM C91 masonry cements as reported for 2014. Error bars indicate the range of values reported in the survey.

CHARACTERISTICS OF PLASTIC (STUCCO) (ASTM C1328) AND MORTAR CEMENTS (ASTM C1329)

Although data is available for a limited number of plastic and mortar cements, physical data for plastic or stucco cements (ASTM C1328) reported for 2014 are given in Table 19 and for mortar cements in Table 20. For Table 19, summary data are reported as mean, standard deviation, maximum, minimum, and number of cements the following properties:

- Compressive strength (ASTM C109)
- Setting times (Gillmore, ASTM C266)
- Autoclave expansion (ASTM C151)
- Water retention (C1506)
- Air content (ASTM C185), and
- Fineness (ASTM C430)

Due to the small number of cements reported, data for all 4 mortar cements were averaged together for the following properties in Table 20:

- Compressive strength (ASTM C109, modified)
- Setting times (Gillmore, ASTM C266)
- Autoclave expansion (ASTM C151)
- Water retention (ASTM C1506),
- Air content (ASTM C185), and
- Fineness (ASTM C430).

Table 19. Physical Data for ASTM C1328 Plastic (Stucco) Cements reported for Cements Reported for 2014. *

Cement type	Statistic	Compressive strength, MPa (psi)		Setting time (Gillmore), minutes		Autoclave expansion, %	Water retention, %	Air content, %	Fineness 45-µm (No. 325) sieve, % retained
		7-d	28-d	Initial	Final				
M	Mean	23.9 (3470)	28.9 (4190)	203	321	0.019	97.8	15.2	19.4
	SD	3.79 (550)	4.32 (630)	40	38	0.046	1.38	0.79	4.89
	Maximum	27.3 (3960)	32.3 (4680)	258	362	0.087	99.8	15.8	23.6
	Minimum	18.5 (2680)	22.8 (3310)	163	290	-0.012	96.8	14.1	13.0
	n	4	4	4	3	4	4	4	4
	Spec limit	≥12.4 (1800)	≥20.0 (2900)	≥90, ≤1000	–	≤1.0	≥70	≥8, ≤20	≤24
S	Mean	13.8 (2000)	17.3 (2510)	175	–	0.000	96.1	17.0	17.3
	SD	1.12 (160)	1.50 (220)	36	–	0.007	2.68	2.29	2.30
	Maximum	14.8 (2150)	18.9 (2740)	216	–	0.007	98.9	19.0	19.0
	Minimum	12.3 (1780)	16.0 (2320)	149	–	-0.007	92.8	14.0	14.7
	n	4	4	3	–	3	4	4	3
	Spec limit	≥9.0 (1300)	≥14.5 (2100)	≥90, ≤1000	–	≤1.0	≥70	≥8, ≤20	≤24

Key: SD = Standard deviation; n= number of values; — = no limit or not enough data; "Spec limit" = specification limit.

Table 20. Physical Data for ASTM C1329 Mortar Cements reported for Cements Reported for 2014.*

Cement type	Statistic	Compressive strength, MPa (psi)		Setting time (Gillmore), minutes		Autoclave expansion, %	Water retention, %	Air content, %	Fineness 45-µm (No. 325) sieve, % retained
		7-d	28-d	Initial	Final				
All	Mean	25.7 (3720)	29.8 (4320)	181	282	0.080	5.3	13.2	19.1
	SD	2.69 (391)	4.54 (659)	52	70	0.060	5.72	2.62	4.12
	Maximum	29.6 (4290)	35.3 (5120)	258	362	0.120	13.5	15.0	13.6
	Minimum	23.4 (3400)	25.2 (3650)	140	242	-0.007	0.2	9.3	22.2
	n	4	4	4	3	4	4	4	4
	Spec limit	varies	varies	≥90 or ≥120, ≤1000	–	≤1.0	≥70	≥8, ≤15 or ≤17	≤24

Key: SD = Standard deviation; n= number of values; — = no limit; "Spec limit" = specification limit.
*Data is average for all C1329 cements received: 1 Type M, 1 Type N and 2 Type S.

CONCLUSIONS

This report summarizes mean values for cement characteristics obtained in a 2015 survey of hydraulic cements in the US, which requested yearly average data for cements produced in 2014 under ASTM C150/AASHTO M 85 (portland cements), ASTM C595/AASHTO M 240 (blended hydraulic cements), ASTM C1157 (hydraulic cements), ASTM C91 (masonry cements), ASTM C1328 (plastic (stucco) cements), and ASTM C1329 (mortar cements). Data for 251 cements were provided by 68 plants, representing about 72% of active US plants.

Type II portland cements remain the most common type of cement produced in the US, produced at 56 of the 68 plants. The data on blended and Type GU cements produced to meet ASTM C595/AASHTO M 240 and ASTM C1157, respectively, indicate broadly similar setting times and strength development characteristics to Type I and Type II portland cements.

Data on cements for masonry are provided for 66 cements produced to meet ASTM C91, with C1328 and C1329 cements being less commonly produced.

ACKNOWLEDGEMENTS

This research report (PCA R&D SN3284) reflects the views of the author, who is responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association. The author would like to thank Brian Schmidt of PCA's Market Intelligence group for assistance in conducting the survey.

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