Evaluation of Autoclave Expansion Test for Fly Ashes

Summary of Literature Review

FINAL REPORT
July 21, 2020
WJE No. 2020.0276

PREPARED FOR:
American Coal Ash Association (ACAA)
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INTRODUCTION

Numerous studies were conducted, and papers published, on volume stability and autoclave expansion/soundness testing. Almost every study arrived at the same conclusion: serious objections still exist with respect to the test methods used and current limitations in the corresponding specifications. Furthermore, the development of the autoclave expansion test currently specified in ASTM standards, was completed before "*present understanding of the hydration of portland cement compounds and cements*."[6] The objections to the significance and use of the current autoclave expansion test method was summarized in a paper published in 1978 by P. K. Mehta:

1) *exaggerated expansion values are obtained by destroying the cohesive forces present in a normally hardened cement paste;*
2) *the test conditions force the crystalline MgO present to hydrate and expand, whereas in normally cured commercial portland cements, within permissible chemical limits, the MgO present is either inert or hydrates at a rate too slow to be of any consequence;*
3) *the magnitude of the expansion in neat cement bars due to hydration of free CaO normally present in cement may be high, but in corresponding concretes, it may not be high enough to cause cracking;*
4) *no correlation has ever been shown between the autoclave test specification limits and soundness of concrete.*

HISTORY OF SOUNDNESS TESTING

One of the earliest reports of unsoundness was in 1884, when several bridges and viaducts failed in France due to high MgO content in cement that lead to concrete expansion.[11] Similar problems associated with expansion leading to cracking were observed in Germany. The MgO content of the German cement was about 27% and 16% to 30% in the French cement. In the 1920s, some field failures were attributed to excess free lime in the concrete coming from the portland cement.

In 1904, ASTM C01 Committee released its first standard ASTM C9, *Standard Specification for Cement*, which was eventually replaced with ASTM C150. ASTM C9 specified soundness testing of cement using visual observations of a cement "pat" cured for 28 days; the standard also set a limit of 5% for the MgO content. The "pat" test referenced in the cement specification was meant to provide an indication of free lime expansion problems. In 1917, a new version of the soundness test was adapted, where a cement "pat" was steam-cured for five hours at 100 °C following a normal curing for 24 hours. ASTM C151-40T replaced the "pat" test and is now the standard test method for "*determination of the expansion of a hardened cement paste when exposed to the autoclave conditions*." ASTM C151 "*provides an index of potential delayed expansion caused by the hydration of CaO or MgO, or both, when present in hydraulic cement*."

The limits for expansion for portland cement changed several times.[10] The initial 1.0% in 1937 was recommended as a result of PCA meetings. A 0.5% expansion was specified upon adaption of the tentative ASTM C151-40T in 1940, and in 1963 the limit was increased to 0.8%, a value specified in the current ASTM C150 and ASTM C618 standards.

METHODS FOR SOUNDNESS TESTING

There are three main test methods to assess potential for expansion caused by hydration of calcium oxide and magnesium oxide. Autoclave test (ASTM C151) is the only one that is specified for testing in the United States. Various “pat” tests and Le Chatelier method are used in Europe and other countries.

Expansion Reactions

The autoclave expansion test is conducted to assess the potential for expansion due to the presence of calcium oxide (free lime or f-CaO), magnesium oxide (periclase or MgO), or both. The measured expansion is typically associated with two primary reactions: 1) MgO reacting with water to form $Mg(OH)_2$ or brucite, and 2) f-CaO reacting with water to form $Ca(OH)_2$ or portlandite. Other parameters in portland cement such as tricalcium aluminate (C_3A), sulfur trioxide (SO_3) of cement, and “Blaine” specific surface area have also been correlated to autoclave expansion. MgO, C_3A, and free lime in fly ash have been noted to impact autoclave expansion, with free lime having the most significant impact.[12] An alkali-silica reaction when testing cement-fly ash mixtures has also been known to contribute to expansion in the autoclave testing.

The Pat Test

A cement paste of normal consistency is formed into a “pat” that is cured in a moist room for 24 hours followed by curing in air or water for 28 days. The test can be also performed by exposing the cured “pat” to steam or boiling water at 100 °C for up to five hours.

A visual inspection of the “pat” for warping or cracking after 28 days or after steam/boil curing was the criteria for soundness. The “pat” test was more of a qualitative with respect to results, a test that did not provide any means for comparison. Work by PCA showed that the “pat” test was not a reliable indicator of expansion due to a high f-CaO content of cement.[11]

Le Chatelier Test

The Le Chatelier soundness test (EN 196-3) is widely used throughout the world, including Europe, India, and Brazil, in place of the autoclave expansion test.

The Le Chatelier apparatus is a brass mold with indicator needles soldered to the rim of the mold. For the testing, a specimen is placed in the mold and cured in a moist environment for 24 hours. Upon completion of curing, the mold with the hardened paste is boiled at 100 °C for three hours. After the mold is cooled, the expansion is measured as a difference in the distance between indicator needles before and after boiling. Due to the testing temperature, the Le Chatelier test has been shown not to be susceptible to MgO (periclase) induced expansion, while the ASTM C151, autoclave expansion test is.[13]

The Autoclave Expansion Test

The autoclave expansion test method, first standardized by ASTM and designated as ASTM C151, is still in use today. The results of this testing, as the differences in the length measurement before and after autoclaving, is reported as expansion or contraction.

The specimens in the autoclave expansion test are made using molds specifically used for determination of length change of hardened cement paste. The prepared paste is placed into molds and moist cured for 24 hours. After de-molding, the bars are placed into an autoclave in a way that the specimens can be exposed to saturated steam during testing. The pressure and temperature of the saturated steam (2 MPa or 295 psi and 216 °C or 420 °F) of the autoclaving process is expected to convert the un-hydrated f-CaO and MgO to hydrates. The percentage of increase (decrease) in length of the specimen bar before and after autoclaving is reported as expansion or contraction.

EXPANSION DUE TO THE PRESENCE OF FREE LIME AND PERICLASE

The hydration of free lime as well as periclase within a hardened cement paste results in the expansive pressure leading to failure of the soundness testing. The extent of the pressure generated is typically proportional to amount, distribution and particle size of these two constituents.

Effect of Free Lime (f-CaO) on Expansion

Two important factors contribute to the expansive behavior of cement: particle size and amount of free lime. To significantly contribute to the expansion properties of cement, the size of f-CaO particles must be large, an uncommon occurrence in modern cement. The f-CaO, typically found in cements, is very reactive and will hydrate to portlandite during the final stages of cement production and storage. The typical cause of cement unsoundness is the hydration of hard burned f-CaO. The hard burned f-CaO, found in cement due to problems with fineness or proportioning of cement raw mix, is reactive under normal condition. No high temperature and pressure are needed to assess the expansive behavior of this free lime. The soundness of cement containing hard burned lime can be simply verified by moist curing specimens for several days under slightly elevated temperature.[11]

Effect of Periclase (MgO) on Expansion

The effect of periclase hydration on expansion depends on its particle size, crystallinity and reactivity, which in turn depends on the calcination temperature (calcined vs. dead-burned, per ASTM C71). Calcined dolomite is produced at a relatively low temperature of calcination, and it is highly porous and reactive. Dead-burned dolomite, a product obtained after the additional calcining, is normally dense and less reactive. The expansion, as measured by ASTM C151, is typically associated with the presence of dead- burned, more crystalline MgO.

The calcination temperature of dolomite has a profound effect on hydration properties of MgO. Below 900 °C temperature of calcination, MgO is highly reactive and its normal hydration can lead to expansion. The reactivity of MgO will be reduced significantly when the temperature of calcination is in the 900 °C to 1200 °C temperature range. The hydration of MgO, produced by calcination at temperatures at or above 1200 °C, even after storage under favorable curing conditions (moisture and temperature at 32 °C), is considerably impaired. The MgO exposed to temperature above 1500 °C, the temperature of cement clinker production, is considered inert under ambient temperature of hydration.[11]

The dead-burned, crystalline periclase hydrates relatively slow, however, the hydration product, brucite, occupies a considerably greater volume than the initial constituent, resulting in expansion and cracking. The size of MgO particles also has an effect on the degree of expansion, that is, for a given MgO content the expansion will increase with an increase of MgO particles size.[3] X-ray diffraction analysis of specimens subjected to various methods of curing and soundness testing showed that the amount of brucite formed correlates to the severity of the testing conditions.[13]

Several studies were published on the effect of fly ash addition on expansion in cements having high MgO content. Most authors agreed that the pozzolanic reaction associated with the addition of fly ash leads to the formation of a stronger microstructure of calcium silicate hydrate (C-S-H) and a better containment of forces associated with the hydration of MgO.[6]

SOUNDNESS OF CEMENT-FLY ASH MIXTURES

The current versions of ASTM C618 and AASHTO M 295 include specific limits for autoclave expansion or contraction, which is 0.8% for test specimens containing 20% fly ash or natural pozzolan. ASTM C618 references ASTM C311, which in turn references ASTM C151, as the test method for determining autoclave expansion of cement-fly ash mixtures.

Over the years, several studies confirmed that the amount of free lime in the cement-fly ash mixtures is one of the major factors contributing to autoclave expansion.[17] However, the results of one study involving the assessment of properties of fly ash having various free lime contents showed that while fly ashes with a higher free lime content exhibit higher expansion in the testing, the autoclave results can still meet the ASTM C618 limits.[9]. Similar laboratory studies on effect of free lime content on the results of autoclave testing indicate that mixtures with a 20% fly ash replacement, where the free lime content was up to 10%, met the expansion limit as specified in ASTM C618.[12] In both studies, it was postulated that when using fly ashes with a higher free lime content (up to 4.51%), the cement/fly mixtures performed better in autoclave testing than neat cement samples due to the consumption of calcium hydroxide.

Several studies were published on the effect of fly ash addition on expansion in cements with high MgO content. Most authors agreed that the pozzolanic reaction associated with the addition of fly ash leads to formation of a stronger microstructure of C-S-H and a better containment of forces associated with the hydration of MgO. [1, 6, 14, 15] Specifically, the addition of fly ash "*leads to a denser, homogeneous morphology and higher strength, resulting in lower expansion.*"[1]

Under the conditions of autoclaving, an "*unintended*" alkali-silica reaction (ASR) can also take place in the test specimens.[20] It was further suggested that this type of reaction will not occur under ambient conditions, and the *"alkali-silica (quartz) gel may introduce a significant amount of expansion in the autoclave"* specimen. The author conclusion was that ASTM C151 is not a suitable test to assess cement-fly ash system, and "*such an application can misidentify the beneficial functions of alkali to promote the pozzolanic reaction*" of fly ash.

CONCLUSIONS

Since no correlation was ever established between the expansion as measured by the ASTM C151 test method and the expansion in concrete, a review of the existing specifications and/or the test method was needed. The quality of a fly ash proposed for use in concrete is assured if this fly ash meets ASTM or AASHTO requirements; however, these specifications are not put in place to assure the quality and performance of the concrete incorporating the tested fly ash. However, it should be imperative that the fly ash properties prescribed in the specifications "*are those reflecting performance*." [19]

Responses to a survey of coal fly ash users and specifiers, conducted as a part of the NCHRP study sponsored by AASHTO, also "*indicated a need for specifications and tests that better predicted performance*" of fly ashes in concrete.[18] Table 2.2 of NCHRP Project 18-13 report (Figure 1) demonstrated the "*issues* *and concerns*" with mandatory requirements for fly ashes, further indicating that performing the autoclave expansion test does not provide any useful information on the performance of fly ash in concrete. This report includes a review of literature on the autoclave expansion of fly ash and the assessment of the current ASTM C151 test method with respect to its use in the testing of cement-fly ash mixtures. The information presented should provide enough justification for a possible replacement of this standard with a standard that better predicts the performance of fly ash or to remove in its entirety the requirement for soundness testing from the appropriate specifications.

Summary of Literature Review

A summary of the literature review on autoclave expansion testing of fly ashes is provided below:

- Autoclave expansion method was originally developed as a test for expansion of cement paste; however, it is still specified in ASTM C618 as a method for soundness of fly ash in concrete.
- Expansion caused by MgO and C_3A as measured according to ASTM C151 does not correlate to expansion in concrete cured under normal conditions.[6]
- ASTM C151 testing allows to determine expansion due to the hydration of free lime and periclase. Due to a lower temperature of testing, the Le Chatelier test is more suitable to access expansion related to the hydration of free lime only.
- Pozzolanic reaction associated with the addition of fly ash leads to formation of a stronger microstructure of calcium silicate hydrate (C-S-H) and a better containment of forces associated with the hydration of MgO. Specifically, the addition of fly ash "*leads to a denser, homogeneous morphology and higher strength, resulting in lower expansion.*"[1]
- The testing of portland cement-fly ash-standard system according to ASTM C151 can sometimes result in excessive expansion due to alkali-silica reaction (ASR). This author concluded that ASTM C151 is not a suitable test to assess cement-fly ash systems due to the prospect of ASR, and "*such an application can misidentify the beneficial functions of alkali to promote the pozzolanic reaction*" of fly ash.[20]
- The results of autoclave expansion of a cement-fly ash paste are typically more affected by the presence of free lime. However, many fly ashes high in free lime, especially Class C ashes, may still pass the soundness test if the reactivity of free lime is affected by other factors. Tricalcium aluminate (C_3A) and periclase (MgO) may also contribute to the expansion, but to a lesser extent than free lime.
- Data suggests that soundness failure pertained to fly ashes from "*a specific source rather than appearing sporadically in all fly ashes.*"[17]
- Free lime, periclase and C_3A, mineral constituents found in fly ashes, can contribute to expansive behavior; however, the soundness test does not provide any additional data on specific causes for expansion.[17]
- Mixtures where cement is replaced with 20% fly ash containing higher amounts of free lime still can meet the expansion limits as specified in ASTM C618 due to the consumption of portlandite as a result of pozzolanic reaction.

Autoclave Expansion Test - Factors to Review

The review of literature on the soundness testing suggests that the results of autoclave expansion tests of cement or cement-fly ash mixtures can be influenced by various factors. The list of factors and considerations pertaining to autoclave expansion testing are provided below:

- ***Control Cement***: The control cement used by a laboratory in the soundness testing per the requirements of ASTM and AASHTO specifications may contribute to the expansion since "*both the cement and fly ash can contain the expansive constituents (free lime, periclase, and C_3A) that contribute to the overall measured expansion of the test specimen.*"[17]
- ***Water/Cementitious Ratio***: ASTM C151 requires to use sufficient water to achieve normal consistency as per ASTM C187. This means that the water/cementitious materials ratio (w/cm) of cement-fly ash mixtures will vary depending on the fly ash used in testing. Class C fly ashes typically require less mixing water to achieve normal consistency, leading to a lower w/cm ratio. If less mixing water was used to reach normal consistency, the hydration process will be inhibited, producing less expansion in the specimens. Conversely, if more mixing water is required to achieve normal consistency, the hydration of the expansive constituents will be accelerated, possibly leading to higher expansion results.[17]
- ***Specimen Curing Time***: Specimens for expansion testing are subjected to 24 hours of moist cure prior to autoclaving; however, studies indicate that increased cement hydration time may results in less expansion.[5]
- ***Testing Conditions***: The elevated temperature and pressure settings of the soundness testing contributes to the conversion of cement hydration products, such as calcium-silicate-hydrate (C-S-H) and calcium sulfoaluminate hydrates, to weaker materials, thus creating a cement paste with reduced strength.[11]
- ***Specifications Limit***: The original maximum expansion of 0.5% for portland cement, approved in 1940 based on test results presented to ASTM, was changed to 0.80% in 1963, where it remains now.[6] The current limit requirement for autoclave expansion, as stated in ASTM and AASHTO specifications for use of coal fly ash in concrete, is set at 0.8%. No published papers or proceedings were found that provide justification for using a specification limit for cement-fly ash mixture originally intended for portland cement.
- ***Correlation to Concrete Performance***: There is no data available that demonstrates the correlation between the expansion as measured by ASTM C151 testing and soundness of concrete.[11]
- ***Precision of ASTM C151 Testing***: Recent work conducted by ASTM C01.31 Subcommittee on Volume Change has shown poor reproducibility of ASTM C151 testing results when expansion levels are near the specified limit of 0.80%. The disagreement between the recent results and the precision statement in ASTM C151 is alarming and questions the usefulness of this test method in a material specification standard such as ASTM C618.
- ***Safety***: The autoclave expansion is very attractive with respect of providing results in a relatively short period of time. Nonetheless, the high temperature and pressure conditions of autoclaving is a potential safety issue for the personnel conducting the expansion test.[13]

- ***Limited Use of the of ASTM C151***. The ASTM C151 autoclave expansion test to predict soundness and the limits established for expansion in various specifications were never incorporated in standards outside North America. T. Patzias, in his response to the paper by P. K. Mehta[11], provided the following comment on the absence of the autoclave expansion test from European cement specifications: "*concrete experts believe that that the autoclave test is not relevant to the practical application of concrete since they have not experienced any concrete failure in practice due to MgO unsoundness as long as MgO content is limited*."

  Figure 2 and Figure 3 show very limited usage of soundness testing in countries around the world.[6]

REFERENCES

Acronyms:

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CSA	Canadian Standards Association
EN	European Standard
NCHRP	National Cooperative Highway Research Program
PCA	Portland Cement Association

Standards:[1234]

1. ASTM C71, Terminology Relating to Refractories.[1]
2. ASTM C150, Specification for Portland Cement.[1]
3. ASTM C151, Test Method for Autoclave Expansion of Hydraulic Cement.[1]
4. ASTM C187, Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste.[1]
5. ASTM C311, Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete.[1]
6. ASTM C618, Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.[1]
7. AASHTO M 85, Specification for Portland Cement.[2]
8. AASHTO M 295, Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.[2]
9. CSA A3000, Cementitious materials compendium.[3]
10. EN 196-3, Methods of testing cement - Part 3: Determination of setting times and soundness.[4]
11. EN 197-1, Cement - Part 1: Composition, specifications and conformity criteria for common cements.[4]

[1] American Society for Testing and Materials. For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

[2] American Association of State Highway and Transportation Officials. 1995. AASHTO provisional standards. Washington, D.C.: American Association of State Highway and Transportation Officials.

[3] Canadian Standards Association, Toronto, Canada.

[4] European Committee for Standardization.

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APPENDIX - FIGURES

Table C2.2. Mandatory requirements for coal fly ash (as per AASHTO M 295).

Test	Issues or concerns	Specification Limits	
		Class F	Class C
$SiO_2+Al_2O_3+Fe_2O_3$	Prescriptive not performance	70% min.	50% min.
SO_3	Prescriptive not performance	5.0% max.	5.0% max.
Moisture content	Few fail - why measure it?	3.0% max.	3.0% max.
Loss on Ignition	Does not reflect AEA adsorption	5.0% max.	5.0% max.
Fineness	Too simple to be meaningful	34% max.	34% max.
Strength Index	Does not fail finely ground materials that are not pozzolans	75% min.	75% min.
Water Requirement	Few fail - why measure it?	105% max.	105% max.
Soundness	Few fail - why measure it?	0.8% max.	0.8% max.
Uniformity			
Density		5% max.	5% max.
Fineness	Too hard to meet	5% max.	5% max.

Figure 1. Source: Specification and Protocols for Acceptance Tests of Fly Ash Used in Highway Concrete", Final Report for NCHRP Project 18-13, Attachment C.[19] *"Table C2.2. summarized general level of acceptance of various requirements of AASHTO M 295 specification."*

Table 5-1 Comparison of specified fly ash between Japan and other countries *4

Name of country				JAPAN				EU			USA		
Standards				JIS A 6201				EN450-1			ASTM C 618		
Year of establishment				2015				2012			2008		
Types				I	II	III	IV	A	B	C	N	F	C
Chemical components	Silicon Oxide		%	---				---			---		
	Silicon Dioxide		%	≧45				---			---		
	Sulfur Trioxide		%	---				3≧			4≧	5≧	
	Moisture content		%	1≧				---			3≧		
	Ignition loss		%	3≧	5≧	8≧	5≧	5≧	7≧	9≧	10≧	6≧ *2	6≧
	Chloride ion		%	---				0.1≧			---		
	Free Calcium Oxide		%	---				1.5≧ *1			---		
	Active Calcium Oxide		%	---				10≧			---		
	Magnesium Oxide		%	---				4≧			---		
	Total of Silicon Dioxide + Ferric Oxide + Aluminum Oxide		%	---				≧70			≧70		≧50
	Alkali content		%	---				5≧			---		
Physical properties	Density		g/cm^3	≧1.95				---			---		
	Fineness	Specific surface area	cm^2/g	≧5000	≧2500	≧2500	≧1500	---			---		
		Percentage retained over 45µm sieve	%	10≧	40≧	40≧	70≧	Division by fineness N: 40≧, S: 40≧			34≧		
	Activation index	7 days	%	---				---			≧75 *3		
		28 days	%	≧90	≧80	≧80	≧60	≧75			≧75 *3		
		91 days	%	≧100	≧90	≧90	≧70	≧85			---		
	Ratio of flow value (Ratio of water content)		%	≧105	≧95	≧85	≧75	(S: 95≧)			(115≧)	(105≧)	
	Soundness	Expansion ratio by autoclave	%	---				10mm≧			0.8≧		
Other specified items				Specific surface area: ±450 cm^2/g Percentage retained over 45µm sieve: ±5%				Density: ±0.15 g/cm^3 Percentage retained over 45µm sieve: ±10% *1: In the case of Free Calcium Oxide over 1.0%			Density: ±5% Percentage retained over 45µm sieve: ±5% *2: In the case of user's approval, limit of 12% may be applied *3: The age of index should be prescribed by the specifications		

Japan Concrete Institute: Reduction in Shrinkage Cracks and Improvement of Durability in View of Admixture, Committee Report of the JCI, pp. 89-99, 2010

Figure 2. Source: "Guidelines for Control of Cracking of Mass Concrete 2016," *Report JCI-R-001-2016*, Japanese Concrete Institute.

Table 5-2 Comparison of specified fly ash between Japan and other countries [*1]

Name of country				UK			AUSTRALIA				CHINA								REPUBLIC of KOREA	
Standards				BS3892			AS3582.1				GB1596								KSL5405	
Year of establishment				1993			1998b				2005								2009	
Types				PART I	PART II		Special*2	Normal			I		II		III		For cement mixture		Type 1	Type2
					A	B		Fine	Medium	Coarse	F	C	F	C	F	C	F	C		
Chemical components	Silicon Oxide		%	---	---	---	---	---	---	---	---						---		---	
	Silicon Dioxide		%	---	---	---	---	---	---	---	---						---		≧45	
	Sulfur Trioxide		%	2≧	2.5≧		---	3≧			3≧						3.5≧		---	
	Moisture content		%	0.5≧	0.5≧		---	1≧			1≧						1≧		1≧	
	Ignition loss		%	6≧	7≧	12≧	4≧	4≧	5≧	5≧	5≧		8≧		15≧		8≧		3≧	5≧
	Chloride ion		%	0.1≧	---		---	---			---						---		---	
	Free Calcium Oxide		%	10≧	---		---	---			1≧	4≧	1≧	4≧	1≧	4≧	1≧	4≧	---	
	Active Calcium Oxide		%	---	---		---	---			---						---		---	
	Magnesium Oxide		%	---	4≧		---				---						---		---	
	Total of Silicon Dioxide + Ferric Oxide + Aluminum Oxide		%	---	---		---	---			---						---		---	
	Alkali content		%	---	---		---	---			---						---		---	
Physical properties	Density		g/cm^3	≧2	---		---	---			---						---		≧1.95	
	Fineness	Specific surface area	cm^2/g	---	---		---	---			---						---		≧4500	≧3000
		Percentage retained over 45µm sieve	%	12≧	30≧& ≧12.5	60≧& ≧30	25≧	25≧	35≧	50≧	12≧		25≧		45≧		---		10≧	40≧
	Activation index	7 days	%	≧80 (8days)	---			---			---						---		---	
		28 days	%	---	---			---			---						≧70		≧90	≧80
		91 days	%	---	---			---			---								≧100	≧90
	Ratio of flow value (Ratio of water content)		%	(95≧)	---			---			(95≧)		(105≧)		(115≧)		---		105≧	95≧
	Soundness	Expansion ratio by autoclave	%	---	---						---						---		---	
Other specified items				For structural concrete	For grout		*2: Relative strength > 105%				---						---		---	

*1: Japan Concrete Institute: Reduction in Shrinkage Cracks and Improvement of Durability in View of Admixture, Committee Report of the JCI, pp. 89-99, 2010

Figure 3. Source: “Guidelines for Control of Cracking of Mass Concrete 2016,” *Report JCI-R-001-2016*, Japanese Concrete Institute.