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Three simple tests for selecting low-crack cement

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Abstract

On projects involving restrained concrete such as bridge decks, the risk of cracking can be reduced by selecting low-crack Portland cement as was done with the Rudolphstein Bridge in Bavaria. A test, RILEM TC 119 TCE 3, was used to establish the cracking risk from thermal contraction and autogenous shrinkage [ACI Monograph 11 (1998)]. No equivalent ASTM test exists. The new drying shrinkage cracking test, AASHTO 34 98 is not directly applicable to the early-age cracking problem in bridge decks as this cracking is caused by thermal contraction and autogenous shrinkage.

This paper presents two methods, much simpler than the RILEM test, for estimating the cracking tendency of Portland cement: a 12-h semi-adiabatic compressive strength test, and a 12-h chemical shrinkage test. A simple drying shrinkage test using cement paste is also discussed.

It is concluded that the strength test and the chemical shrinkage test measures the thermal cracking tendency of Portland cement and can be used to select low-crack Portland cement for important projects involving restrained concrete. The tests, particularly, the chemical shrinkage test, should be considered for inclusion in the Standard Performance Specification for Hydraulic Cement, ASTM C 1157. This is important because the United States is experiencing more cracking problems than in some other countries such as Germany where it has been reported that bridge deck cracking is not a problem [ACI Monograph 11 (1998)]. They have coarser cements and limit the cement content.

Keywords: Bridge decks; Cement composition and fineness; Cracking; Durability; Strength; Test methods

1. Introduction

For many years, concrete tutorials in North America have recommended Type II cement for less cracking. However this once-good advice has become worthless because of the changes in Portland cement that have occurred over the years due to the failure to put maximum limits on early strength, fineness and C3S as has been done in some other countries (Fig. 1). Bryant Mather recommended this to the ASTM for North American cements in 1973 but was ignored. This neglect is a major cause of the deterioration of concrete according to Adam Neville [2].

When Type II cement is specified, one could be lucky and get a crack-resistant cement with a 7-day strength of 23 MPa, but one could also be unlucky and get a crack-prone cement with strength of 38 MPa (Fig. 2). Because of this problem, a new slow-hardening cement with a maximum 7-day strength of 23 MPa is being balloted by the ASTM. It is patterned after the best crack-resistant cements of 1954. Figs. 3 and 4 compare bridge decks built with the cement of 1954 with those built with modern cement. The excellence of the 1954 bridge is no fluke, as 164 other bridges built in Colorado in the 1950s have not been replaced by highway widening operations and these old bridges are still in excellent condition. The reinforcing steel was not coated with epoxy. The bridges are deiced but there is no evidence whatsoever of any problem with the corrosion of the reinforcing steel, even after almost 50 years. However, it is unrealistic to expect a quick resolution because of the scope of the proposed changes.

Concrete, in restrained applications like bridge decks, tends to crack if it gains strength too rapidly. This is because of the self-stresses from thermal contraction, autogenous shrinkage and drying shrinkage, coupled with a reduced creep capacity to relieve the self-stress.

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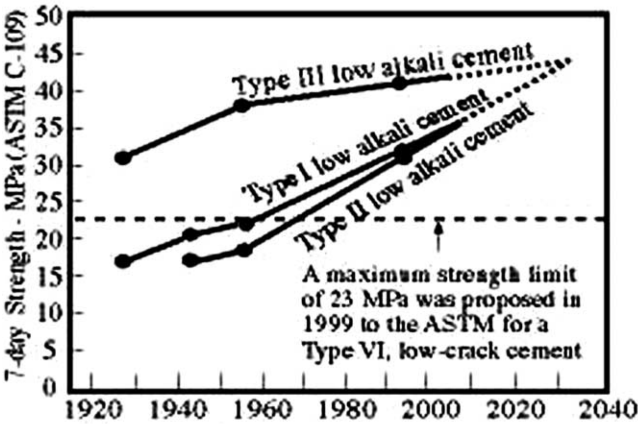


Fig. 1. The great change in the early strength of Portland cements due to uncontrolled increases in fineness and C3S. One fast-hardening cement by 2030? A disaster!

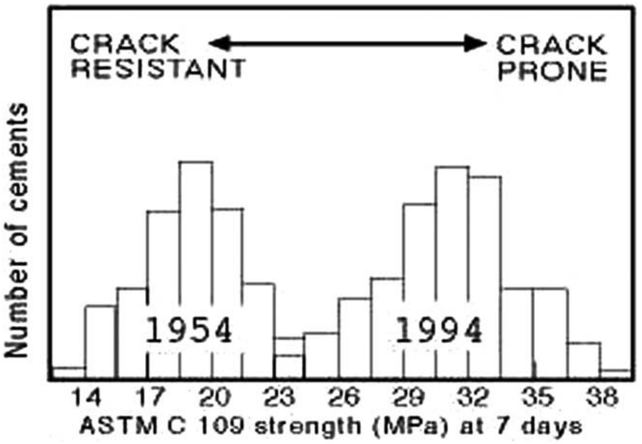


Fig. 2. The change in the early strength of Type II cements from 1954 to 1994.

Fig. 3. Cement X was a slow-hardening Portland cement typical of the low-crack North American cements of 1954. Some form marks, not cracks, are visible.

Fig. 4. Cement Y had the highest C3S + C3A of all the cements in North America in 1994—72%. High Strength concrete is not necessarily High Performance Concrete.

The higher modulus also contributes. As a general rule, materials become more crack-prone as they get stronger. This is true of metals, glass, and plastics—and also of concrete.

Concrete can be too quickly strong and brittle because of too much cement or because the cement hardens too rapidly. The problem of too much cement has been recognized by State Transportation Departments like Colorado and Maryland who are now limiting the cement content in bridge decks to around 326 kg/cu m (550 lb/cu yd). However, the hardening rate of the cement is even more important. According to the PhD thesis of Rolf Breitenbucher, increasing the water–cement ratio from 0.40 to 0.45 lowers the thermal contraction cracking temperature by 5 °C but changing from a fast-hardening Type II cement to a slow-hardening Type II cement lowers the cracking temperature by as much as 20 °C, a four times greater effect [3].

Problems with fast-hardening cement are beginning to receive attention. For example, Pierre-Claude Aitcin has written that, to avoid rheology (slump loss) problems in High Performance Concrete, the Portland cement should have low values of fineness, C3S and C3A [4]. He chooses his cements from the available Type V cements. Dale Bentz of NIST has recommended low-fineness cement for High Performance Concrete in order to reduce autogenous shrinkage stress [5]. At least 65 studies have shown that slow-hardening cement (low fineness, C3A, C3S, and alkalies) benefits both the early-age cracking problem and the long-term durability [6].

Aitcin wrote that the cement of the future will have to be more uniform and fulfill tighter requirements. He stated that changes must be made by the cement industry—an industry that for too long had only to pick up orders—an industry that has for too long been showing very little interest in concrete, which is its only market [4].

The new performance specification for hydraulic cement, ASTM C 1157 is encouraging but it lacks a performance test for cracking. It does however, have maximum limits on strength, such as 30 MPa at 7 days for Type GU (general purpose) cement. Since about two-thirds of all American Type I and II cements exceed this strength limit, fly ash would probably be added to bring the strength below 30 MPA. But a crack-prone cement will still be crack-prone after the fly ash is added. If one specified no fly ash, then the cement probably would not be supplied since a change in the clinker or coarser grinding would be involved.

2. RILEM TC 119 TCE 3

Before discussing the tests, it is necessary to review some of the findings from Rolf Breitenbucher's 1988 doctoral thesis at the Technical University of Munich [3]. His investigation was initiated in 1983 to explain the cracking of concrete in German highways. To investigate the problem, he developed the thermal contraction cracking test which has now been standardized as RILEM TC 119 TCE 3 (Fig. 5).

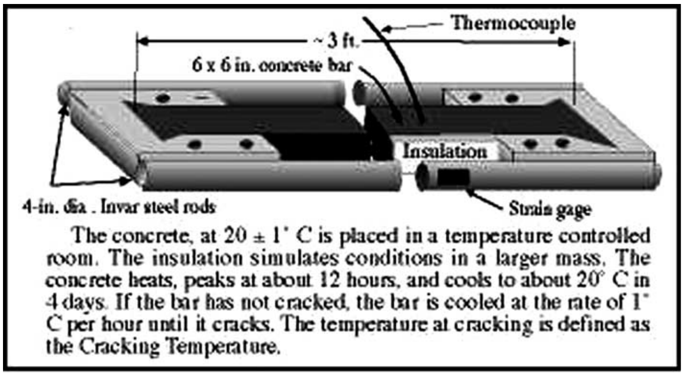
His work, partly summarized in Fig. 6, provides most of the information needed to solve the early-age cracking problem in bridge decks and other restrained concrete applications. The chart shows that the placing temperature is very important, stressing the importance of practices such as evening placements, cooling the materials, and cooling the concrete with wet mats for 24 h. For example, the Standard Specification for High Performance Concrete for the City of Montreal requires that the concrete be placed at night if the daily ambient temperature is expected to exceed 20 °C. It is interesting that this limit has been imposed even though the climate in Montreal is cooler than, say, Texas in the USA. It is not surprising that the High Performance Concrete in the Louetta Overpass Bridge in Texas cracked. The fresh concrete temperature was over 35 °C.

Fig. 6 shows that the composition and fineness of the cement are very important. A crack-resistant cement generally has low values of fineness, tricalcium aluminate (C3A) and soluble alkalies. The effect of changing the water–cement ratio is significant when the w/c is below 0.45 but less important at higher ratios as the autogenous shrinkage stress is relatively low. Fly ash is not effective in reducing the thermal cracking tendency. Some believe that thermal cracking can be eliminated by using fly ash, but the use of 20% fly ash failed to eliminate the thermal cracking in New York State's High Performance Concrete as would be expected.

Nor is blast furnace slag the answer. It performed poorly in testing at the University of Munich. It reduced the heat of hydration but the concrete cracked early because of the low tensile strength. Slag also increases the autogenous shrinkage because of the high fineness of the particles. It has also caused scaling and problems with plastic shrinkage cracking in Virginia. The very high fineness of silica fume also increases the cracking tendency by increasing autogenous shrinkage and the rate of strength gain.

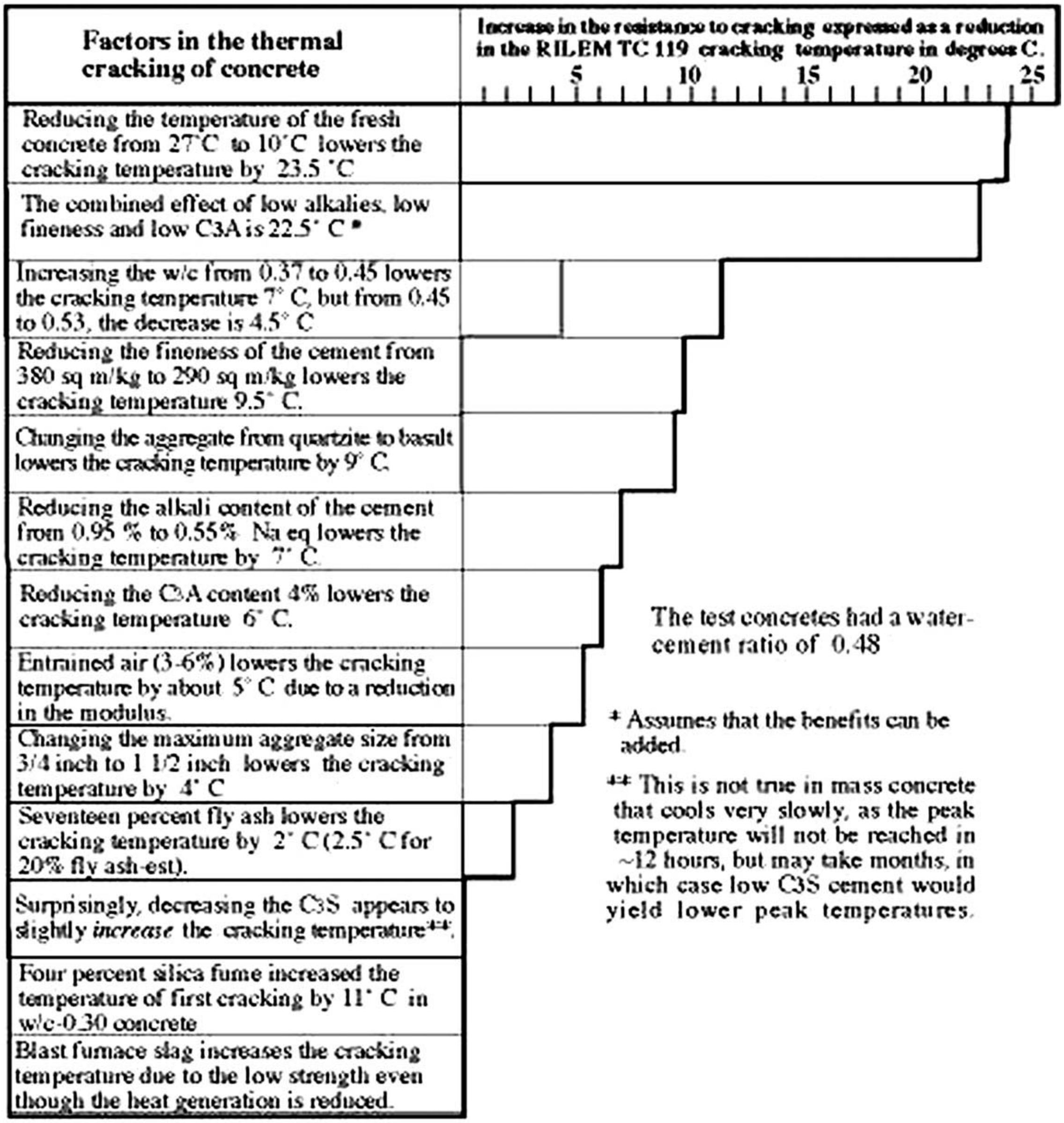
While the individual effects of alkalies, fineness, and C3A seem small, the cumulative effect can be large. A fine-ground, high-alkali cement with high C3A should certainly be shunned for restrained concrete applications like bridge decks. However, such cement is usually suitable for prestressed concrete as the prestressing prevents tensile stress and the resulting cracking.

Fig. 7 shows the strong influence of the alkalies and the weak benefit of fly ash. The soluble alkalies in cement, mostly potassium sulfate, dissolve in the mix water in the first few minutes and markedly accelerate the hydration reaction and the early strength gain as shown in Fig. 8. This causes higher peak temperatures as shown in Fig. 9. Some contractors prefer high-alkali cement as it provides more early strength for earlier form removal. However, the strength at 28 days is lower, reflecting the inferior CSH morphology that was first observed by Thaddeus Merriman in 1929 [7]. It has been found that an increase in alkali of 0.1% decreases the 28-day strength by 2%. Mori et al. attributed this to the



The concrete, at 20 ± 1° C is placed in a temperature controlled room. The insulation simulates conditions in a larger mass. The concrete heats, peaks at about 12 hours, and cools to about 20° C in 4 days. If the bar has not cracked, the bar is cooled at the rate of 1° C per hour until it cracks. The temperature at cracking is defined as the Cracking Temperature.

Fig. 5. Description of the thermal contraction cracking test RILEM TC 119 TCE 3, developed by Roll Breitenbucher.



Factors in the thermal cracking of concrete

Increase in the resistance to cracking expressed as a reduction in the RILEM TC 119 cracking temperature in degrees C.

Reducing the temperature of the fresh concrete from 27°C to 10°C lowers the cracking temperature by 23.5 °C

The combined effect of low alkalies, low fineness and low C3A is 22.5° C *

Increasing the w/c from 0.37 to 0.45 lowers the cracking temperature 7° C, but from 0.45 to 0.53, the decrease is 4.5° C

Reducing the fineness of the cement from 380 sq m/kg to 290 sq m/kg lowers the cracking temperature 9.5° C.

Changing the aggregate from quartzite to basalt lowers the cracking temperature by 9° C.

Reducing the alkali content of the cement from 0.95 % to 0.55% Na eq lowers the cracking temperature by 7° C.

Reducing the C3A content 4% lowers the cracking temperature 6° C.

Entrained air (3-6%) lowers the cracking temperature by about 5° C due to a reduction in the modulus.

Changing the maximum aggregate size from 3/4 inch to 1 1/2 inch lowers the cracking temperature by 4° C

Seventeen percent fly ash lowers the cracking temperature by 2° C (2.5° C for 20% fly ash-est).

Surprisingly, decreasing the C3S appears to slightly *increase* the cracking temperature**.

Four percent silica fume increased the temperature of first cracking by 11° C in w/c-0.30 concrete

Blast furnace slag increases the cracking temperature due to the low strength even though the heat generation is reduced.

The test concretes had a water-cement ratio of 0.48

* Assumes that the benefits can be added.

** This is not true in mass concrete that cools very slowly, as the peak temperature will not be reached in ~12 hours, but may take months, in which case low C3S cement would yield lower peak temperatures.

Fig. 6. Relative importance of the factors affecting the thermal contraction cracking of concrete in a bridge deck as derived from Roll Breitenbucher's doctoral thesis (1988).

alkalies causing lath-like C3S formations rather than the more desirable accicular (needle-like) structures [8]. Ramachandran et al. examined the fracture surfaces of cement pastes with the SEM and found the same thing [9].

Fig. 10 shows the influence of C3A on the peak temperature. Fig. 11 shows the rather surprising finding that increasing the C3S actually reduced the cracking temperature. This occurred because lower C3S produced higher peak temperatures as shown in Fig. 12. Breitenbucher concluded that the alkalies accelerate the early hydration reaction more in low C3S cements. However, low C3S cements are desirable in mass concrete as the cooling rate is much slower and the later-occurring peak temperature would be determined by the C3S, not the alkali content.

Fig. 13 shows the correlations between the cracking temperature and the 1-day and the 7-day strengths. At one day there was a crude correlation between strength and cracking tendency and at 7 days this correlation was reversed. There are probably two reasons for this reversal. Cements A, E, R, and Y were high-alkali cements and their inferior strength at later ages was becoming apparent. In addition, the longer term effect of the higher C3Ss on the strength is beginning to show up. However, at 12 h, there was a significant correlation between the strength and the cracking temperature, as shown in Fig. 14.

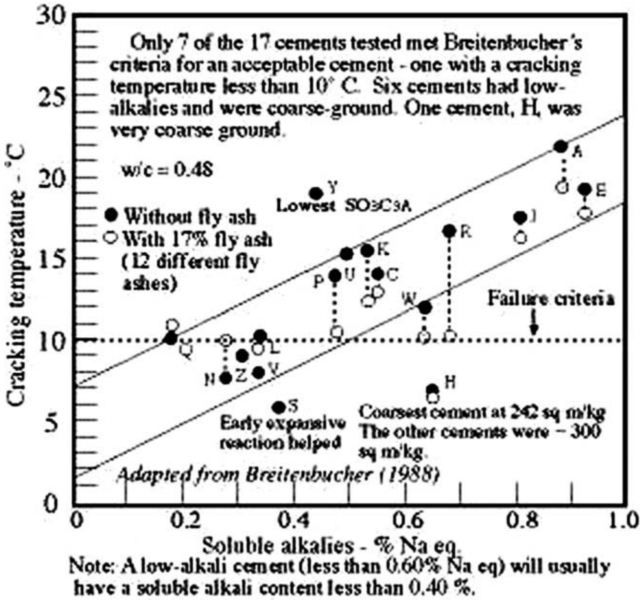


Fig. 7. Effect of alkalies, fineness, and fly ash on the thermal cracking of w/c—0.48 concrete.

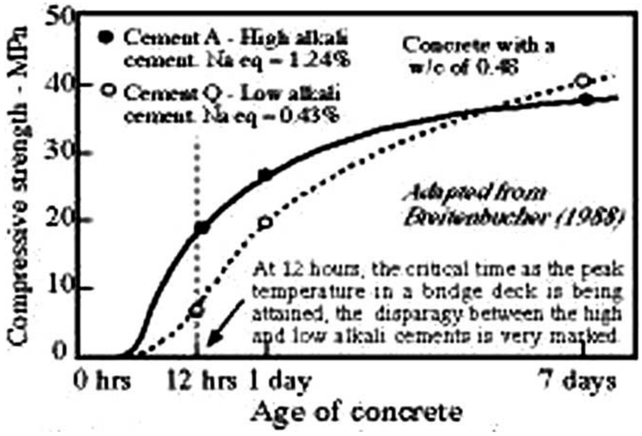


Fig. 8. The acceleration of the hydration reactions due to the alkalies produces much higher strengths (and temperatures) at the critical time of 12 h.

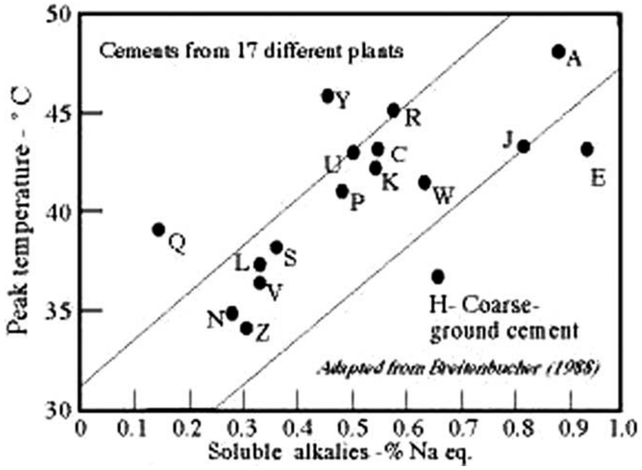


Fig. 9. Effect of alkalies on the peak temperature in a bridge deck.

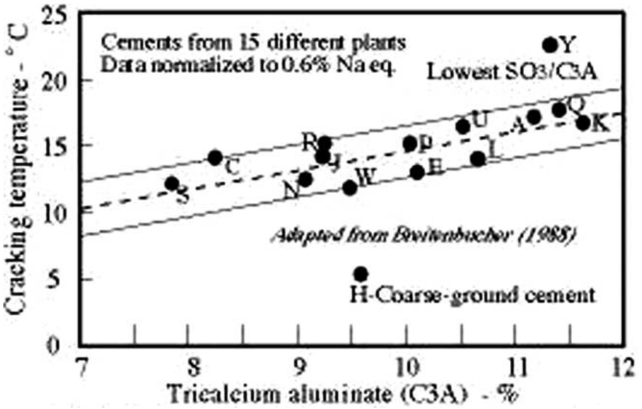


Fig. 10. Decreasing C3A by 4% lowers the cracking temperature by 6 °C.

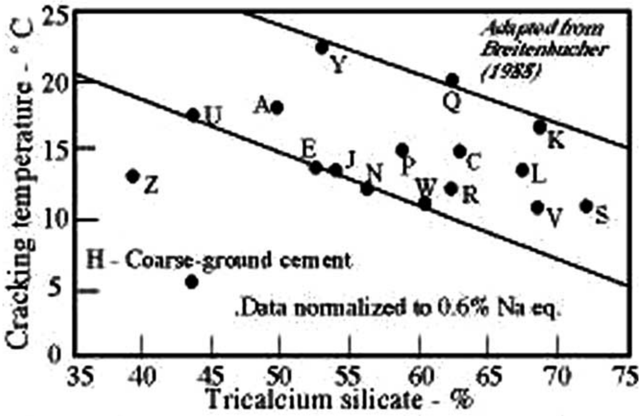


Fig. 11. The cracking temperature was negatively correlated to the C3S, an effect persisting only at 12 h.

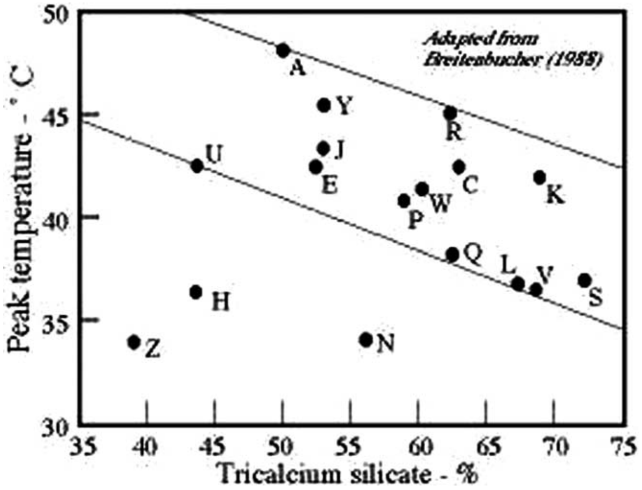


Fig. 12. Lower C3S resulted in higher peak temperatures causing Breitenbucher to theorize that the alkalies accelerate the hydration of C2S to a greater degree.

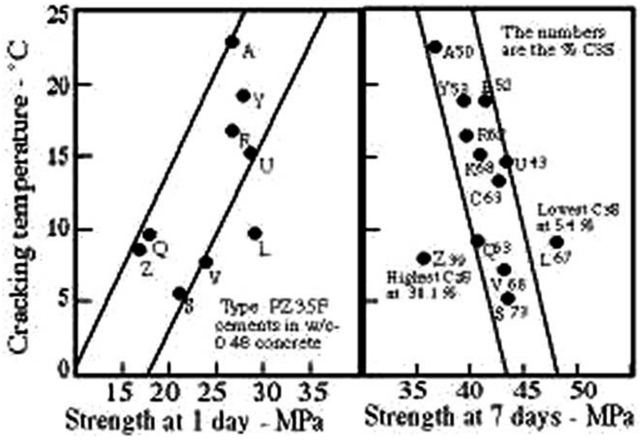


Fig. 13. Correlation of the cracking temperature with the semi-adiabatic strengths at 1 day and at 7 days.

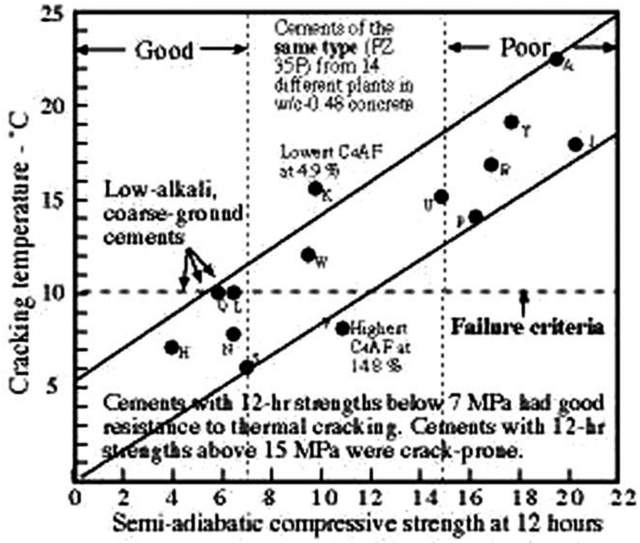


Fig. 14. Correlation of the cracking temperature with the semi-adiabatic strengths at 12 h.

3. The 12-h semi-adiabatic strength test

In a bridge deck, the risk of cracking from thermal contraction depends on the peak temperature that is attained just after placing. The peak temperature occurs at about 12 h and depends on the degree of hydration that has occurred at that time. This is the reason for measuring the semi-adiabatic strength (insulated mold) at 12 h. Breitenbucher's correlation between the 12-h semi-adiabatic strength and the cracking temperature is shown in Fig. 14.

The cement for the Rudolphstein Bridge in Bavaria was selected to have a cracking temperature less than 10 °C. In 17 cements tested by Breitenbucher, seven cements passed the test (American cements would fare less well). Fig. 14 shows that the cracking temperature equates to a 12-h semi-adiabatic strength less than 7 MPa. Using the criteria that the 12-h strength should be less than 7 MPa (∼1000 psi), this simple test passed the same cements as the complex and expensive RILEM TC 119 TCE 3 test with one exception, Cement V, which erred in the conservative direction. In performing the test, the initial temperature of w/c—0.48 concrete should be 21 °C. The specimen size should be at least a 152 × 304 mm (6 × 12-in.) cylinder (for lower heat losses) with the specimen cast in a paper or plastic mold that is insulated against rapid heat loss. This is necessary because the Breitenbucher data that was used to establish the above criteria was obtained using this semi-adiabatic condition to better simulate actual bridge deck temperatures.

Greg Sellers, at the University of Texas, conducted tests using both insulated molds (semi-adiabatic conditions) and non-insulated molds (semi-isothermal conditions) finding that the 12-h strength with uninsulated molds was 58% of the insulated molds in the case of slow-hardening cements but 80% in the case of fast-hardening cements. Because this ratio is not constant, it is necessary to conduct the semi-adiabatic test rather than doing the conventional uninsulated procedure and then attempting to convert the strength to the semi-adiabatic condition. Thus, it is postulated that a 12-h semi-adiabatic strength less than 7 MPa is indicative of a crack-resistant cement while a strength greater than 15 MPa indicates a crack-prone cement. If it is intended that a mineral admixture such as fly ash be blended with the cement, the cement should be first tested and selected without the presence of fly ash. The test is attractive because it is simpler, faster, and cheaper to conduct than RILEM TC 119 TCE 3.

4. Chemical shrinkage test

The 12-h semi-adiabatic strength is a measure of the degree of hydration (and heat) that has occurred at about the time that the bridge deck concrete has reached its critical peak temperature. There is yet another and even simpler way to measure this—a 12-h chemical shrinkage test. When Portland cement and water react, the volume of the hydration products is less than the original volume of the cement plus the water. Tazawa found that low chemical shrinkage is associated with low values of fineness, C3S, C3A, and alkalies [10]. These same parameters are closely associated with higher durability in terms of autogenous shrinkage, plastic shrinkage, thermal contraction, drying shrinkage, and also, the long-term durability [6].

The setup for the chemical shrinkage test is shown in Fig. 15. The University of Texas and the US Bureau of Reclamation performed the proposed Japanese Standard Test developed by Tazawa [10] which expresses the

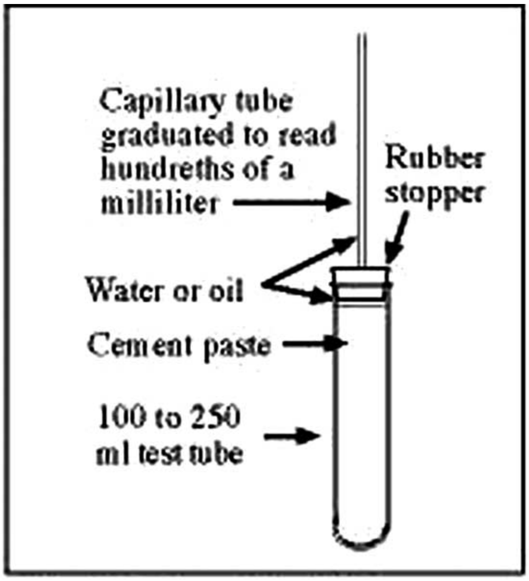


Fig. 15. Chemical shrinkage test.

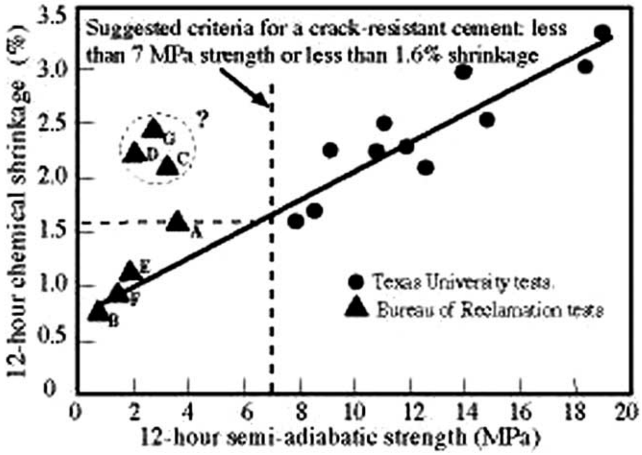


Fig. 17. Relationship between chemical shrinkage and strength.

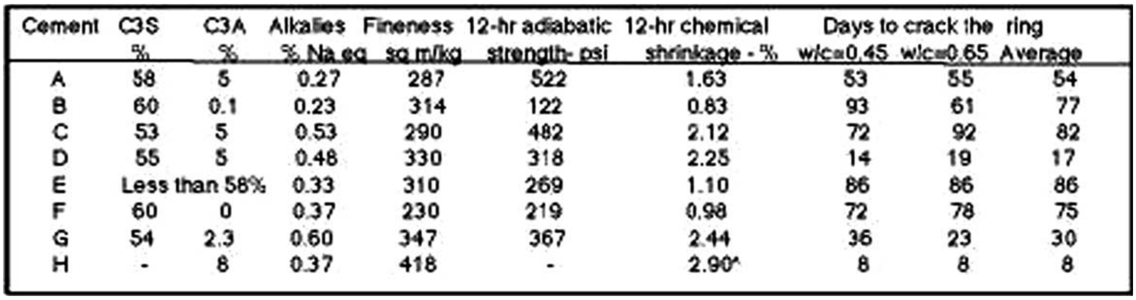
chemical shrinkage as the percent reduction in the volume of cement paste with a water–cement ratio of 0.50.

Recently, Dale Bentz of NIST proposed a chemical shrinkage test for an ASTM standard. It is similar except it advises keeping the temperature constant with a water bath and expresses the chemical shrinkage as the milliliters of water absorbed by one gram of cement. His test uses cement paste with a w/c of 0.40.

The characteristics of eight cements tested by the Bureau are shown in Fig. 16. The Bureau has been engaged in developing crack-resistant concrete for the thin repairs of their structures. These cements were specifically selected to be slow-hardening; that is, low values of fineness, alkalies, and C3A, characteristics which are most apt to be found in Type V and oil well cements. The characteristics of the eleven cements tested by the University of Texas, and additional test results will be shown in their report, now in preparation. Fig. 17 shows the correlation between the 12-h semi-adiabatic strength and the 12-h chemical shrinkage. The criterion for the crack-resistant cement selected for the Rudolphstein Bridge was a cracking temperature less than 10 °C. Taking this value as our goal, the value was shown to equate to a 12-h semi-adiabatic strength of 7 MPa. Fig. 17 shows that this, in turn, equates to a 12-h chemical shrinkage of 1.6% by volume of a w/c—0.50 cement paste. Thus, the chemical shrinkage test is a very simple tool that could be used to select low-crack cements. It is probably more reproducible than the strength test as it is so simple that few things can go wrong, unlike a concrete strength test with variables associated with bleeding effects and aggregate segregation.

Had the chemical shrinkage test been conducted under semi-adiabatic conditions, perhaps the correlation in Fig. 17 would have been even better. With a small sample of cement paste, such as 100 g, this would be difficult to do because of the rapid heat losses from the sample. This could be rectified by using a larger and insulated, sample such as 500–1000 g. Another approach would be to use a small sample warmed by a water bath at 45 °C to better simulate the bridge deck temperatures in the first 12 h. With such a test, the criterion of acceptance would be appreciably higher than 1.6%.

The USBR also conducted drying shrinkage cracking tests using concrete rings cast around a section of a 25 mm (1-in.) thick steel pipe stock 254 mm (10 in.) in diameter. The rings had an outside diameter of 318 mm (12.5 in.). They were moist cured for one day and the



Cement	C3S %	C3A %	Alkalies % Na eq	Fineness sq m/kg	12-hr adiabatic strength- psi	12-hr chemical shrinkage - %	Days to crack the ring		
							w/c=0.45	w/c=0.65	Average
A	58	5	0.27	287	522	1.63	53	55	54
B	60	0.1	0.23	314	122	0.83	93	61	77
C	53	5	0.53	290	482	2.12	72	92	82
D	55	5	0.48	330	318	2.25	14	19	17
E	Less than 58%		0.33	310	269	1.10	86	86	86
F	60	0	0.37	230	219	0.98	72	78	75
G	54	2.3	0.60	347	367	2.44	36	23	30
H	-	8	0.37	418	-	2.90^	8	8	8

Fig. 16. Cement properties and test results for the USBR tests.

cracking sensitivity was measured by the number of days to crack the rings when stored at 21 °C and 50% relative humidity. As shown in Fig. 18, the chemical shrinkage was also related to the cracking time due to drying shrinkage and again shows the superiority of slow-hardening cement to resist cracking. Another example is Fig. 19, from an NCHRP study [11]. Concretes with 21 cements were tested by the shrinkage ring test, AASHTO 34 98. The slow-hardening cement had high resistance to cracking. These results are consistent with the tests of Douglas and McHenry, Brewer and Burrows and R.L. Blaine, who all used the ring shrinkage test and found that coarse-ground, low C3A, low-alkali cement has superior resistance to cracking from drying shrinkage [1].

Detailed information about the ring test can be found in Jason Weiss' doctoral dissertation at North Western University [12].

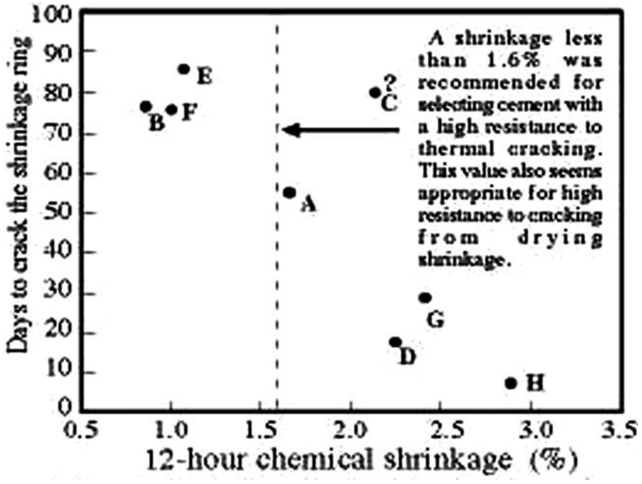


Fig. 18. The chemical shrinkage correlated with the cracking from drying shrinkage.

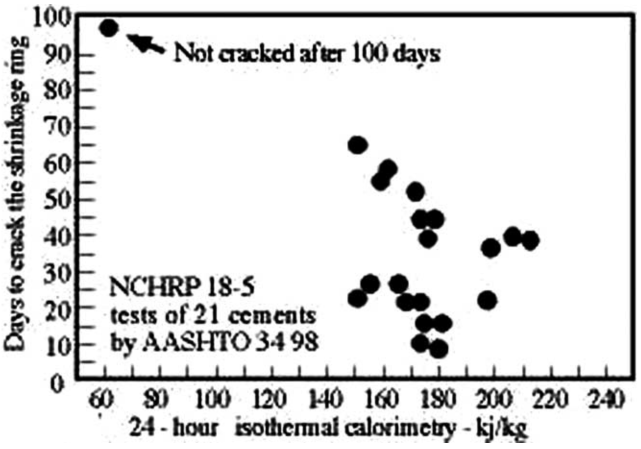


Fig. 19. The superiority of a slow-hardening cement.

The desired qualities for high resistance to cracking are most apt to be found in a coarse-ground, low-alkali Type V cement, unfortunately now quite rare in the Unites States. It is concluded that the chemical shrinkage test could be used to select Portland cement for concrete with a low tendency to crack under both the conditions of thermal contraction and drying shrinkage. If a cement with the desired low value of chemical shrinkage is not locally available, then the cement with the lowest shrinkage should be used for restrained concrete applications.

It has been recommended to ASTM Committee C1.10 that the chemical shrinkage test be considered as a performance test for low-crack cement for inclusion into ASTM C 1157 98a.

5. The drying shrinkage cracking of cement paste

Some believe that tests of cement paste are not relevant to concrete. In fact, R.L. Blaine's shrinkage ring tests of 199 cement pastes were discounted for this reason [1]. The test was once considered but never adopted as a RILEM test. One does not need a restraining ring, as a drying cylinder of paste made with a modern cement will crack merely from the restraint provided by the undried core. This was not the case with the old-fashioned cements. In 1910, Professor M.O. Withey, at the University of Michigan, exposed specimens of cement paste to outdoor weathering. After 10 years, when the tests were discontinued, the specimens had still not crumbled apart [13]. In 1950, the USBR found that only pastes made with coarse-ground cement did not crack (Fig. 20). In 1971, Gjorv and Shah subjected w/c—0.50 and w/c—0.70 cement pastes specimens to mild wetting

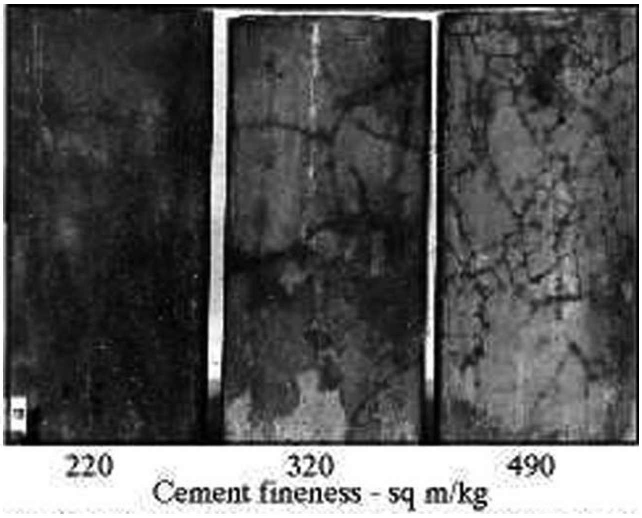


Fig. 20. There was little evidence of cracking with the coarsest ground cement.

and drying cycles and found that the w/c—0.50 specimens cracked sooner but all the specimens broke into pieces shortly after 15 cycles [14]. In 2000, the authors subjected cement pastes made from different cements to mild wetting and drying cycles. One cement broke apart after only two cycles (Fig. 21). These results are indicative of the changes in the fineness and the C3S content that has occurred in normal Portland cements from 1910 to 2000. Fineness has increased from 190 to 400 sq m/kg and C3S has increased from 29% to 57%.

In concrete, Portland cement is the glue that holds the rocks together. The ASTM has a standard weathering test for glue—ASTM D 1183. It consists of cycling between soaking in water at 21 °C and drying at 82 °C. Portland cement paste would be lucky to survive a single cycle. When incorporated into concrete, the concrete survives only because of the interruption of the cracks by the crack arresting effect of the aggregate particles so that many microcracks are formed rather than one macrocrack.

For the present investigation, a 152×304 mm (6×12-in.) cylinder of paste with a water–cement ratio of 0.45 was made from each cement, moist cured 21 days and then dried at 21 °C and 50% r.h. Fig. 22 shows the cracking at 50 days that was typical of the cements with chemical shrinkages over 2%. Fig. 23 shows Cement B with a chemical shrinkage of only 0.83%. Whereas Fig. 22 shows open cracks, Cement B (Fig. 23) had incipient (zero crack widths) cracks. The drying shrinkage had stretched the grain structure without actually cracking it. It would seem that this type of incipient cracking would be much more easily repaired by autogenous healing. It is perhaps relevant to mention that the cracking in cement paste of higher water–cement ratios tends to be less continuous and two investigators independently found that the autogenous healing capability is greater at higher water–cement ratios [15,16]. Coarse-ground cement also provides more capability for autogenous healing because of the presence of unhydrated cement particles.

Fig. 21. Broken cement paste after only two mild cycles of wetting and drying.

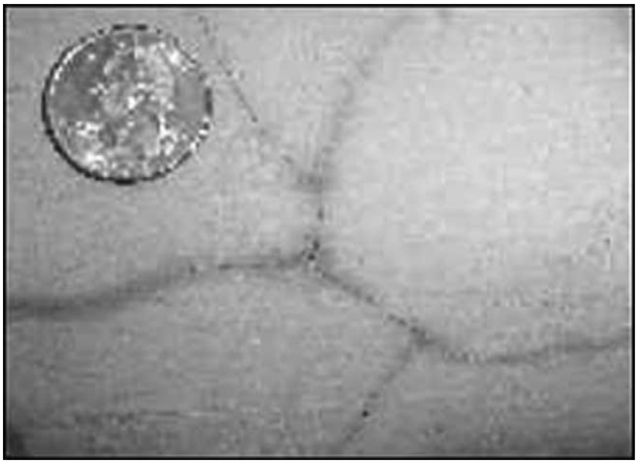


Fig. 22. Typical cracking of cements with 12-h chemical shrinkages from 2% to 2.5%.

Fig. 23. Incipient (closed) cracks in cement with a 12-h chemical shrinkage of 0.74%.

Fig. 24 is a Type III white cement from another investigation that had a high chemical shrinkage of 3.6% and which began to disintegrate after a single drying cycle. It was characterized by a fineness of 550 sq m/kg and a very low C4AF of 0.8%, features that Blaine found to be very conducive to cracking [1].

It is concluded that the test is a qualitative rather than a quantitative test for the cracking tendency of cement. It will differentiate between cements of low and high cracking resistance but differentiation in the range of the intermediate cements is imprecise because the subtle differences in the various crack patterns that occur are difficult to quantify.

It should be noted that the use of a short curing time such as one day would not have produced any cracking, an interesting phenomenon that was first observed by

Fig. 24. Disintegration of a Type III white cement with a chemical shrinkage of 3.5%.

Roy Carlson in 1942. The longer he cured his shrinkage rings, the sooner they cracked, an experiment that was later repeated by Douglas and McHenry. Other writers such as T.C. Powers, Bryant Mather, and Adam Neville have written that extended moist curing before drying makes concrete more crack-prone [1]. This is due to the loss of creep and the higher modulus. The greater amount of shrinkable gel and the fewer unhydrated particles to act as crack arrestors may also be factors. Despite this knowledge, 20 DOTs still believe that the bridge deck cracking problem can be mitigated by a longer period of moist curing.

6. Concluding remarks

There is a very wide variation in the cracking tendencies of concretes made with Portland cements of the same type from different plants. Because of the non-uniformity of cements of the same type, certain measures should be taken to avoid the inadvertent acquisition of a crack-prone cement on important projects where the cracking risk is high such as in cast-in-place bridge decks. Some State Departments of Transportation have reduced the cracking of bridge decks by reducing the cement content. However, Rolf Breitenbucher has shown that the cement composition and fineness play an even greater role. A low-crack cement is a slow-hardening cement, characteristically low in alkalies, fineness and C3A, properties more likely to be found in a Type V coarse-ground, low-alkali cement.

Such cements, available in some other countries, are difficult to find in North America. However, with important projects involving restrained concrete structures, it would be prudent to screen the available cements and select the most crack-resistant cement. Two test methods for accomplishing this are RILEM TC 119 TCE 3 (thermal contraction); and AASHTO 34 (drying shrinkage).

This paper recommended two other test methods that are simpler and more economical. Both are 12-h tests. This is because the temperature rise in the concrete in a bridge deck peaks at about 12 h and it is the magnitude of this temperature rise that determines the risk of cracking from thermal contraction.

6.1. 12-h chemical shrinkage test

For the Rudolphstein Bridge in Bavaria, a cement with a cracking temperature less than 10 °C was used as the criteria for a low-crack cement. The value of 10 °C was shown to correlate with a 12-h semi-adiabatic compressive strength of 7 MPa, which, in turn, correlated with a 12-h chemical shrinkage of 1.6% by volume of a w/c—0.50 cement paste. Because of the uncertainty connected with this two-stage correlation, the chemical shrinkage tests of M.A. Swayze and also of H. Justness et al. were studied [17,18]. Both of these studies indicate a somewhat lower value—1.3%. Therefore, this is the value recommended as the maximum 12-h limit for a low-crack cement. Dale Bentz's proposed ASTM chemical shrinkage test expresses chemical shrinkage in terms of the water imbibed by one gram of cement. In these terms, a low-crack cement would imbibe less than 0.0105 ml of water per gram of cement in 12 hours.

6.2. 12-h semi-adiabatic compressive strength test

This test is performed with 21 °C concrete with a water–cement ratio of 0.48. The mold is insulated so that the heat of hydration raises the temperature simulating a bridge deck. A strength less than 7 MPa indicates a crack-resistant cement. A strength more than 15 MPa indicates a crack-prone cement.

6.3. Observation of the cracking of cement paste from drying shrinkage

The same factors that contribute to a low risk of cracking from thermal contraction are about the same as those that provide a low risk of cracking from drying shrinkage—they are low values of fineness, C3A and alkalies. Although it was found that fast-hardening cements cracked more, this test is not recommended because the degree of cracking cannot be easily quantified numerically to establish a success/failure criterion.

6.4. ASTM C 1157

It is hoped that these tests, particularly the 12-h chemical shrinkage test will be reviewed by ASTM Committee C1.10 for possible inclusion in the specification as a performance test for cracking. This would be appropriate because of the prevalence of concrete cracking problems that are being encountered. The test should be employed on the Portland cement prior to any blending with fly ash, slag, or other materials because Breitenbucher showed that these materials will not overcome the cracking tendency of a crack-prone Portland cement. If fly ash is added to a crack-prone Portland cement, the blended cement will still be crack-prone even though it manages to pass the chemical shrinkage test.

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