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The effect of pozzolans and slag on the expansion of mortars cured at elevated temperature
Part I: Expansive behaviour

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Abstract

The expansive behaviour of heat-cured mortars containing pozzolans and slag was investigated. In most cases, the addition of any amount of these materials to the mixture typically reduced the long-term expansion, slowed the rate of expansion, and delayed the onset of expansion. However, the efficacy of a particular pozzolan or slag in controlling expansion may depend on its Al_2O_3 content. Metakaolin, which contains a high amount of reactive Al_2O_3, was the most effective at controlling expansion at relatively low cement replacement levels. Slag and fly ash, which are also sources of Al_2O_3, were also effective at suppressing expansion at higher replacement levels. Silica fume was less effective at controlling expansion at conventional replacement levels, and even at higher replacement levels expansion may only be delayed.

Keywords: Ettringite; Expansion; Metakaolin; Slag; Fly ash; Silica fume; Heat curing

1. Introduction

It has been observed that some cement products, when cured at elevated temperatures (above ~70 °C), may exhibit expansive behaviour if subsequently exposed to sufficient moisture at ambient temperature. The resulting expansion can lead to cracking of concrete resulting in loss of strength, a decreased service life, or other serviceability and durability problems. This manner of deterioration has been referred to as delayed ettringite formation (DEF) due to the prevalence of ettringite deposits found in the voids, cracks, and gaps around aggregate particles of the damaged concrete. DEF in field concrete, though uncommon, can be potentially costly, and precautions should be taken to avoid the problems associated it.

Although the DEF expansion mechanism has not been fully explained, it is generally understood that three things are essential to promote expansion: (1) exposure to elevated temperatures (above ~70 °C) during curing, whether deliberate or incidental, for a sufficient period, (2) subsequent exposure to moisture, and (3) a cement that has a potential for expansive behaviour when heat cured at excessive temperatures. Controlling or eliminating any one of these three elements may be adequate to prevent expansion.

While there have been some claims of DEF occurring in concrete cured at ordinary temperatures [1–3], in practice, the most effective method of controlling expansion is to avoid exposure to elevated temperatures during curing for a prolonged period of time. Moreover, the apparent role of elevated temperatures on the occurrence of DEF has led a number of countries to impose restrictions on the heat-curing process used in the manufacture of precast concrete [4,5]. These include limits placed on preset times, rates of heating and cooling, and the maximum allowable concrete temperature. However, the risk of damage from DEF is not necessarily limited to heat-cured precast concrete elements alone; internal concrete temperatures may rise above 70 °C, to levels sufficient to promote DEF, in massive cast-in-place concrete, due to the heat evolved from hydration, or in concrete that is placed under high external temperatures (i.e., hot weather). In such instances controlling the internal

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Table 1
Chemical composition (wt.%) and Bogue potential phase composition of the Portland cements used in this study

Cement	A	B
ASTM designation	Type III	Type III
SiO_2	20.2	18.7
Al_2O_3	4.91	5.51
TiO_2	0.28	0.26
P_2O_5	0.12	0.27
Fe_2O_3	2.17	2.75
CaO	62.5	61.5
SrO	0.09	0.33
MgO	2.38	2.64
Mn_2O_3	0.07	0.12
Na_2O	0.21	0.44
K_2O	1.04	1.03
LSO_3	4.34	4.47
LOI	1.69	2.03
Total	100.00	99.99
Na_2O soluble	0.12	0.23
K_2O soluble	0.87	0.85
Na_2Oe	0.90	1.12
SSB (cm^2/g)	5800	5320
C_3S	52.4	54.5
C_2S	18.4	12.4
C_3A	9.3	10.0
C_4AF	6.6	8.4

concrete temperature below 70 °C may not be possible, and other mitigative measures may be necessary.

There have been a number of attempts to relate expansion from DEF to cement composition [6–9], but no reliable correlation exists that can be applied to all cements. It is, however, apparent from laboratory studies that high-early strength cements have the greatest potential to exhibit expansive behaviour when heat cured at excessive temperatures. Consequently, it has been suggested that the risk of damage may be lessened to some extent by using cements that are low in SO_3, tricalcium aluminate, alkalis, MgO, and alite, and which do not have a high fineness. However, such cements are likely to have relatively slow early strength development and may not be particularly suited for precast concrete. Furthermore, controlling the cement chemistry does not necessarily eliminate the risk of expansion; Hobbs [10] concluded that, based on available data, a suitable choice of Portland cement composition does not preclude expansion in materials that have experienced temperatures above 70 °C.

It has been demonstrated that additions of slag, trass (a natural pozzolan), or fly ash can reduce the expansion of heat-cured mortars and concrete if used in sufficient quantity [11,12]. This could, in part, be due to the addition of Al_2O_3 present in these materials, though there are other effects of incorporating these materials that may also be beneficial. Despite these positive results, little work has been done since to better understand the mechanisms by which pozzolans and slag may suppress expansion.

This paper examines the potential mitigating effect that pozzolans and slag may have on the expansion of mortars cured at elevated temperature. The work presented here is part of an extensive study aimed at developing a fuller understanding of the role of supplementary cementing materials in controlling DEF. Data are presented for mortar prisms made from two ASTM Type III high-early strength cements, incorporating various amounts of silica fume, fly ash, high-reactivity metakaolin, and/or slag as a partial cement replacement, which were cured at elevated temperatures (up to 95 °C) and then stored in lime-saturated water at ambient temperature for as long as 4 years.

A subsequent paper will investigate the chemical and microstructural aspects of heat-cured mortars containing pozzolans and slag. In particular, pore solution extraction, X-ray diffraction and electron microscopy with energy-dispersive X-ray analysis was performed to help elucidate the role that these materials may have in controlling expansion.

2. Experimental

The chemical compositions of the cements, pozzolans, and slag used in this investigation are given in Tables 1–3. The Type III cements used in this study can be characterized as being relatively high in sulfate, alkali, C_3A content (as determined by Bogue calculations), and fineness. The silica fume that was used was in the form of an undensified powder. The high-reactivity metakaolin used was a commercially available grade made from Georgia (USA) kaolin conforming to ASTM C 618 as a natural pozzolan. The blast furnace slag used in this investigation was a ‘Grade 100’ slag ground to a specific surface area of 550 m^2/kg. Five Class C and two Class F fly ashes of fairly different chemical compositions were used in this study. Both of the Class F fly ashes had relatively low alkali and sulfate

Table 2
Chemical composition of silica fume, metakaolin, and blast furnace slag used in this study

	Silica fume	Metakaolin	Blast-furnace slag
SiO_2	95.52	52.06	35.55
Al_2O_3	0.15	45.29	9.42
TiO_2	0.01	1.64	0.83
P_2O_5	0.11	0.1	0
Fe_2O_3	0.04	0.6	0.48
CaO	0.3	0.05	38.02
SrO	0.01	0.1	0.01
MgO	0.15	0	11.01
Mn_2O_3	0.01	0.02	0.85
Na_2O	0.1	0.21	0.4
K_2O	0.75	0.16	0.44
LSO_3	0.22	0	3.50 *
LOI	2.11	0.51	– 1.69**
Total	99.48	100.74	100.51
Na_2Oe	0.59	0.32	0.69
Average particle size (μm)	0.45	< 2	9.9

* Mostly present as sulfide, but expressed as SO_3.
** 750 °C.

contents, as did the Class C fly ash, C1. Fly ash C2, C4, and C5 had fairly high sulfate contents. Fly ash C3 had a moderately high alkali content, while C5 had a very high alkali content. All of the fly ashes used in this study conform to the requirements of ASTM C 618.

ASTM standard 25 × 25 × 280-mm mortar prisms were cast at a water–cementitious ratio of 0.48 and a sand–cement ratio of 2.75. A standard 20–30 coarse quartz sand meeting the requirements of ASTM C 778 was used to prepare the mortars because it was reported to produce greater expansion in heat-cured mortars than graded sands [13]. Pozzolans and/or slag were incorporated as a partial cement replacement by mass. The metakaolin, slag, and fly ashes were dry blended with the cement prior to mixing. The silica fume was pre-slurried with a portion of the mix water using a high-shear mixer to aid in dispersion. The water content for all mixes was fixed, though a naphthalene sulfonate high-range water-reducer was used to adjust the flow of the mortars containing silica fume or metakaolin to within ±5 of the flow of the control mortars, which contained ordinary Portland cement alone as the binder.

Immediately after casting, the molds were sealed in polyethylene bags along with a small amount of water and placed in a test chamber capable of controlling temperature and humidity, and the mortars were heat cured. The heat-curing cycle that was used was based in part on a curing cycle used by Kelham [8], which incorporates some of the heat-curing restrictions found in several standards. It comprised a preset time of 4 h at 23 °C, followed by an increase in temperature at a rate of 20 °C/h until the maximum curing temperature of 60, 70, 80, or 95 °C was reached. The maximum temperature was maintained for 12 h, and then the specimens were cooled to 23 °C at a rate of 20 °C/h. The relative humidity was maintained at 100% throughout the heat curing. Following the heat-curing cycle, the specimens were demolded and subsequently placed in lime-saturated water for long-term storage at ambient temperature. Length measurements were taken periodically and expansion was determined as the average change in length of four prisms relative to the initial lengths measured at 1 day.

Table 3
Chemical composition of fly ashes used in this study

Fly ash	F1	F2	C1	C2	C3	C4	C5
ASTM classification	Class F	Class F	Class C	Class C	Class C	Class C	Class C
SiO_2	47.12	66.49	34.74	34.09	33.64	32.05	35.12
Al_2O_3	21.89	18.23	18.4	19.32	17.57	15.93	19.57
TiO_2	1.09	1.29	1.47	1.59	1.49	1.11	1.22
P_2O_5	0.31	0.04	1.98	0.8	1.26	0.56	0.59
Fe_2O_3	14.19	2.76	6.72	5.83	6.07	8.23	8.25
CaO	6.47	7.6	25.98	26.42	27.44	28.7	16.91
SrO	0.35	0.18	0.34	0.27	0.26	0.33	0.95
MgO	0.83	1.7	4.59	4.48	6.25	5.89	3.81
Mn_2O_3	0.06	0.06	0.03	0.06	0.03	0.23	0.04
Na_2O	0.63	0.33	1.72	1.77	2.48	0.64	6.52
K_2O	1.51	0.92	0.36	0.36	0.37	0.38	0.81
LSO_3	1.46	0.19	1.65	3.12	1.7	3.93	3.74
LOI	2.5	0.15	0.17	0.37	0.47	0.6	0.79
Total	98.41	99.87	98.15	98.44	99.03	98.58	98.29
Na_2Oe	1.62	0.94	1.96	2.00	2.72	0.89	7.05
Average particle size (μm)	20.5	16.0	13.7	12.7	10.3	12.1	12.6

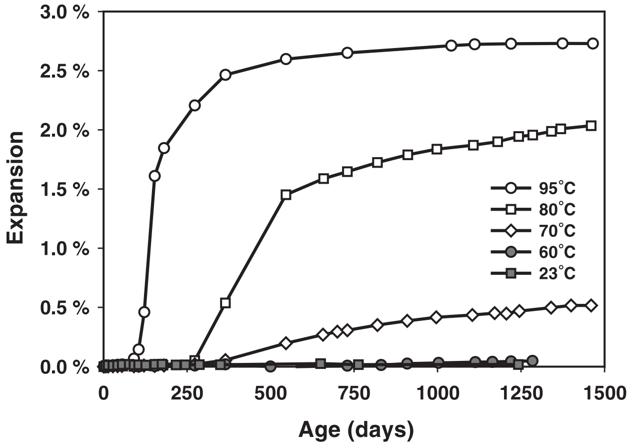

Fig. 1. Expansion of Portland cement mortars made with cement A cured at different temperatures.

3. Results

3.1. Expansion of Portland cement mortars

Figs. 1 and 2 show the expansive behaviour of mortars made with the Type III cements A and B when heat cured at maximum temperatures of 60, 70, 80, and 95 °C, as well as when continuously cured at 23 °C. There was a systematic increase of the ultimate expansion of mortars with increasing curing temperature. The mortars made with cement A expanded more than those made with cement B when cured at 95 °C, even though cement B had a higher sulfate and alkali content. At 80 °C, the expansion was similar with both cements, but at 70 °C, the mortars made with cement B expanded considerably more than those with cement A.[1] There was also some long-term expansion (~0.1%) of mortars made with cement B when heat cured at 60 °C. There was no appreciable expansion with the mortars cured at 23 °C after more than 3 years.

Expansion typically followed an S-shaped curve, which is perhaps characteristic for the test conditions used in this study. For mortars cured at 80 or 95 °C and subsequently stored in limewater, there was generally an induction period

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[1] It should be noted that while both of these cements exhibited expansive behaviour when cured at 70 °C, this is not typical of all cements. As part of a more extensive study by the authors, only two of more than a dozen Type I and Type III cements investigated demonstrated expansive behaviour at 70 °C. Moreover, while there is general agreement in the literature that ~70 °C is the threshold temperature, below which expansion does not occur, the actual temperature may be slightly higher or lower than 70 °C, depending on the cement composition [7].

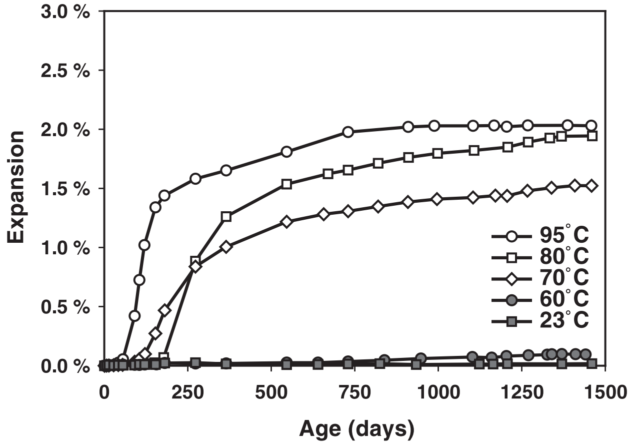

Fig. 2. Expansion of Portland cement mortars made with cement B cured at different temperatures.

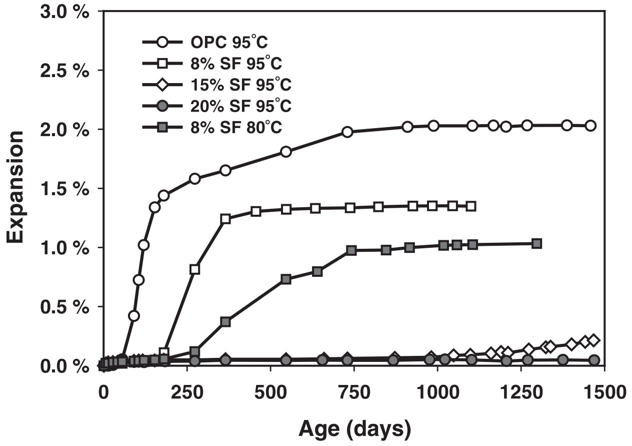

Fig. 4. Expansion of mortar bars made with cement B and silica fume (SF) heat cured at 80 or 95 °C.

of several months preceding a period of rapid expansion, which subsided beyond a period of 1–2 years. In most cases, the onset of expansion was sooner with mortars heat cured at higher temperatures, the exception being the cement B mortars cured at 70 °C, which inexplicably started to expand earlier than the 80 °C mortars.

3.2. Expansion of mortars with pozzolans and slag

Figs. 3 and 4 show the expansion evolution of mortar bars made with cements A and B, respectively, incorporating different levels of silica fume. At a replacement level of 8%, there was a reduction in the overall expansion of mortars cured at 95 °C, though there was still a significant long-term expansion of approximately 1.5% with both cements. The onset of expansion was delayed and the rate of expansion was slightly less compared to the Portland cement specimens. Although 15% silica fume was relatively effective at controlling expansion at 95 °C, beyond ~700 days of storage in limewater, the 15% silica fume specimens began to show signs of a slow, yet steady expansion, and expanded by almost 0.3% at 4 years. This might indicate that expansion is only prodigiously delayed with silica fume, though the significance of such a long-term expansion in this accelerated test on concrete under normal service conditions is uncertain. At a 20% replacement level, there was no significant expansion after more than 4 years. When heat cured at 80 °C, the 8% silica fume mortars expanded significantly with cement B, but not with cement A. However, with the later, expansion was ~0.09% at the last measurement and appeared to be increasing.

Mortars incorporating high-reactivity metakaolin did not expand appreciably at a replacement level of 8% or more, when heat cured at 95 °C with either cement A or B, after more than 4 years of storage in limewater. Although there was some expansion with these mortars (~0.02–0.04%), it generally occurred within the first 90 days after immersing the mortar bars in limewater and was greater with higher replacement levels. This was also observed with the silica fume mortars, and is thought to result from the uptake of water. The reduction in expansion with metakaolin was much greater than with similar levels of silica fume, which is somewhat similar in performance to metakaolin in many other respects. In particular, both silica fume and metakaolin will consume portlandite and bind alkalis through pozzolanic reaction, and both are capable of refining the paste pore structure, achieving a denser, less-permeable concrete [14]. This would indicate that the mechanism by which metakaolin suppresses or perhaps eliminates expansion is markedly different from that of silica fume and is distinct from mere pozzolanic reaction, though these effects may also be relevant.

The expansion of 95 °C heat-cured mortars made with cement B and 25% or 35% slag is shown in Fig. 5. The 25% slag mortars began to expand after about 600 days, and expanded by ~0.2% at ~1200 days. With 35% slag, the long-term expansion was only ~0.01%. Mortars made with cement A did not expanded appreciably (i.e., ~0.01%) with

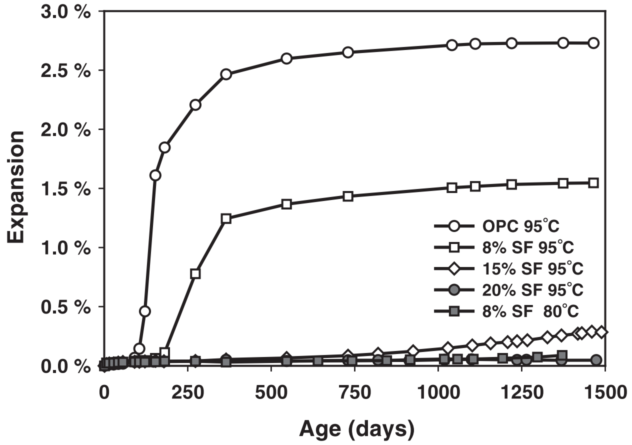

Fig. 3. Expansion of mortar bars made with cement A and silica fume (SF) heat cured at 80 or 95 °C.

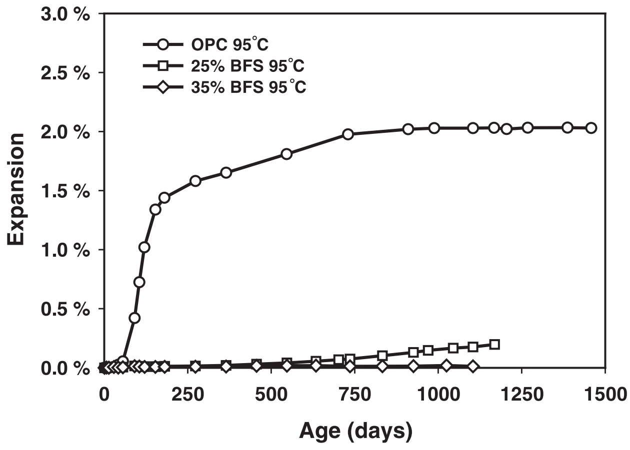

Fig. 5. Expansion of mortar bars made with cement B and blast furnace slag (BFS) heat cured at 95 °C.

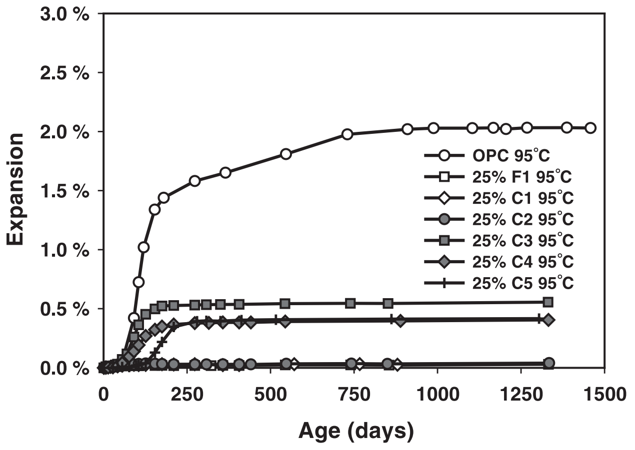

Fig. 7. Expansion of mortar bars made with cement B and 25% fly ash heat cured at 95 °C.

either 25% or 35% slag. Lower replacement levels of slag and lower curing temperatures were not investigated with these cements.

Figs. 6 and 7 show the expansion of 95 °C heat-cured mortars incorporating 15% fly ash with cement A and 25% fly ash with cement B, respectively. There was considerable disparity in the performance of the fly ashes. At a 15% replacement level, mortars with the high-lime Class C fly ash, C1, expanded by more than 0.8%. Mortars with the moderate lime Class C fly ash, C5, expanded less (i.e., ~0.3%), despite the very high alkali content and high sulfate content of the C5 fly ash. The Class F fly ashes were relatively more effective at controlling expansion than the Class C fly ashes at 15%, though there was still ~0.1% expansion with the 15% F1 mortars. Together, this might suggest that the effectiveness of a given fly ash at controlling expansion might depend greatly on its CaO content. With cement B, there was considerable expansion with 25% of the Class C fly ashes, C3, C4, and C5, but not with C1 (up to at least 800 days), or C2, or the Class F fly ash, F1. This may to a certain extent be due to the composition of the fly ashes. In particular, fly ash C4 and C5 had the highest sulfate contents of the ashes investigated, while fly ash C3 and C5 had the highest alkali contents. Fly ash C3 and C4 also had somewhat lower Al_2O_3 contents than the other ashes. With cement A, mortars with 25% of C3, C4, and C5 have not expanded more than ~0.1% after ~800 days of storage; data are not available for later ages. There was no notable expansion with 35% of any of the fly ashes after as much as 3 years, with either cement A or B.

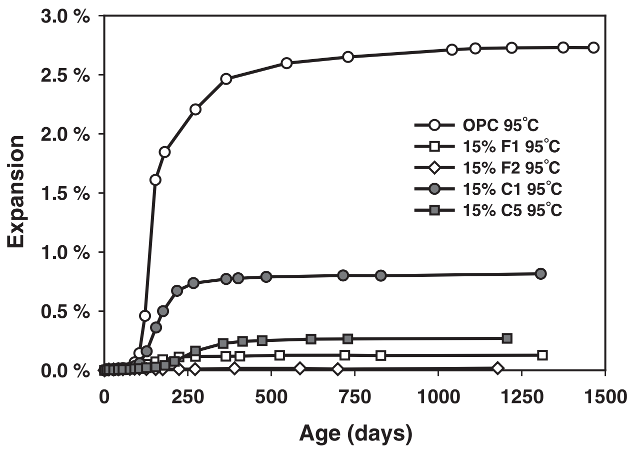

Fig. 6. Expansion of mortar bars made with cement A and 15% fly ash heat cured at 95 °C.

Although slag and fly ash may be fairly effective at controlling expansion, the relatively high replacement levels required might compromise early strength development, compared to concretes with either silica fume or metakaolin, or with cement alone as the only binder, which may not be favourable for precast concrete operations. However, ternary blends of slag or fly ash in combination with silica fume were found to be effective at controlling long-term expansion while still providing early strength. The idea being that a sufficient amount of slag or fly ash is incorporated to control expansion and a small amount of silica fume (or possibly metakaolin) is included to increase the early strength. The actual amount of slag or ash required to control expansion, when used in combination with silica fume, may even be less than is required if the slag or ash were used alone. For example, 95 °C heat-cured mortars made with cement B incorporating 20% of the Class C fly ash, C5, and 5% silica fume expanded by only ~0.03% after almost 3 years, whereas with 25% of the C5 fly ash alone, the long-term expansion was more than 0.4%. Moreover, ternary-blended cementitious systems have other additional benefits for the long-term durability of concrete [15,16].

4. Discussion

It has been reported that if Portland cements are hydrated at sufficiently high temperatures, the normal formation of ettringite does not occur [17,18]. This results in a prolonged high concentration of sulfate in the pore solution throughout the heat treatment. It has also been reported that a significant amount of sulfate enters the inner C–S–H product that forms during heat treatment, the extent of which increases with temperature [19–21]. This uptake of sulfate has been described as an adsorption phenomenon, such that desorption of sulfate from the inner C–S–H can occur after some time under certain conditions. This sulfate can then react with monosulfoaluminate that is intermixed throughout the outer C–S–H to form ettringite, which can result in a loss of dimensional stability.

Early work by Brown and Bothe [17] indicated that a reduction in the pH of the pore solution should result in the precipitation of ettringite and removal of sulfate from solution. More recently, Famy [21] demonstrated that a decrease in the pore solution pH, caused by the leaching of alkalis, instigates the desorption of sulfate from the inner C–S–H, probably because as the pH is reduced and sulfate is removed from the bulk pore solution, a concentration gradient occurs between the sulfate in the pore solution and the sulfate adsorbed in the inner C–S–H. More importantly, Famy [21] also demonstrated that if the leaching of alkalis from the pore solution is reduced, the sulfate tends to remain in the C–S–H, and expansion is inhibited. This could partly explain why silica fume seems to delay the onset of expansion and lower the rate of expansion. In particular, silica fume will produce a denser and less-permeable paste pore structure that will reduce the rate at which the alkalis are leached out of the pore solution during storage, although these benefits may not be realized in cracked concrete. However, as mentioned, metakaolin is also capable of refining the paste pore structure and should similarly reduce the rate at which the alkalis are leached from the pore solution. However, while the 8% silica fume mortars expanded, the 8% metakaolin specimens did not. This disparity in performance would suggest that the efficacy of a pozzolan or slag at controlling expansion from DEF is related to its Al_2O_3 content.

Although no reliable correlation has been found relating expansion to chemical composition, early work showed a general trend that the potential for expansion increased with the SO_3/Al_2O_3 molar ratio [6], beyond a certain threshold level. Later work [22] indicated rather that there might be a pessimum SO_3/Al_2O_3 ratio for which expansion occurs. Taylor et al. [23] explain the occurrence of this pessimum as follows: if there is no SO_3, ettringite cannot form, and if there is too much SO_3, ettringite may persist at elevated temperatures, and the amount formed during subsequent storage may be less. In addition, if there is no Al_2O_3, ettringite will not form, and if there is too much Al_2O_3, monosulfoaluminate rather than ettringite will form. The specific value of this pessimum SO_3/Al_2O_3 ratio is not necessarily universal for all cements, but the majority of Portland cements are probably on the low-SO_3, high-Al_2O_3 side of the pessimum [23], such that anything that binds Al_2O_3, effectively increasing the SO_3/Al_2O_3 ratio, may increase expansion. This could explain why cements with high MgO contents are more susceptible to expansion, since MgO can bind Al_2O_3 in a hydrotalcite-type phase [8]. Conversely, this implies that anything that increases the availability of reactive Al_2O_3 may therefore reduce expansion by effectually moving the SO_3/Al_2O_3 ratio away from the pessimum. This could partly or wholly explain why certain pozzolans, such as metakaolin or fly ash and slag, which are sources of additional Al_2O_3, are effective at reducing or eliminating long-term expansion.

It follows that materials with lower Al_2O_3 contents would be less efficient and that a greater quantity may be required to control expansion. It should also be mentioned that not all of the Al_2O_3 present in pozzolans and slag is necessarily available to form sulfoaluminates; some Al_2O_3 may be present in nonreactive phases such as mullite [24], while some may enter other phases such as hydrogarnets or strätlingite [25]. Furthermore, the amount of a particular pozzolan or slag (i.e., additional Al_2O_3) required to control expansion will also depend on the chemical composition of the cement (e.g., the SO_3/Al_2O_3 ratio or the SO_3 and alkali contents), as well as the composition of the pozzolan or slag itself. In particular, the performance of fly ash may be highly variable depending on its calcium, sulfate, and alkali contents, apart from its Al_2O_3 content. Furthermore, the fineness of the material is probably important in determining the rate at which Al_2O_3 becomes available for reaction. It should also be said that the levels of pozzolans or slag, which are required to control expansion, presented in this paper may not necessarily be applicable to cements that have markedly different chemical compositions from those used in this investigation.

There are other effects of incorporating pozzolans or slag into mortars or concrete that may also be beneficial in reducing expansion, such as the consumption of portlandite and reduction in pore solution alkalinity. The solubility of ettringite is affected by the concentration of both alkalis and Ca^{2+} in the pore fluid, and any modification to these concentrations may effect the early formation of ettringite or monosulfoaluminate. In particular, the presence of K^+ in the pore fluid has been shown to inhibit the formation of ettringite, allowing sulfate to enter the inner C–S–H that is formed [17]. Thus, a reduction in the pore solution alkalinity by incorporating pozzolans or slag might adventitiously lower the concentration of SO_4^{2-} present in the pore fluid, such that the uptake of sulfate by the inner C–S–H during heat curing may be reduced. However, this is not entirely consistent with the performance of the 8% metakaolin and 8% silica fume mortars, the latter expanding significantly at 95 °C, even though both mortars might be expected to have lower pore solution alkalinity and perhaps also lower pore solution sulfate ion concentrations compared to the heat-cured Portland cement mortars. It is more likely that high concentrations of sulfate exist in the pore fluid during heat treatment, and a significant amount of sulfate is still adsorbed by the C–S–H with or without the incorporation of pozzolans or slag. The addition of Al_2O_3 with these materials may be more important than the reduction in pore solution alkalis and sulfate concentrations, possibly because it affects the formation of the sulfoaluminate phases either during curing or at later ages. This will be discussed further in a subsequent paper.

5. Conclusions

1. At the conventional replacement levels used in concrete (i.e., ~8%), silica fume was not effective at controlling long-term expansion related to DEF when heat cured at high temperatures. The onset of expansion may only be delayed as a result of the lower permeability of the silica fume mortars.
2. Metakaolin is effective at suppressing or perhaps even eliminating long-term expansion at relatively low levels (8% or more), when used as a partial replacement for a cement that exhibits expansive behaviour when heat cured. This is attributed to the high content of Al_2O_3 in the metakaolin.
3. Blast furnace slag may also be able to control expansion if used in sufficient quantity. A replacement level of 25% may suppress long-term expansion with most cements, but higher levels may be required when used with cements having very high sulfate or alkali contents.
4. Fly ash may be effective at controlling expansion, though the quantity required to suppress expansion may depend on its composition. Low-lime fly ashes appear to be more effective at lower replacement levels (i.e., 15–25%), while high-lime fly ashes may be effective at higher replacement levels (i.e., 25–35%). The sulfate and alkali content of the ash may also be important.
5. Although fly ash and slag may control expansion, the high replacement levels required might compromise the early strength development of the concrete, which may make them unsuitable for precast concrete. This effect may be offset by incorporating a small amount of silica fume (e.g. ~5%), to increase the early strength development, in addition to a sufficient amount of slag or fly ash to control expansion.

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