THE EFFECT OF DRYING ON REACTIVE AGGREGATE AND MORTAR EXPANSIONS

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SYNOPSIS

The paper discusses the fact that most testing to date has been under conditions of constant humidity and examines the effect of repeated wetting and drying on the expansion performance of concrete made with expansive aggregates.

SAMEVATTING

In die referaat word die feit bespreek dat toetse tot op hede meestal in toestande van konstante humiditeit uitgevoer is en die uitwerking van herhaalde benatting en droging op die uitsettingsgedrag van beton wat met uitset-aggregate gemaak is, word ondersoek.

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1. Summary

Since moisture absorption by reacted aggregate particles is a factor which largely determines the extent of expansion and disruption induced in mortar and concrete, it has become normal practice to maintain test specimens in moisture saturated atmospheres for their entire test period. When specimens are subjected to intermittent drying in low humidity and re-wetting in moisture saturated atmospheres, their expansion performance indicates the type of behaviour that can be expected of concrete which is subjected to normal environmental conditions and emphasises the difference between the shrinkage and expansion movements.

2. Introduction

Although the significance of maintaining a large free moisture content in mortar and concrete test specimens has long been recognised, and the function of moisture in promoting volume increases in reacted particles and in the expansion of mortar and concrete has been demonstrated by Vivian (1950), the effect of changing moisture content on these expansions has not been studied extensively. It has been generally accepted that expansion tests should be carried out on specimens stored continuously in a moisture saturated atmosphere. Under these conditions, as they absorb water, reacted aggregate particles undergo physical changes concomitantly with their volume increases. Changes in moisture content directly affect the volume of hardened cement paste and reacted aggregate particles and indirectly affect the overall expansion of specimens by modifying the deforming tendencies of reacting particles and consequently changing their capacity to transmit expansive forces to the surrounding concrete. The dimensional changes of concrete are therefore compounded from all these simultaneous movements.

The purpose of the present paper is to indicate the order of magnitude of the various shrinkage and expansion movements and to discuss the effect of intermittent drying on expansion measurements, expanding aggregate particles and the permanent physical changes induced in mortar and concrete.

3. Experimental

Mortar specimens were made from an ordinary portland cement containing 0,09% Na_2O and 0,45% K_2O and aggregate consisting of 95% quartz sand from Leighton Buzzard and 5% by mass of opaline rock (V17) from Butcher's Ridge, East Gippsland, Victoria. The alkali content of these mortars was increased by the addition of sodium hydroxide dissolved in the mix water and ranging from 1 to 10 per cent by mass of the cement. Cement and aggregate were mixed in the proportion 1:2 by mass and the water/cement ratio was 0,5 by mass for all specimens.

Two series of specimens were made. Series 1 was demoulded after 24 h, measured and then stored at ambient temperatures in a sealed moisture saturated container for (a) 1 month, (b) 5 months, and (c) 3½ years. After these initial storage times in moisture saturated air; the specimens were dried at ambient temperatures and humidities for various periods of time and were then returned to moisture saturated air storage. Series 2 specimens, when demoulded and measured were (a) dried immediately in air at ambient temperature and humidity, (b) stored in moisture saturated air for 1 week and then dried in air at ambient temperature and humidity for 1 week and (c) stored in moisture saturated air for 5 weeks and then dried in air at ambient temperature and humidity for 1 week. After the initial drying treatments specimens were returned to the moisture saturated environment. Series 2 specimens were also weighed to identify the changes which resulted from storage under dry and moist conditions.

Table 1 records the length changes and Table 2 both length and mass changes of Series 1 and Series 2 mortar specimens respectively and their storage times in moisture saturated air and under drying conditions. The mass changes recorded in Table 2 are resultants which represent losses in the free water content of specimens and gains in the amount of carbon dioxide absorbed from the atmosphere. The mass losses were generally greater for specimens which were dried initially after a minimum curing time in moist air and were generally reduced as the amount of added sodium hydroxide was increased. Curing in moist air promoted hydration reactions and the combination of free water with clinker compounds on the one hand and the loss of free water by evaporation as the temperature of the specimen increases as a result of the exothermic hydration reactions on the other. Sodium hydroxide tends to reduce mass loss by absorbing carbon dioxide in proportion to its concentration. Apart from the effects of alkalis and the reactivity of the aggregate the magnitude of mortar or concrete expansion is clearly influenced by storage conditions and the availability of moisture.

4. Discussion

Although the expansion of these specimens is very variable, they indicate the changes that are induced by different storage conditions. The early onset of drying reduces or inhibits the alkali aggregate reaction and thus limits the amount of expanding aggregate in the mortar or concrete. Moreover although the decreased amount of available free water reduces aggregate expansion, the expansive characteristics range from rigid (less hydrous) to a deformable (more hydrous) gel or ultimately to a sol condition. It is clear that aggregate reaction and expansion can be arrested by removing water at an early age from mortar or concrete. The expansion of mortar and concrete will also be inhibited as long as resorption of water or water vapour is prevented. If a sufficiently large quantity of water or water vapour is reabsorbed by the mortar or concrete, the soluble alkalis will further attack the reactive aggregate and the reaction product will swell and disrupt the mortar or concrete.

When free water is removed from mortar or concrete after the aggregate reaction has begun and caused some mortar or concrete expansion, the disruption caused by the swelling particles is irreversible and cannot be eliminated. The major portion of the overall expansion of mortar or concrete is

TABLE 1 : Expansion of mortar specimens which contained different amounts of added sodium hydroxide when stored for various times in moisture saturated air (MSA) and under drying conditions

Storage condition and exposure time	Percentage expansions of specimens which contained the following percentages of sodium hydroxide				
	Nil	1%	2%	5%	10%
MSA (1 Mo)	- 0,02	0,03	0,05	- 0,04	0,20
Drying (1 Mo)	- 0,10	- 0,06	- 0,06	- 0,12	- 0,11
MSA (1 Mo)	0,03	0,37	0,19	- 0,06	3,02
Drying (1 Mo)	- 0,04	0,26	0,09	- 0,17	2,46
MSA (1 Mo)	0,05	0,43	0,20	- 0,09	2,69
Drying (1 Mo)	- 0,01	0,33	0,10	- 0,20	2,45
MSA (1 Mo)	0,07	0,46	0,22	- 0,13	2,54
MSA (7 Mo)	0,26	0,81	0,34	- 0,07	2,61
Drying (1 Mo)	0,18	0,70	0,22	- 0,15	2,43
MSA (3 Mo)	0,26	0,79	0,32	- 0,11	2,55
MSA (12 Mo)	0,43	0,92	0,33	- 0,04	2,62
MSA (33 Mo)	0,95	1,05	0,45	0,08	2,73
Drying (2 Mo)	0,82	0,92	0,28	- 0,07	2,62
MSA (1 Mo)	0,93	1,02	0,38	0,01	2,70
MSA (6 Mo)	1,05	1,03	0,43	0,13	2,72
MSA (5 Mo)	0,41	0,35	0,22	0,05	0,30
Drying (1 Mo)	0,34	0,27	0,13	- 0,04	- 0,02
MSA (1 Mo)	0,43	0,37	0,18	- 0,01	0,11
Drying (1 Mo)	0,36	0,28	0,07	- 0,15	- 0,20
MSA (1 Mo)	0,53	0,44	0,18	- 0,09	- 0,07
MSA (7 Mo)	0,60	0,50	0,22	- 0,02	- 0,05
Drying (1 Mo)	0,49	0,39	0,11	- 0,14	- 0,21
MSA (3 Mo)	0,57	0,47	0,19	- 0,08	- 0,12
MSA (12 Mo)	0,61	0,50	0,23	- 0,01	- 0,10
MSA (33 Mo)	0,73	0,67	0,42	0,79	0,08
Drying (1 Mo)	0,58	0,51	0,25	0,49	- 0,22
MSA (1 Mo)	0,66	0,60	0,33	0,57	- 0,15
MSA (6 Mo)	0,71	0,66	0,42	0,90	- 0,13
MSA (1 Mo)	0,01	0,01	0,03	0,04	0,18
MSA (6 Mo)	0,44	0,47	0,25	0,15	0,28
MSA (12 Mo)	0,62	0,70	0,29	0,18	0,31
MSA (24 Mo)	0,62	0,69	0,28	0,15	0,28
MSA (42 Mo)	0,63	0,83	0,30	0,17	0,29
Drying (2 Mo)	0,50	0,59	0,17	- 0,07	- 0,03
MSA (1 Mo)	0,59	0,68	0,23	0,02	0,05
MSA (6 Mo)	0,60	0,70	0,28	0,06	0,06

permanent because movements are caused by the development and widening of cracks which produce marked displacements and which become partly filled with incompletely deformable, mobile reaction product. Although drying inhibits aggregate expansion and induces shrinkage movements in the hydrated cement paste, the overall shrinkage is relatively small compared with the expansion. When water is resorbed by the mortar or concrete, the hydrated cement will undergo a limited swelling recovery while the reacted aggregate particles can undergo excessive swelling which will be partly translated into additional mortar or concrete expansion.

The presence of very large amounts of alkali accelerates aggregate reaction and water absorption. The surface zone or, if particles are small, the entire particle, converts rapidly from a swelling rigid gel to a deformable gel and finally to a sol. In some instances the surface zone of aggregate particles may undergo these changes before the core of the particle reacts and commences expanding. Under these conditions the deforming gel or sol, which continues to absorb water, moves into spaces contiguous with the original particle surface and those in the cement paste without causing large mortar or concrete expansions. Early drying of such specimens can delay the rapid conversion of rigid gel to deforming gel or sol and, if followed by slow resorption of water vapour, large mortar or concrete expansions may occur. Late drying of such specimens merely dries the dispersed reaction products which cannot develop damaging expansions when allowed to resorb water vapour.

At late ages the expansion increments of all mortars and concretes may be diminished for reasons other than exhaustion of the supply of one of the major reactants. The swelling aggregate particles by producing cracks in mortar or concrete create space which can accommodate large volumes of deformable gel or sol without undergoing further change. In addition the deforming gel or sol comes into contact with an increasingly large amount of hydrated cement paste and can react with calcium hydroxide to form a non-water absorbing, non-swelling calcium hydroxide-silica complex.

5. Conclusions

(a) Overall measurements of mortars and concretes are the summation of volume changes which occur in hydrated cement paste and those which are produced by reacting aggregate particles. Hydrated cement paste may undergo negligibly small shrinkage or expansion movement when stored continuously in moisture saturated air. The magnitude of the drying shrinkage movement of hydrated cement paste in mortar or concrete is very small compared with the expansion movement produced by reacting aggregate particles.

(b) Although drying induces a limited shrinkage in hydrated cement paste and inhibits the expansion of reacted aggregate particles, moisture re-sorption reverses both processes. On resorbing moisture, hydrated cement generally expands by amounts slightly less than or equivalent to the magnitude of the initial shrinkage while reacted aggregate particles resume their excessive swelling tendencies and, provided their non-deforming properties are maintained, will further increase the overall mortar or concrete expansion.

(c) In the presence of large amounts of alkali and free water, aggregate particles not only react rapidly but the reaction product also transforms very rapidly from a rigid gel which expands and disintegrates mortar and concrete to a deformable gel or to a sol which cannot cause expansion.

(d) Mortar and concrete expansions are caused by the lengthening and widening of cracks. Displacements induced within the mass, and the presence of the reaction product in cracks, ensure that expansion is permanent and that damage is irreparable.

REFERENCE

1. VIVIAN H E *Studies in Cement-Aggregate reaction*. Bull. No. 256, p. 21, Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia, 1950.

DISCUSSION

Note by editor: The comments on fly-ash (pulverised fuel ash) are in response to remarks made by the author on the subject while delivering his paper. These do not appear in the written presentation.

Prof S Diamond (Purdue University, USA) commented that this business of 'recycling alkalis' had been floating around in the literature for many, many years. He rather doubted that it existed, because despite a very diligent search he had been unable to find any evidence that he could interpret in terms of the rate of change of alkali concentration in reacting mortars. The slides he had presented that morning had shown a gradual depletion of the alkali content of pore solution, which had tapered off to an almost equilibrium situation. There were no rises and falls that might indicate any sort of a rythmic process involving the regeneration of alkali. He wondered if the explanation might not lie in the fact that when the fluid alkali silica gel flows through concrete, it picks up calcium, presumably by dissolving calcium hydroxide crystals. Perhaps the calcium was simply added to the existing alkali silicate burden so as to give a mixed alkali silicate without necessarily liberating much of the sodium and/or potassium.

Mr H E Vivian thought that this was possible because the alkali silicate complexes were usually deficient in alkali metal ions. He had made the point because the safety procedure was just to add a little more pozzolanic material to take up any alkali that might be separating.

Dr L S D Glasser (Aberdeen University, Scotland) pointed out that because one did not see any evidence of cyclic change in the pore fluid was no evidence that it was not in fact taking place because what one was observing in the pore fluid was the bulk composition. She did not see it that the sodium swept in, reacted and then swept out again. The fact that the sodium concentration in the pore fluid did not drop to zero, might be very good evidence that such a process was in fact taking place.

Mr D A St John (DSIR, New Zealand) said that it was common parlance that the interior of the concrete expanded as a result of the alkali-aggregate reaction and that the outer shell cracked as a result of the tensions that were set up. However, when one looked at thin sections of the so-called expansive interior of concrete one could never find any sign of gel, either in the aggregate or in the cement paste. He asked Mr Vivian whether when he had done his radio-active sodium experiments there had been any indication that this sort of thing occurred. 'Are we trying to look at something which we cannot see', he asked 'or is it not there?' Was there any evidence to show what was happening in that supposedly uncracked interior which people kept on referring to?

Mr Vivian said that he had always observed cracks internally and that they were there but that one was always rather surprised that there were not as many as one might have expected to see. However, it must be remembered that one was not seeing the concrete in a three-dimensional sense and some of the cracks that were cutting the cleaved plain at a low angle were very difficult to detect. The other thing was that the cracks were always there, in association with reactive particles. The cracks near the surface were not necessarily filled with any reacted gel because after all it was virtually a levering action and the point of force was at the swelling particle.

TABLE 2 : Percentage expansion and mass increases in mortar specimens containing different amounts of added sodium hydroxide when cured for different times in moisture saturated air (MSA)

Initial curing	Subsequent storage	Expansion and mass increases in mortars containing the following percentage of sodium hydroxide									
		Nil		1%		2%		5%		10%	
		% Exp-ansion	% Mass change	% Exp-ansion	% Mass change	% Exp-ansion	% Mass change	% Exp-ansion	% Mass change	% Exp-ansion	% Mass change
Nil	Drying (1 Wk)	-0,06	-7,9	-0,09	-6,7	-0,08	-6,7	-0,02	-3,9	-0,07	-3,4
	MSA (1 Wk)	-0,05	-6,7	-0,05	-4,5	-0,06	-6,1	-0,02	-3,2	-0,06	-1,9
	MSA (1 Mo)	-0,05	-6,6	-0,05	-4,2	-0,07	-5,5	0,02	-3,3	-0,08	-1,9
	MSA (6 Mo)	0,04	-5,6	0,82	-3,3	1,15	-4,1	0,42	-2,0	-0,03	0,3
	Drying (1 Wk)	-*	-*	-*	-*	-*	-*	0,36	-3,7	-0,06	-2,6
	MSA (12 Mo)	0,08	-5,3	1,01	-3,0	1,42	-3,9	0,42	-2,2	-0,01	0,6
	MSA (24 Mo)	0,25	-3,0	1,19	-1,5	1,56	-1,1	0,49	1,1	0,02	1,1
	MSA (26 Mo)	0,34	3,1	1,27	-0,3	1,57	3,3	0,52	2,3	0,03	1,0
	Drying (2 Wk)	0,31	±0,0	1,20	-1,8	1,53	-0,4	0,45	-0,6	-0,09	-2,3
	MSA (2 Mo)	0,32	0,7	1,25	-1,0	1,55	0,7	0,49	0,4	-0,02	-1,1
MSA (2 Wk)	**	-0,01	-3,9	0,01	-1,1	±0,00	-1,7	-0,02	-0,2	-0,03	0,9
	Drying (1 Wk)	-0,07	-5,7	-0,03	-3,6	-0,05	-3,7	-0,02	-2,9	-0,03	-2,9
	MSA (1 Wk)	-0,06	-5,5	-0,03	-3,4	-0,04	-3,5	±0,00	-2,7	-0,03	-2,2
	MSA (1 Mo)	-0,06	-5,4	-0,02	-3,3	-0,01	-3,1	0,14	-2,6	-0,05	-2,0
	MSA (6 Mo)	-0,05	-4,9	1,40	-2,7	1,14	-1,8	0,47	-1,3	±0,0	-0,2
	Drying (1 Wk)	-*	-*	-*	-*	-*	-*	0,41	-3,1	-0,05	-2,7
	MSA (12 Mo)	-0,05	-4,8	1,63	-2,5	1,38	-1,6	0,47	-1,5	0,01	-0,2
	MSA (24 Mo)	0,01	-3,7	1,91	-0,2	1,49	0,8	0,52	1,4	0,05	1,5
	MSA (36 Mo)	0,32	0,2	1,99	1,5	1,52	4,1	0,55	2,5	0,06	1,5
	Drying (2 Wk)	0,27	-1,0	1,88	-1,3	1,46	0,5	0,47	±0,0	-0,06	-2,0
	MSA (2 Mo)	0,29	-0,3	1,97	±0,0	1,49	1,6	0,51	0,7	-0,01	-1,3
MSA (5 Wk)	**	-0,03	-3,6	-0,02	-1,7	0,01	-2,1	0,15	-1,2	-0,05	±0,0
	Drying (1 Wk)	-0,10	-4,6	-0,05	-3,2	-0,03	-3,5	0,14	-3,2	-0,09	-2,6
	MSA (1 Wk)	-0,06	-4,0	-0,01	-2,8	0,04	-3,1	0,17	-2,8	-0,10	-2,2
	MSA (1 Mo)	-0,03	-3,9	0,37	-2,5	0,32	-2,8	0,26	-2,6	-0,08	-1,7
	MSA (6 Mo)	0,29	-3,3	1,32	-1,8	1,03	-2,0	0,37	-1,6	-0,03	-0,1
	Drying (1 Wk)	-*	-*	-*	-*	-*	-*	0,31	-3,4	-0,08	-2,8
	MSA (12 Mo)	0,34	-3,2	1,57	-1,6	1,25	-1,9	0,37	-1,8	-0,03	-0,1
	MSA (24 Mo)	0,67	-2,3	1,82	-0,8	1,42	-0,8	0,44	1,9	0,02	1,1
	MSA (36 Mo)	1,28	-0,4	1,95	3,8	1,54	3,1	0,50	2,5	0,02	1,1
	Drying (2 Wk)	1,19	-1,9	1,86	±0,0	1,40	-0,6	0,40	-0,4	-0,10	-2,4
	MSA (2 Mo)	1,32	-1,1	1,92	1,3	1,45	0,4	0,45	0,4	-0,03	-1,2

*   Specimens not dried.

**   Length and mass changes of specimens during the initial curing period.