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Expansive Cement Concrete for Drilled Shafts

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This research is aimed at developing techniques for the use of highly expansive cement concrete in drilled shafts to produce a stronger bond between the shaft concrete and the surrounding soil, thus strengthening the system to carry a higher load. An expansive cement containing high-alumina cement (HAC) as the Al-bearing material was tested for expansion, strength, and setting characteristics. Although other properties were excellent, the cement showed unacceptably fast-setting behavior. To overcome the rapid slump loss of concrete using this HAC-type expansive cement, a two-stage mixing process with various admixtures is suggested. Although applicable in certain situations, this technique may not be suitable for general field application where quality control is lacking or where a delay in the expansion phase is required. An innovative solution for the problem is suggested in which the HAC is replaced with hydrated HAC (H-HAC) in the preparation of expansive cements. Concrete made with H-HAC expansive cement displayed the required properties before and after setting.

This paper reports the properties of a select group of cement pastes and concretes made from HAC-type and H-HAC-type expansive cements that include slump loss, compressive strength, free and two-dimensionally restrained expansion, expansion pressure, and friction stress obtained from especially designed test methods. Some of the expansive concretes tested during this study had compressive strength in the range of 70 MPa (10,150 psi) and developed a self-stress in excess of 8 MPa (1160 psi).

Keywords: confined concrete; **drilling;** ettringite; **expansion; expansive cement concretes; expansive cements;** high-alumina cements; restraints; **self-stressing cements.**

In the early 1970s, a special concrete with free expansion of up to 4 percent was first reported[1] for use in drilled shafts (bored piles) to produce a stronger bond between the shaft concrete and the surrounding soil, thus strengthening the shaft-soil system to carry a higher load. Previous tests[2] indicated that, at 2 months after casting, the use of expansive cement concrete resulted in 25 to 50 percent higher skin friction capacity of the shafts built in over-consolidated clay, and the settlement was reduced by about 50 percent. In the long term (approximately 18 months after casting), the base capacities of the shafts were found to be significantly higher than those in the early tests,[3] while the enhancements in frictional capacity and stiffness due to expansive cement were maintained.

The cements tested during this investigation were patterned on the earlier cement[1] and were produced by mixing a series of commercially available materials: ordinary portland cement (OPC), high-alumina cement (HAC), molding plaster ($CaSO_4$, 1/2 H_2O), and lime ($Ca(OH)_2$). These expansive cements have quick-setting behavior, usually hardening in less than 10 min. ASTM Type D admixture was able to retard the setting time to 20 min but caused a significant decrease in expansion.[1]

This paper demonstrates a set of techniques in mix design and mixing process to make such highly expansive concrete usable in actual construction by improving its setting behavior with minimal adverse effects on the properties of hardened concrete, such as compressive strength, expansion, friction stress, expansion pressure, etc. Due to the particular hydration process and the restraint conditions in drilled shafts, some standard test methods are no longer applicable to such special materials. A series of especially designed test methods were employed in this research.

RESEARCH SIGNIFICANCE

Use of highly expansive cement in drilled shafts is an innovative idea that was advanced several years ago as a means of enhancing strength and stiffness of the shaft-geomaterial system. The main drawback of the expansive cement developed for that purpose was its quick-setting characteristics. The research reported here presents a few solutions for this drawback. One of the more practical and attractive solutions is the use of hydrated high-alumina cement as the Al-bearing material in the expansive cement.

TEST PROGRAM

The test program was divided into two parts, which are discussed in the following paragraphs.

1. Cement paste tests—In this part of the study, tests were conducted to establish an optimum mixture with satisfactory setting and expansion behavior and to investigate the effects of several factors, such as the types and dosages of

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Table 1— Design of special mixing processes

Type of mixing processes	Procedures of mixing
MPD-I (one stage mixing process)	Mix all the cementitious materials (and aggregates, if any) in the mixer for 3 minutes. Add the water with dissolved retarder and superplasticizer and mix for 3 minutes.
MPD-II (two-stage mixing process)	Mix portland cement, plaster and water with dissolved retarder and superplasticizer in the mixer for 3 minutes; Wait for 5 minutes; Add the rest of the materials (HAC , lime and fly ash) with the previously mixed paste for 3 minutes.
MPD-III (two-stage mixing process)	Mix portland cement, fly ash, plaster and water with dissolved retarder in the mixer for 3 minutes; Wait for 5 minutes; Add the rest of the materials (HAC, lime and superplasticizer) with the previously mixed paste for 3 minutes.
MPD-IV (two-stage mixing process)	Mix portland cement, fly ash and water with dissolved retarder (and aggregates, if any) in the mixer for 3 minutes; Wait for 5 minutes; Mix the expansive components and superplasticizer with the previously mixed paste for 3 minutes.

admixtures, the types and contents of expansive components, the types of mixing processes, etc., on the flowability, setting time, and free expansion of the cement pastes.

2. Concrete tests—In this part of the study, the properties of expansive concrete with the cements selected from the preceding study were investigated for setting and expansion characteristics and strength properties.

Initial attempts at improving the properties of fresh concrete were concentrated at expansive cements using high-alumina cement as the Al-bearing material. Despite the use of various admixtures and special mixing processes, improvements in setting characteristics of expansive cements were limited if the high-usable expansive potential were to be maintained. It was then decided to investigate different forms of Al-bearing material in expansive cements. Prehydration of HAC was one of the alternatives that proved to be the most promising.

Materials and sample preparation

The commercially available materials for this test program included: 1) ordinary portland cement (OPC)—ASTM Type 1 or CSA Type 10 portland cement; 2) expansive components (EC) including high-alumina cement (HAC), quick-setting plaster (hemihydrate), and hydrated finishing lime (calcium hydroxide); 3) admixtures including a commercial retarding agent based on organic phosphonic acid and hydroxycarbocyclic acid, retarder sodium citrate, nephatlene sulfonate condensate powdered superplasticizer, and fly ash; 4) aggregates including sand and crushed limestone with a maximum size of 20 mm; and 5) water.

The hydrated high-alumina cement (H-HAC) was made from HAC in the lab by the following process: a) mixing HAC paste with water using a water-cement ratio equal to 0.5, and casting it in 100 x 200-mm plastic cylinder mold; b) after hydration for one of the designated ages (30 min before final set, 1— hr after final set, 24 hr after mixing with water, and 7 days), crushing the cylinder paste, and then drying it at room temperature for 24 hr; c) grinding it into fine powder and separating in three different sizes by sieving (< 75, 75 to 150, and 150 to 300 μm). For the prehydration age of 30 min before final set crushing and grinding was not needed.

Cement paste tests

For HAC-type expansive cements, a series of admixtures, retarder, superplasticizer and fly ash, and special mixing processes were employed, but for H-HAC-type expansive cement, only the superplasticizer was needed. A total of 53 samples of expansive cement pastes were tested for this phase of the study.[4] Large variations of admixtures were tested for their effects on expansion and setting characteristics of expansive cements. Results from only a select group of samples that contain the proportions of raw ingredients within practical limits are presented here. Details of the mixing processes are listed in Table 1, and the proportions of the expansive cement pastes tested for different variables are given in Table 2.

A flow table (ASTM C 230-68) was used to determine the change of flowability of the paste. The method employed did not exactly follow the ASTM Standard because the flows of the pastes with admixtures usually exceeded the range of the table. In most cases, the paste flowed by gravity without performing any drops. The setting time of the paste was determined by a method of ASTM C 807-89. After the flow decreased with time to less than 10 percent, the paste was compacted in a PVC cone, the surface was finished, and the initial and final setting time were measured by the Vicat apparatus.

When the flow of the paste had decreased to less than 10, two expansion specimens were cast in steel prism molds, giving 25 x 25 x 125-mm (1 x 1 x 5-in.) specimens with expansion studs at the ends, providing a gage length of 125 mm (5 in.). The specimens were cured initially in a sealed plastic box under the relative humidity of 100 percent and temperature of about 23 ±3 C (74 ±5 F). Some specimens were demolded after 24 hr and the others just after final setting. Initial lengths of the specimens were measured immediately after demolding. After 24-hr curing in the sealed boxes, the specimens were set in water. The expansions

Table 2 — Mix design of expansive cements

Specimen no.	Type of mixing process	Portland cement	High-alumuna cement (HAC)	H-HAC Content	H-HAC Particle size, μm	H-HAC Pre-hydration age	Quick set plaster	Hydrated lime	Water	Commer-cial retarding agent	Sodium citrate	Superplas-ticizer	Fly ash
EP1	MDP-I	480	200	—	—	—	96	24	320	—	—		—
EP2	MDP-I	480	200	—	—	—	96	24	320	4	—	12	—
EP37	MDP-I	400	250	—	—	—	120	30	320	2.4	—	12	—
EP38	MDP-I	400	250	—	—	—	120	30	320	—	0.3	12	—
EP40	MDP-I	400	250	—		—	120	30	368	—	0.3	12	120
EP41	MDP-II	400	250	—	—	—	120	30	368	—	0.3	12	120
EP42	MDP-III	400	250	—	—	—	120	30	368	—	0.3	12	120
EP43	MDP-IV	400	250	—	—	—	120	30	368	—	0.3	12	120
EP49	MDP-I	480	—	200	75-150	1 day	96	24	320	—	—	6	—
EP50	MDP-I	480	—	200	No grinding needed	30 min before final set	96	24	320	—	—	6	—
EP51	MDP-I	480	—	200	75-150	1,5 hr after final set	96	24	320	—	—	6	—
EP52	MDP-I	480		200	75-150	7 days	96	24	320	—	—	6	—
EP53	MDP-I	480		200	< 75	1 day	96	24	320	—	—	6	—
EP54	MDP-I	480		200	150-300	1 day	96	24	320	—	—	6	—

Table 3— Proportions of expansive concrete mixes

Speci-men no.	Type of concrete	Type of mixing process	OP/EC	Portland cement	(HAC)	H-HAC	Molding plaster	Hydrated lime	Water	*w/c*	Stone	Sand	Sodium citrate	Super-plasti-cizer	Fly ash
E6	HAC	one-stage	60/40	306	128	—	61	15	217	0.43	902	742	—	—	—
E7	HAC	two-stage	60/40	306	128	—	61	15	217	0.43	902	742	0.19	0.19	—
E8	HAC	two-stage	60/40	306	128	—	61	15	316	0.54	756	524	0.19	0.19	76
E9	HAC	two-stage	50/50	260	163	—	78	19	300	0.50	772	534	0.20	0.20	70
E11	H-HAC	one-stage	60/40	306	—	128	61	15	217	0.43	902	742	—	—	—

were read once a day, until either the specimens cracked or the lengths of the specimens became constant.

Concrete tests

With expansive cements and admixtures selected from the cement paste tests, a series of 12 concrete mixes were designed to evaluate the effects of factors such as admixtures, type of A1-bearing materials and mixing process (described in Table 1), on the properties of fresh and hardened concrete. A select group of these concrete mixes is shown in Table 3.

Compressive strength and friction stress tests—To simulate the actual stress state with three-dimensional restraint, a set of steel tub molds for casting and curing expansive concrete was designed, as shown in Fig. 1. The lateral expansion of concrete was restrained by the steel tube, and the longitudinal expansion was restrained by two steel end plates tightly held in place by three 8-mm (0.32-in.)-diameter threaded rods. The tube was 100-mm (4-in.) inner diameter and 200 mm (8 in.) long with 6-mm (0.24-in.)-thick wall. Twenty holes of 5-mm (0.2-in.) diameter were made symmetrically in four columns to allow a supply of water during hydration. The concrete with steel mold was cured in air at 100 percent relative humidity and about 25 C (77 F) for 24 hr after casting and then placed in 23 C (73 F) water. At designated ages, the steel plates were removed, and

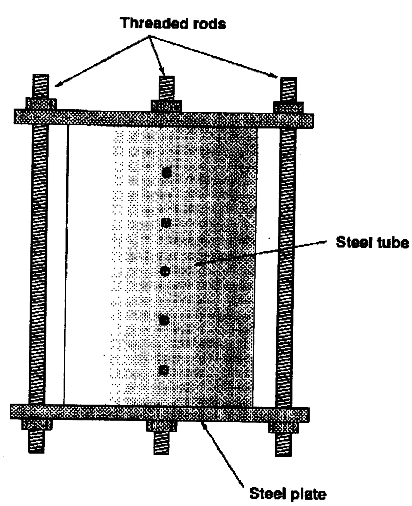

Fig. 1—Steel tube mold for expansive concrete

concrete cylinder was squeezed out using a universal testing machine. During the demolding process, the friction stress between concrete and steel could be measured from the maximum load required to remove the concrete cylinder from the tube. The compressive strength was obtained from

Table 4— Initial and final set of cement pastes

Sample	Initial set, minutes	FInal set, minutes
EP 40	65	78
EP 41	67	72
EP 42	130	210
EP 43	155	230
EP 49	480	510
EP50	27	31
EP51	348	378
EP52	486	516
EP53	426	486
EP54	510	540

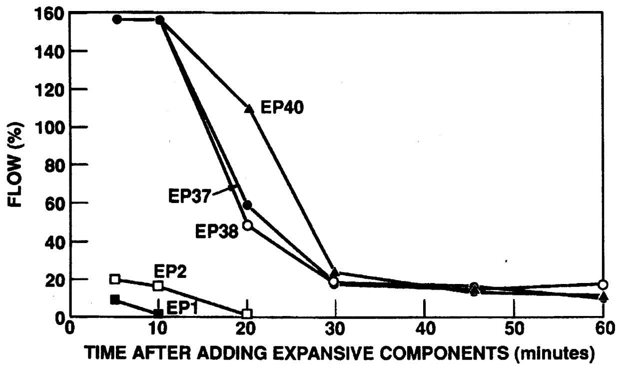

Fig. 2—Effect of retarder and superplasticizer on the loss of flowability of expansive cement paste

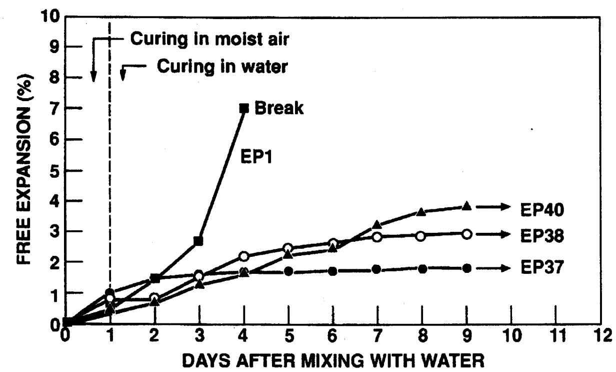

Fig. 3—Effect of admixtures on free expansion of cement pastes

testing the squeezed-out specimens.

Free expansion tests—Concrete was cast in PVC cylinder molds 100 mm (4 in.) in diameter, 200 mm (8 in.) long with 3-mm (0.12-in.)-thick walls with expansion studs embedded at the ends. After 24 hr of curing in moist air, specimens were demolded. The original length of a specimen was obtained by averaging four measured lengths of concrete cylinder on symmetric sides. The initial length, including two targets, was measured immediately after demolding, and then specimens were cured in the water. The length changes were determined daily.

Two-dimensional restrained expansion tests—The concrete specimens for two-dimensional restrained expansion tests were cast in PVC tubes with 3-mm (0.12-in.)-thick walls, 120 mm (4.8 in.) long, and 100-mm (4-in.) inner diameter. Two expansion studs were installed in the center at the ends. The initial length of a specimen was obtained by averaging four measured lengths of concrete cylinder on symmetric sides, including two targets after 1-day moist curing. Then the specimens with PVC tube molds were stored in 23 C (73 F) water. The length changes were determined daily. In this test, the restraint was applied to the concrete from the wall of PVC tube in the lateral direction. In the longitudinal direction, the only restraint could have come from the friction between concrete and the PVC walls.

Expansion pressure tests—A test mold for measuring this parameter was designed, similar to the one shown in Fig. 1. A thin-walled steel tube was used to provide lateral restraint, and two end steel plates tightly installed by three 8-mm (0.35-in.)-diameter threaded rods acted as longitudinal restraint. The concrete specimen inside the tube was 150 mm (6 in.) in diameter and 300 mm (12 in.) long. The wall thickness of the tube was 3 mm (0.12 in.). Several strain gages were installed to measure the changes in lateral and longitudinal strains during concrete expansion. Each rod contained one strain gage in the axial direction. The outer surface of each tube was instrumented with three strain gages, one in the axial direction and two in the circumferential direction. The holes in the steel tubes were made for easy flow of water as mentioned previously for the strength test specimens. One hour after casting concrete, initial strain readings were taken. The specimens were cured in air at 100 percent RH and 25 C (73 F) for 24 hr, and then placed in 23 C (73 F) water. Readings were recorded every day from each specimen.

CEMENT PASTE TEST RESULTS

Results shown in Fig. 2 indicate that the simple use of the commercial retarding agent had a limited effect on improving the flowability of the expansive cement paste. The zero flow was delayed from 10 min in Sample EP1 to 20 min in Sample EP2. The initial flow was not increased much, either. A comparison of Pastes EP2 and EP37 shows that the addition of superplasticizer enhanced the initial flow as well as delayed the setting time. For a similar effect on setting behavior, the required amount of the commercial retarding agent is approximately eight times that of sodium citrate (Samples EP37 and EP38). The measured flow of the paste with superplasticizer (Sample EP37) at 60 min is approximately equal to the flow of Sample EP2 without the admixture at 5 min. However, between 10 and 30 min, the flow of Sample EP37 is reduced drastically. Addition of fly ash (Sample EP40) improves the workability somewhat during this time.

Cement pastes (EP37, EP38, EP40) with improved setting behavior were tested for free expansion and are compared with the paste (EP1) without admixtures in Fig. 3. The term break used at the end of an expansion curve indicates that the specimen is cracked to the extent that further measurements would not be meaningful. Paste EP2, because of its low workability, was not included in further tests. It is obvious that expansion was greatly suppressed by the use of admixtures, despite the larger amounts of expansive components used. The sodium citrate retarder had

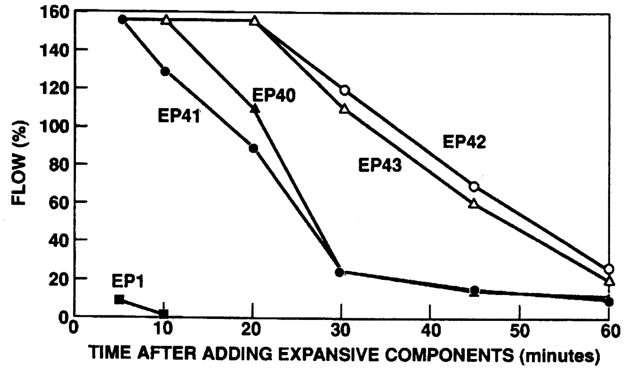

Fig. 4—Effect of mixing procedure on the loss of flowability of expansive cement pastes

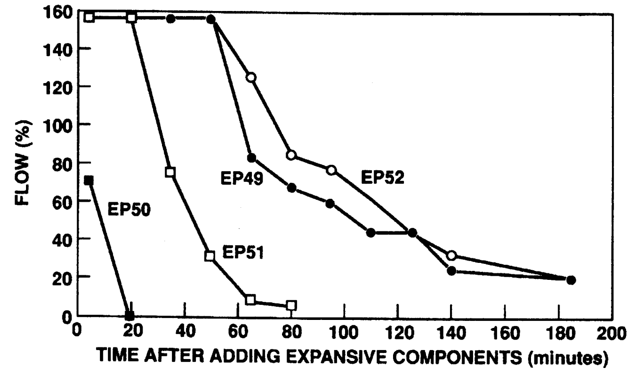

Fig. 6—Effect of prehydration age of H-HAC on the loss of flowability of cement pastes

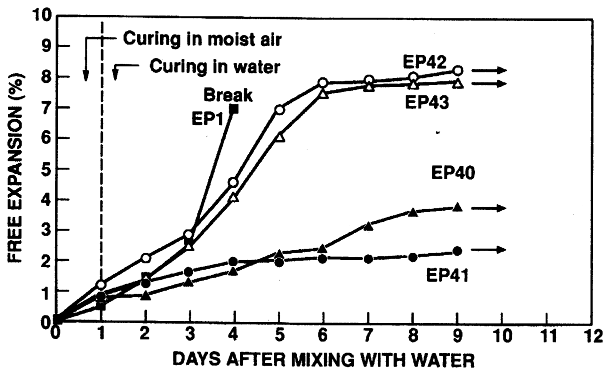

Fig. 5—Effect of mixing procedure on expansion of cement pastes

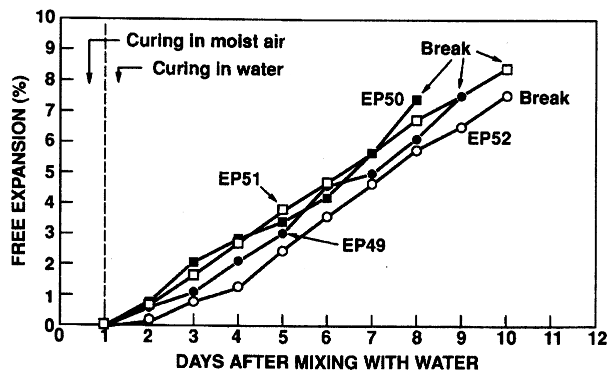

Fig. 7—Effect of prehydration age of H-HAC on expansion of cement pastes

an effect similar to that of the commercial retarding agenton the setting characteristics but demonstrated a smaller adverse effect on expansion. Use of fly ash improved setting as well as expansion behavior of the cement pastes. A beneficial effect of admixtures is the delay in measured expansion, which may allow the cement paste to gain strength and produce higher self-stress when restrained.

The expansive cement paste with fly ash and other admixtures was selected to test the different mixing procedures listed in Table 1. The results from flow and free expansion tests on Pastes EP1, EP40, EP41, EP42, and EP43 are shown in Fig. 4 and 5. Initial and final set times are given in Table 4. Different mixing processes significantly influenced the setting behavior and expansion of the paste. Mixing process MPD II did not improve the required behavior. In fact, the one-stage mixing process MPD I resulted in better flow and expansion characteristics of the paste than MPD II. Results using MPD III and MPD IV are very similar. It appears that mixing superplasticizer in the second stage and fly ash in the first stage is the key to avoid overwhelming reaction phase during the two stages, which results in faster setting and loss of measurable expansion. Compared to Sample EP1, the expansion and setting characteristics of Samples EP42 and EP43 are vastly improved. Although MPD III and MPD IV yield similar results, MPD IV is considered to be a preferred mixing procedure due to practical reasons. Normal portland cement concrete can be prepared at the concrete plant and transported to the site, where the expansive component and superplasticizer can be added just before casting.

Although with the use of admixtures, choice of mixing procedure, and careful supervision, workable expansive cement paste and concrete with acceptable expansion characteristics can be prepared, the sensitivity of the final product to all the variables involved is not very comforting. A different approach was therefore attempted, i.e., to replace the high-alumina cement (HAC) with the hydrated high-alumina cement (H-HAC). It is known that when the normal cement and HAC are mixed together when the quantity of either of the cements is in the range of 20 to 80 percent, a fast rate of reaction results that causes a rapid set.[5] Addition of semihydrated calcium sulfate and hydrated lime would further complicate the phenomenon. Use of hydrated high-alumina cement as the alumina-bearing material should avoid the problem of rapid reaction and set and result in more workable concrete with dependable expansion char-

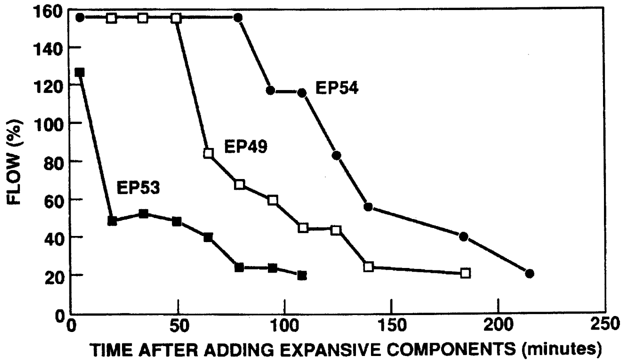

Fig. 8—Effect of particle size of H-HAC on the loss of flowability of cement paste

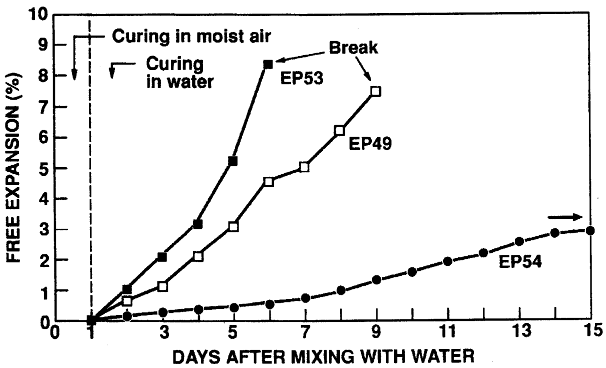

Fig. 9—Effect of particle size of H-HAC on expansion of cement pastes

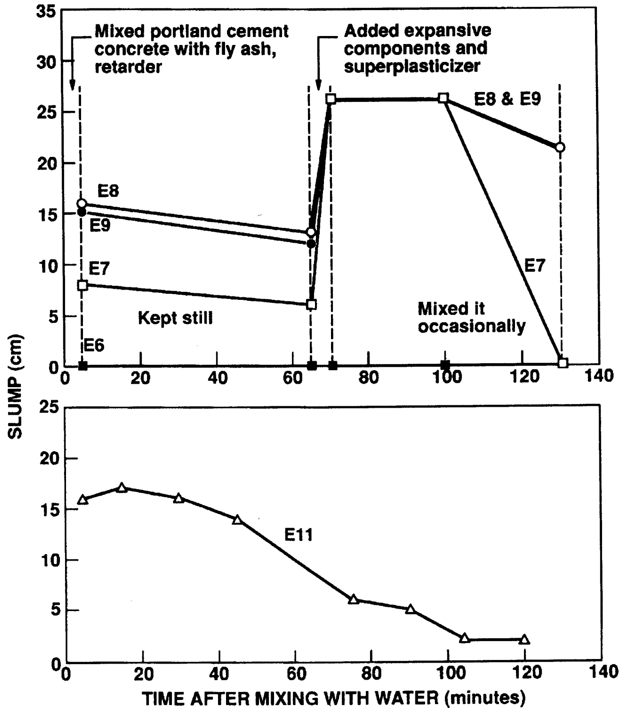

Fig. 10—Slump loss of expansive concrete

acteristics. A small amount of superplasticizer was used in all H-HAC-type expansive cement paste and concrete mixes because it was observed that much larger water-cement ratio *(w/c)* would be needed otherwise to achieve workable concrete. Addition of superplasticizer improved workability of concrete considerably without seriously affecting the expansion properties adversely.

The effects of prehydration age of H-HAC on flow and free expansion of cement pastes are shown in Fig. 6 and 7, and the initial and final set times are compared with other samples in Table 4. The H-HAC particle size in Pastes EP49, EP51, and EP52 varied between 75 and 150 μm. The results indicate that a prehydration age at least equal to the final set time is needed to achieve satisfactory flow characteristics of the expansive cement pastes. Beyond 24 hr, the prehydration age of H-HAC does not seem to have any effect on the flow and setting behavior of the pastes. Even with prehydration age of 1.5 hr longer than the final set of HAC, the initial and final set times of approximately 6 hr were recorded. The effect of prehydration age of H-HAC on free expansion is minimal, as shown in Fig. 7. Compared to HAC-type expansive cement pastes (Fig. 3 and 5), the expansion characteristics of H-HAC-type cement pastes are significantly better with respect to the total expansion and the delay in the expansion phase. Since the use of admixtures in H-HAC-type concrete is minimal, the loss of measurable expansion was minimized, and the delay in reaction between normal portland cement and the aluminates resulted in the delay of expansion phase, which, for the application in drilled shafts, is a very favorable response.

The effects of particle size of H-HAC on flowability and expansion of cement paste are shown in Fig. 8 and 9, and the initial and final set times for these pastes are also given in Table 4. The prehydration age of HAC in Pastes EP49, EP53, and EP54 was 24 hr. As expected, the reduced particle size results in faster reaction at an early age. The higher fineness of H-HAC gave expansive cement pastes a lower flow, a larger flow loss with time, and a faster set. When the particle size decreased from 75 to 150 μm to less than 75 μm, the expansion of the paste developed earlier. The ultimate amount of expansion was, however, very similar in both cases. With an increase in the particle size from 75 to 150 μm to 150 to 300 μm, the development of expansion was greatly delayed. The ultimate expansion was also significantly reduced. For the expansion cement application under consideration, the particle size of H-HAC in the range of 75 to 150 μm appear to be the most suitable.

CONCRETE TEST RESULTS

From the tests on cement paste, it was decided to use sodium citrate as the retarder for concrete specimens. Various concrete mix designs developed on the basis of cement paste tests and properties investigated are listed in Table 3. In the one-stage mixing process, all the ingredients were mixed together at the same time. In the two-stage mixing process, the normal portland cement, fly ash (if any), aggregates, part (about 70 percent) of total water, and the retarder

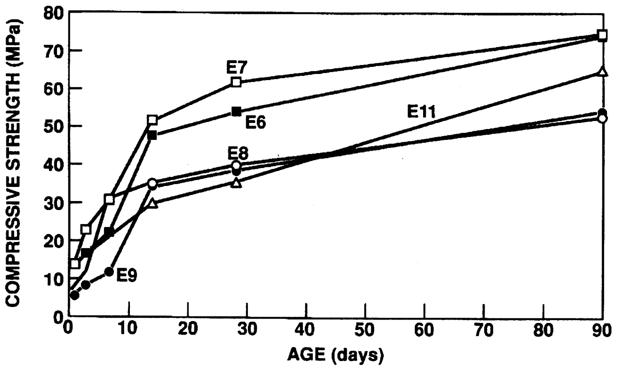

Fig. 11—Development of compressive strength of expansive concrete

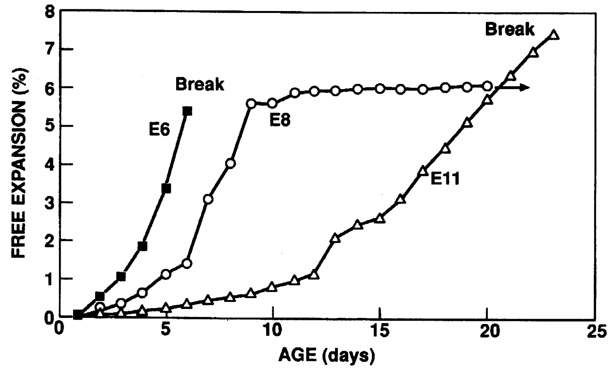

Fig. 12—Free expansion of expansive concrete

were mixed initially for 3 to 5 min. The concrete was then let to rest for an hour, during which it was mixed occasionally, e.g., after every 10 min. The expansive component, superplasticizer, and the remainder of water was then added to the normal cement concrete and mixed for 3 to 5 min.

Slump values measured over 2 hr for the five concrete mixes are shown in Fig. 10. Expansive concrete without any admixture (E6) displayed zero slump immediately after mixing all the ingredients together using one-stage process. Use of admixtures improved the slump of fresh concrete. Fly ash also results in reducing the slump loss. During the first 30 min after the addition of expansive component and superplasticizer, the slump of concrete was very large [~ 260 mm (10.4 in.)]. The change of OPC/EC ratio had no significant effect on slump loss. The behavior of fresh concrete made with H-HAC-type expansive cement was very similar to that of superplasticized normal cement concrete. Initial slump of approximately 160 mm (6.2 in.) maintained for about 30 min and at 60 min slump was still about 100 mm (4 in.).

Development of compressive strength of expansive concretes with different admixtures is shown in Fig. 11. Strength of Concretes E6 and E7, both made with HAC-type expansive cement without fly ash, was the highest among the group mainly because of lower *w/c*. Addition of fly ash and higher *w/c* to make concrete more workable resulted in a reduction of strength, but at 12 days the strength exceeded 30 MPa (4350 psi), which usually is the specified strength of concrete for use in drilled shafts. It should be noted that the compressive strength reported here is for unconfined concrete. In actual field conditions, the concrete will be confined laterally when subjected to axial stress and will, therefore, display much higher strength.[6] Increase in the amount of expansive component from 40 percent of the total cement to 50 percent (E8 versus E9) reduced concrete strength at an early age, but beyond 12 days there was no effect of this variable. The H-HAC-type expansive cement concrete (E11) displayed much lower strength than the comparable HAC-type cement concrete (E6) at an early age, but at later stages the two concretes had similar strength values. Compared to normal concrete, the strength development of expansive concretes shown in Fig. 11 is delayed by several days. This effect is most pronounced in Concretes E9 and E11.

The linear free expansion-versus-age curves of Concretes E6, E8, and E11 are shown in Fig. 12. Addition of fly ash along with higher *w/c* resulted in a delay of expansion by about 2 days. The total free expansion, however, is similar in the two HAC-type concretes (E6 and E8). Use of H-HAC as the Al-bearing material instead of HAC delays development of expansion by about 9 to 10 days. The rate of expansion in H-HAC-type expansive cement concrete (E11) after about 12 days is similar to that in Concrete E6 at about 3 days. The total measured free expansion in the H-HAC-type concrete was slightly higher than that in the HAC-type concrete. It should, however, be noted that the free expansion measurements, due to extensive cracking of specimens, do not necessarily reflect the true quantitative effects of different parameters. They, however, show a qualitative trend that can be further investigated.

Fig. 13, 14, and 15 show, respectively, the variations with age of the longitudinal expansion of concretes in laterally restrained specimens, lateral expansion pressure, and friction stress for all the expansive concretes listed in Table 3. The HAC-type cement concrete without any admixture (E6) displayed the most expansion, the largest expansive pressure, and the largest friction stress. Addition of admixtures (E7 versus E6) greatly reduced the expansive potential, which is apparent in all three parameters studied in Fig. 13 through 15. Increase in *w/c* also reduces expansive potential of the paste, as is obvious from a comparison of Samples E7 and E8. Addition of fly ash is not believed to cause any significant adverse effect on expansion in this comparison. It is obvious that the gain in workability due to admixtures in the HAC-type expansive cement concrete is obtained at the expense of expansive potential. An increase in expansive component (E8 to E9) compensates, to some extent, for the loss of restrained expansion and friction stress without significant adverse effects on strength and workability but the development of lateral expansion pressure is not improved.

Performance of Concrete E11, which contained H-HAC-type expansive cement is quite good compared with the reference concrete E6. Although the restrained expansion of Concrete E11 is somewhat lower than that of Concrete E6, expansion pressure and friction stress in the two concretes (E6 and E11) are of reasonably similar magnitudes. Delay in the development of expansive pressure as a result of pre-

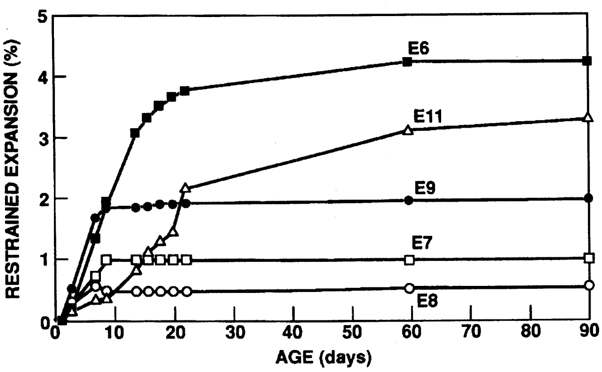

Fig. 13—Longitudinal expansion of laterally restrained concrete

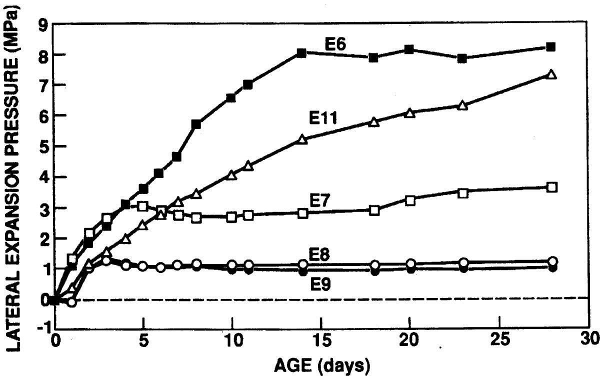

Fig. 14—Lateral expansion pressure curves of expansive concrete

hydration of high-alumina cement is an additional benefit in the application of expansive concrete in drilled shafts.

DISCUSSION

From the test results presented here and those reported elsewhere,[7] it is obvious that the use of admixtures does not delay the formation of ettringite in the early stage, but rather accelerates the reaction process. The action of these admixtures is only to separate the newly formed ettringite crystals and to resist the bond formation among them. After further consumption and absorption of water by hydration, the interlocking of ettringite particles cannot be avoided, and then the setting follows quickly.

The situation when using H-HAC is totally different. According to the "through solution theory,[8]" the rate of ettringite formation is proportional to the concentration of $A1^{+3}$ ions in the concrete pore solution. The solubility of hydration products of HAC is lower than that of HAC, which leads the high-alumina cement concrete to have stable mechanical properties and durability. As a result of prehydration, a cladding of hydration products is formed on the surface of HAC particles which, on one hand, resists water penetration into the unhydrated cores, and, on the other hand, reduces the ability of $A1^{+3}$ ions to disperse from the cladding. A relatively long time period is needed for the reactant ions to reach the saturated concentration under which the ettringite is crystallized. This slow process of accumulating $A1^{+3}$ ions from H-HAC particles allows the paste to have a desired delayed setting behavior.

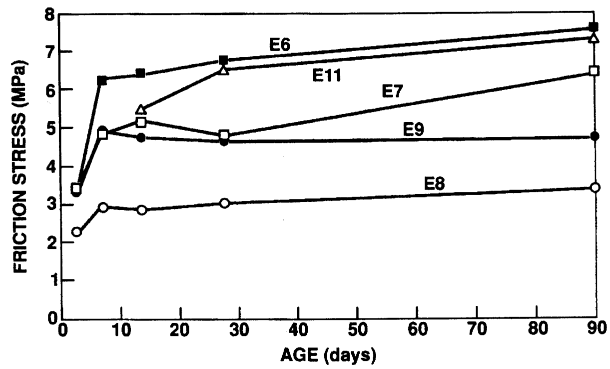

Fig. 15—Friction stress of expansive concrete

From the development of expansion of HAC-type reference expansive cement paste (EP1), it can be found that most of the expansion develops after 24 hr, so the ettringite formation and expansion proceeds with the help of hydrated HAC. This indicates that the use of H-HAC instead of HAC as A1-bearing material in the expansive cement would not adversely influence its total expansion potential.

Both the "crystal growth theory" and the "swelling theory"[9] agree, and other data[10] confirm that the particle size takes an important role in either the concentration of $A1^{+3}$ ions in the solution or the surface area from which the ettringite grows, that is, the increase of particle size of A1-bearing material will decrease the expansion. Therefore, the selection of appropriate fineness of H-HAC is not only a key point to control the quality of expansive cement, but also a meaningful measure to adjust the rate of expansion development and the ultimate value of expansion.

From the test results, it can be seen that the mechanical properties of expansive concretes vary with mix design and mixing processes. Two main factors governing the properties are: expansion of concrete and degree of internal and external restraint. The following states of expansive concrete can exist under different conditions.

When expansive component (EC) is uniformly distributed in the concrete (for example, when using superplasticizer), the ettringite will grow in all the capillaries. When the ettringite crystallization pressure exceeds the strength of the bond structure, the capillary walls will be broken. It is this uniform distribution of EC that makes the destruction overwhelming in the concrete structure, causing very low strength in the early stage. The expansion pressure of concrete in this state is just equal to the stress that damages the weak internal structure of concrete. When the EC is not uniformly distributed in the concrete (for example, in the reference expansive concrete), ettringite formation is limited to certain areas, and thus the expansion pressure causes local cracking only. In the areas away from EC locations, the structure will not be damaged. Most of the ettringite will grow only in limited cracks, where extra potential of crystal formation contributes to the outward expansion pressure approximately equal to the ettringite crystallization pressure.

If, before extensive formation of ettringite starts, a certain strength of concrete has developed, the cracking of concrete will be limited even when the EC is uniformly distributed in the concrete. Ettringite crystals can only grow in weak areas of cracks. The strong parts of the concrete's internal structure without suffering any serious damage will transmit the expansion pressure outward, which may approach the ettringite crystallization pressure.

From the preceding discussion, it can be concluded that there are perhaps three fundamental factors determining the expansion pressure of the concrete: 1) The strength of expansive concrete—The maximum tensile strength should not be much higher than the ettringite crystallization pressure to allow limited cracks suitably forming to produce a large expansion potential outward. 2) Water-cement ratio—This factor influences concrete strength and affects the space where ettringite can grow. Only when the growth of ettringite exceeds the dimension of the voids in expansive concrete, the expansion pressure appears. 3) The uniformity of EC in expansive cement/concrete—There is an optimum dispersion of EC for the maximum expansion. Extreme uniformity will decrease the average distance between ettringite crystals, and the thin matrix wall will be destroyed easily by the crystallization pressure of ettringite, but totally nonuniform distribution of EC is also undesirable for the development of expansion pressure. On one hand, nonuniform expansion will cause uneven deformation of the structure, and, on the other, when the ettringite is so concentrated in some locations, the walls of the hydrated matrix become thick enough to overcome the crystallization pressure to restrain expansion.

CONCLUSIONS

Especially developed cements and concretes with large expansive potential for application in drilled shafts have been investigated for expansion, self-stress, and setting characteristics. The following conclusions can be drawn from this study.

1. The traditional methods of using admixtures such as retarder, superplasticizer, and fly ash can delay the setting of the expansive cement and concrete but will have adverse effects on their expansion characteristics, resulting in reduced useful expansion.

2. A proper mixing process can reduce the loss of expansion of the expansive cements when admixtures are used. The suggested method is mixing portland cement concrete with retarder first, followed by the addition of expansive component and superplasticizer just before casting.

3. Using hydrated high-alumina cement (H-HAC) instead of high-alumina cement as the A1-bearing material can produce expansive cement concrete with normal setting behavior and limited loss of expansion. The prehydration age must be longer than the final setting time of the cement, and the reground particle size of the H-HAC is suggested to be in the range of 75 to 100 μm. The coarser particle size H-HAC will significantly reduce expansion and expansion pressure.

4. The rate of strength development of expansive concretes tested in this program is lower than that of normal concrete in the early stages. Most of the strength is achieved after 14 days, but 28-day strength usually exceeded 35 MPa (5080 psi), and 90-day strength was in the range of 50 to 70 MPa (7250 to 10,150 psi).

5. The expansion pressure of concrete is greatly influenced by *w/c* and use of admixtures. A feasibly low *w/c* and low contents of admixtures are suggested for the design and mixture proportioning of expansive concrete.

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