

“Laboratory Investigation on Effect of Phosphate Ions on Concrete”

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1. Introduction

At the 499th Advisory Committee on Reactor Safeguards (ACRS) meeting, the staff presented its review results on the McGuire/Catawba Nuclear Stations License Renewal Applications. During the staff's presentation, one ACRS member asked the staff why a quantitative allowable phosphate limit is not included as part of the staff's acceptance criteria for defining aggressive groundwater/soil environments in license renewal application reviews. The staff's response was that the current criteria for defining aggressive groundwater/soil environments are primarily based on American Concrete Institute (ACI) standards and industry experts opinion and believes that the current criteria are reasonable for defining groundwater/soil aggressive environment. The staff also committed to take an in-depth review of the issue (ie., if phosphate limits should be a part of the staff's criteria for aggressive groundwater/soil environment).

In a letter dated June 24, 2003 to NRC Chairman Diaz, the Chairman of the Advisory Committee on Reactor Safeguards (ACRS), Dr. Mario Bonaca, made three recommendations. The third recommendation states, "The Generic Aging Lessons Learned Report (GALL) specifies limits for sulfate ion concentrations in below-grade water to avoid decrepitation of concrete. The Staff should consider whether similar limits and guidance are needed for phosphate ion concentration." Based on the above ACRS recommendation, NRR User Need, NRR-2004-002, was developed and forwarded to RES for consideration in January 2004.

2. Objectives of Overall Investigation

The objectives of this investigation are to (1) understand the significant factors that may lead to the establishment of phosphate limits beyond those currently accepted in industry codes and standards documents (e.g., local soil conditions that may lead to an aggressive environment); (2) provide recommendations (technical basis), as appropriate, on whether a limitation on phosphate ion concentration in groundwater is required to avoid degradation of concrete structures; and (3) provide recommendations, as appropriate, in the form of staff guidance on the establishment of phosphate ion concentration limits.

3. Approach

The end product of this research will be a document to assist the Staff in establishing a position on phosphate ion concentrations in groundwater for use in review of license renewal applications. Literature and available industry standards will be reviewed and a letter report prepared summarizing the state-of-the-art. An assessment of the effects of phosphate ions on concrete materials and structures will be made through contacts with cognizant researchers, lessons learned from non-nuclear facilities subjected to high phosphate ion concentrations, and a review of the literature. Results of this assessment will be provided in a letter report that presents an evaluation of the effects of phosphate ions on concrete materials and structures. A

"bench-scale" laboratory study will be conducted to investigate the effect of different phosphate ion concentrations on strength and weight and length change of cubes and prisms fabricated from Portland cement paste. A report that can serve as a primer on factors that affect the durability of concrete materials and structures in nuclear power plants will be prepared. Finally, a NUREG/CR report will be prepared that incorporates results from the prior letter reports and provides guidance for use in establishing limits on exposure of nuclear power plant concrete structures to high phosphate ion environments. If required, recommendations on limits such as those currently in effect for sulfates and chlorides will be provided as well as their basis.

The interim report on assessment of potential phosphate ion-cement interactions was completed and provided to NRC in August 2005. Contained in this report are laboratory results obtained over a 12-month period of the potential for phosphate ion corrosion of ordinary Portland cements.

4. Laboratory Exposure Tests

Results of a literature review and contacts with cognizant concrete research personnel reported previously noted that there was little information concerning the effect of phosphates on cementitious materials. As a result, a laboratory study has been designed and implemented.

4.1 Experimental Program

An outline of the experimental program developed is provided below.

a. Preparation of fresh paste

Type II Portland cement paste having a ratio of water to cement ~ 0.40 was used to fabricate the test articles. This water/cement ratio was selected to generate samples having total porosity representative of that commonly found in current high-strength concrete formulations. Prismatic length-change (16 specimens) and cube specimens (48 specimens) were fabricated from the mix. One-day after casting, the specimens were removed from their molds and cured under saturated conditions (100% relative humidity) until exposure testing initiated.

b. Exposure solutions

The test specimens were exposed to three test solutions. The three solutions represent a control and two concentrations of phosphate ions. The phosphate solutions were selected to provide concentrations of phosphate ions much higher than normally experienced in service.

1. A saturated calcium hydroxide solution (control)
2. A saturated low-soluble phosphate salt, magnesium phosphate (MgHPO_4),
3. A saturated high-solubility phosphate salt, sodium hydrogen phosphate dodecahydrate ($\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$).

Excess solids of these salts were poured onto the bottom of a tray with enough water to cover the cubes and prisms. The aqueous brine solutions become saturated in equilibrium with the excess solids. If the cement extracts phosphate from the brines, this ensures constant concentrations in the exposure brines during the concrete (cement paste)

interaction with the brine. The cubes and prisms are suspended above the excess solids by PVC corner braces.

- c. Specimens and number of samples per time interval
 1. Compressive strength: triplicate 2-in. cubes for each set of test conditions
 2. Dimensional change: 1 x 1 x 11-in. prisms with 4 prisms per set of parameter tested
- d. Time intervals for testing
 1. 30-day,
 2. 3-months,
 3. 6-months,
 4. 1-year, and
 5. 18-months
- e. Testing at each time interval
 1. Compressive strength (ASTM C109)
 2. Dimensional change (ASTM C490)
 3. X-Ray Diffraction (XRD)
- f. Scanning Electron Microscopy (SEM) with energy dispersive X-ray (EDX) probes will be applied if XRD measurements indicate the formation of significant new phases or if visual examinations of the exposed specimens show signs of degradation or secondary mineralization.

4.2 Phosphate-Cement Interactions: Twelve-Month Results

4.2.1 Observations

Figure 1 presents the length change and cube test specimens being conditioned in the three solutions investigated. The solution of Na_2HPO_4 is clear and transparent. The solution of MgHPO_4 contains some carbonates floating on top of the solution, but much less than the solution of calcium hydroxide. In both the magnesium and calcium hydroxide solutions, the specimens are covered with white deposits of carbonates (magnesium and calcium, respectively).

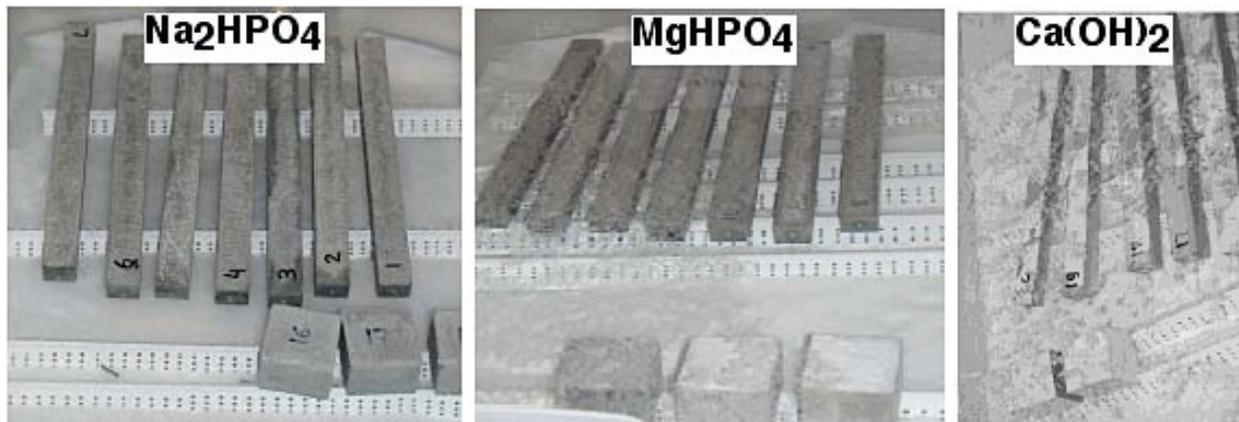


Figure 1 Length change and cube test specimens.

Cube specimens conditioned in the $\text{Ca}(\text{OH})_2$ solution are shown in Figure 2a. A close-up view of one of the cube specimens shows deposits of calcium carbonate (CaCO_3) growing on the surface (Figure 2b). These carbonates result from carbonation by air of the calcium hydroxide from the solution.



Figure 2 Crystals of $\text{Ca}(\text{CO})_3$ present on cube specimens stored in $\text{Ca}(\text{OH})_2$ solution 12 months.

The specimens conditioned in both of the phosphate solutions are beginning to show the formation of small crystals growth on their sides. The crystals seen on the specimens conditioned in the magnesium phosphate solution appear to be larger and more abundant than those seen on the specimens conditioned in the sodium phosphate solution (Figure 3).

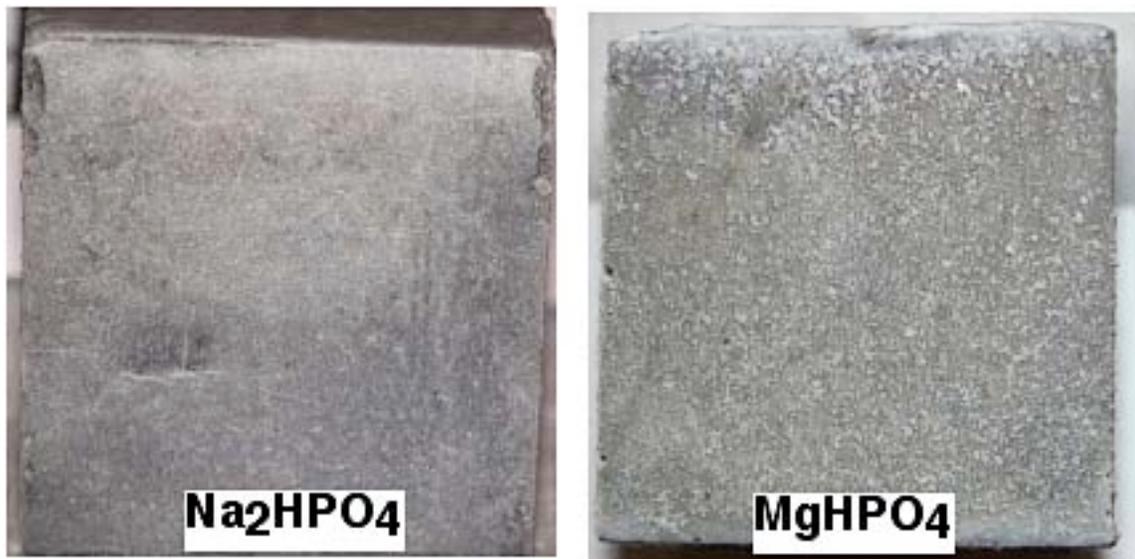


Figure 3 Details of surfaces of cube specimens stored in Na_2HPO_4 and MgHPO_4 solutions for 12 months.

4.2.2 Length and weight change results

The samples conditioned in $\text{Ca}(\text{OH})_2$ provide the reference for comparison with the specimens conditioned in the phosphate solutions. The results obtained for weight and length changes are illustrated in Figures 4 and 5, respectively. The actual data utilized to prepare these figures is found in the appendix. The expansion shown for the specimens conditioned in the

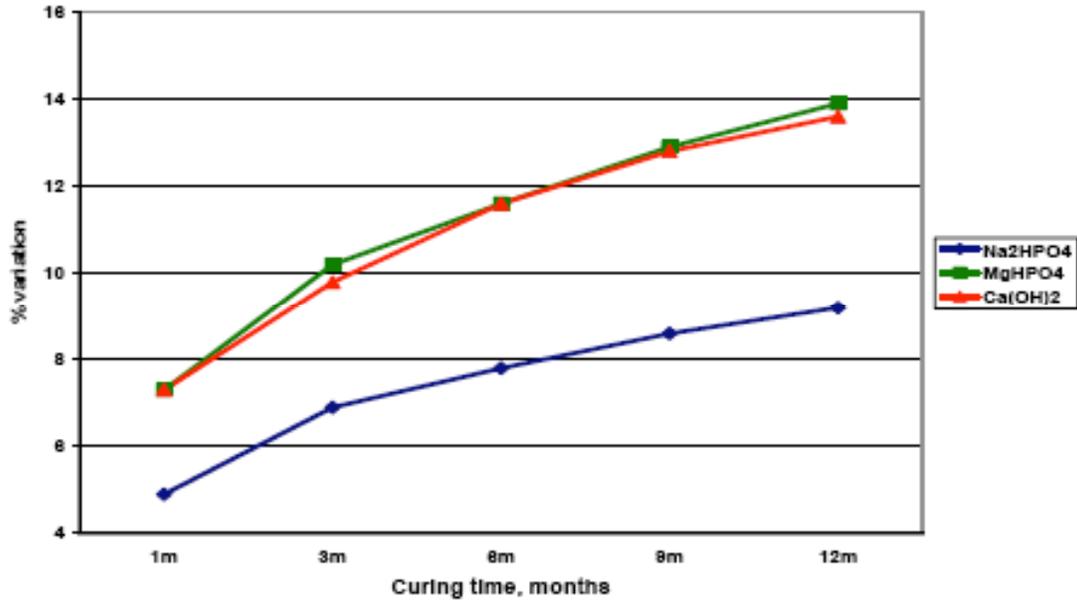


Figure 4 Comparison of length change results as function of time.

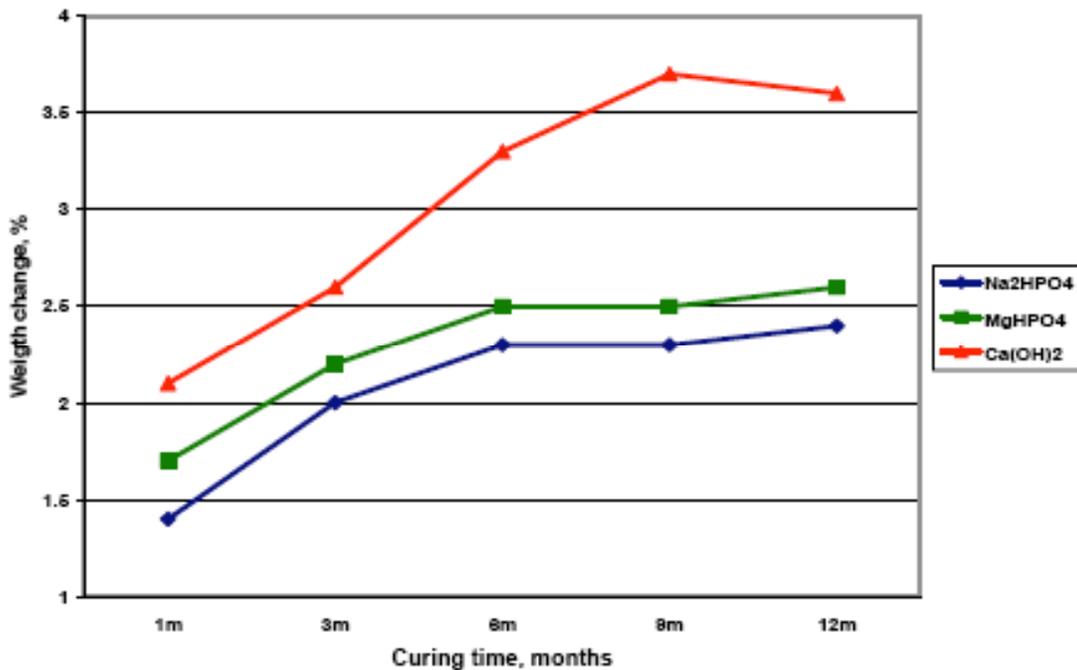


Figure 5 Comparison of weight change results as function of time.

MgHPO₄ solution is comparable to that exhibited by the reference Ca(OH)₂ solution. Results obtained for the specimens conditioned in the Na₂HPO₄ solution exhibit a reduced length change relative to that obtained for the Ca(OH)₂ reference.

The weight change for the specimens conditioned in the phosphate solutions is less than that obtained for specimens conditioned in the reference Ca(OH)₂ solution. The curve obtained for the specimens conditioned in the MgHPO₄ solution shows a slight increase in weight gain relative to the specimens conditioned in the Na₂HPO₄ solution. Some of the differences in weight change can be attributed to differences in the propensity of the solutions for crystal formation on the specimens surfaces (e.g., specimens conditioned in the MgHPO₄ solution tend to also form carbonate crystals).

4.2.3 Compressive strength results

Three specimens were tested after twelve months of conditioning in each of the solutions. The compressive strength tests were performed according to the standard ASTM C109, “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars.” Figure 6 presents a summary of results obtained to date. The error bar associated with each average result

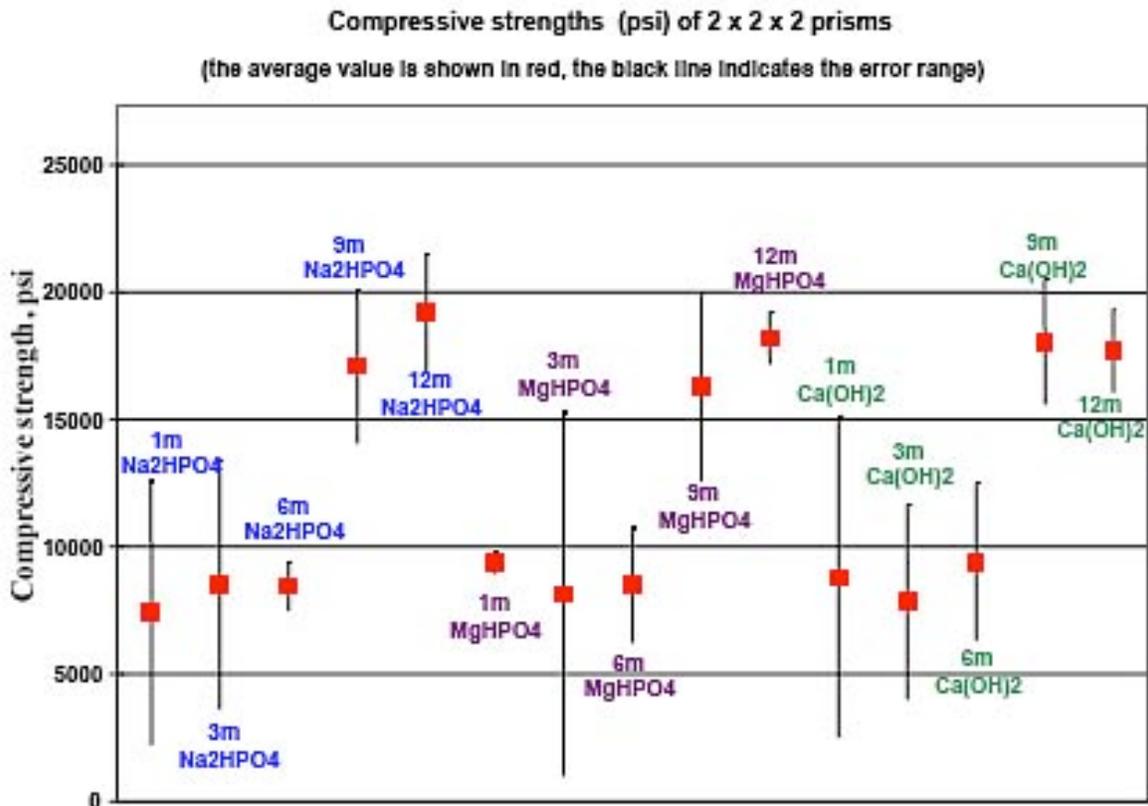


Figure 6 Compressive strength test results.

is also provided on the graph. For some results, the error bar is wide; this is usually caused by some defect present in one of the test specimens. A statistical evaluation of the measurements did not allow removing any measured value as an outlier. The actual data utilized to prepare this figure is found in the appendix. The results indicate that there is no significant difference between the compressive strength of specimens conditioned in the phosphate solutions and the reference $\text{Ca}(\text{OH})_2$ solution.

4.2.4 X-ray diffraction results

Specimens tested after 12 months of conditioning in each of the solutions were first dried for 4 days in an oven at 80°C to remove the non-reacted water to stop further reactions. An aliquot of each specimen was then crushed and sieved to obtain material passing a $75\ \mu\text{m}$ sieve. X-ray diffraction examinations of the material were performed using a Scintag PADV vertical theta/2-theta goniometer available at the ORNL High Temperature Materials Laboratory (HTML). This instrument coupled with the Jade[®] software permits phase identification by means of computer search-match using the entire Powder Diffraction File. The spectra obtained for samples conditioned in each of the solutions were found to be very similar. Hydrated phases identified included: Portlandite [$\text{Ca}(\text{OH})_2$], C-S-H (calcium silicate hydrates), and possibly Ettringite. Peaks of non-hydrated cement phases identified included: C_4AF (Brownmillerite), C_3S (tricalcium silicate) and C_2S (dicalcium silicate). No mineral containing phosphate was identified. X-ray diffraction spectra for material from specimens conditioned in Na_2HPO_4 , MgHPO_4 , and $\text{Ca}(\text{OH})_2$ are presented in Figures 7-9, respectively.

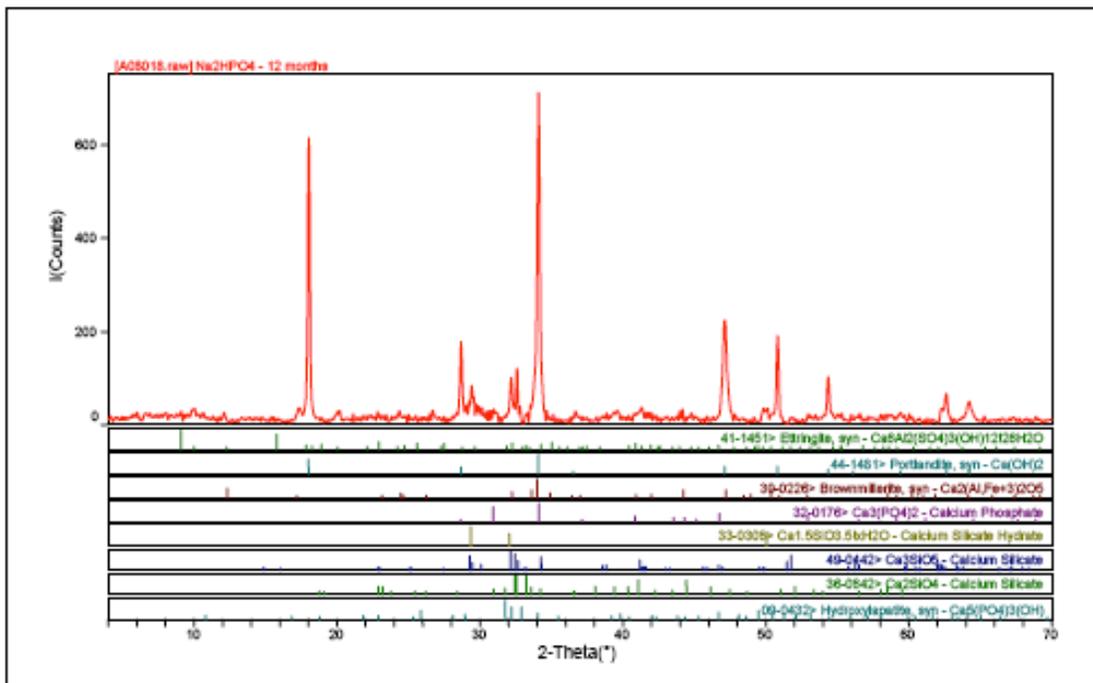


Figure 7 XRD spectrum of specimen conditioned 12 months in Na_2HPO_4 .

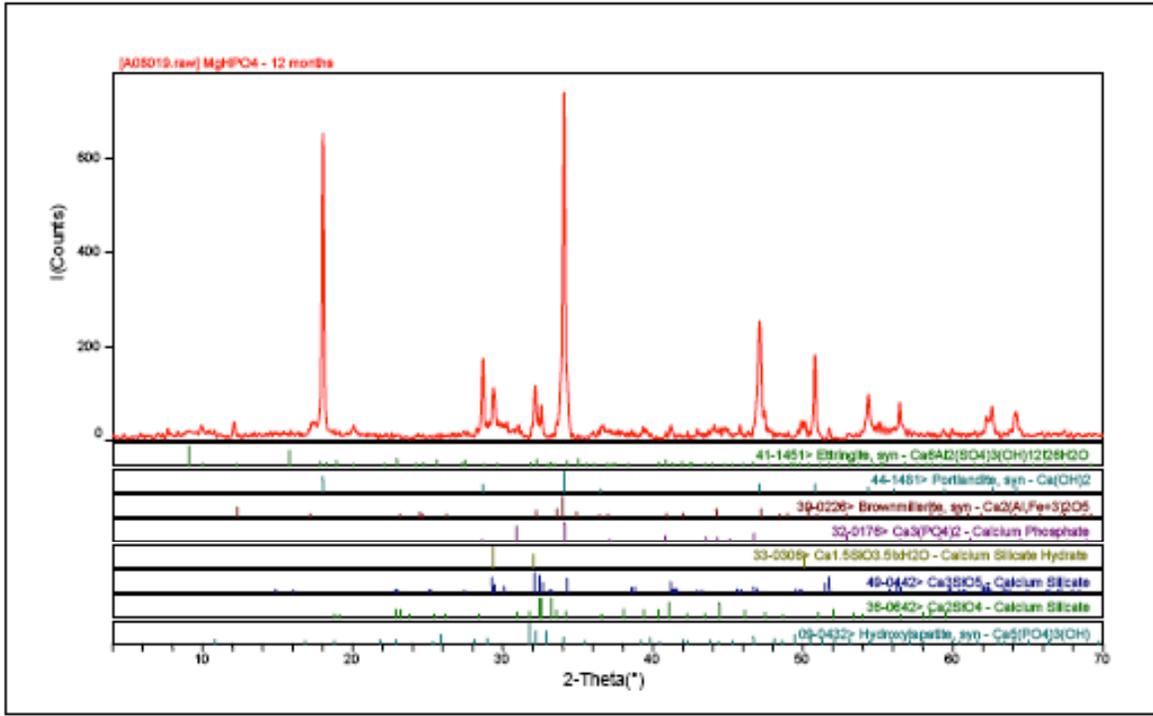


Figure 8 XRD spectrum of specimen conditioned 12 months in MgHPO₄.

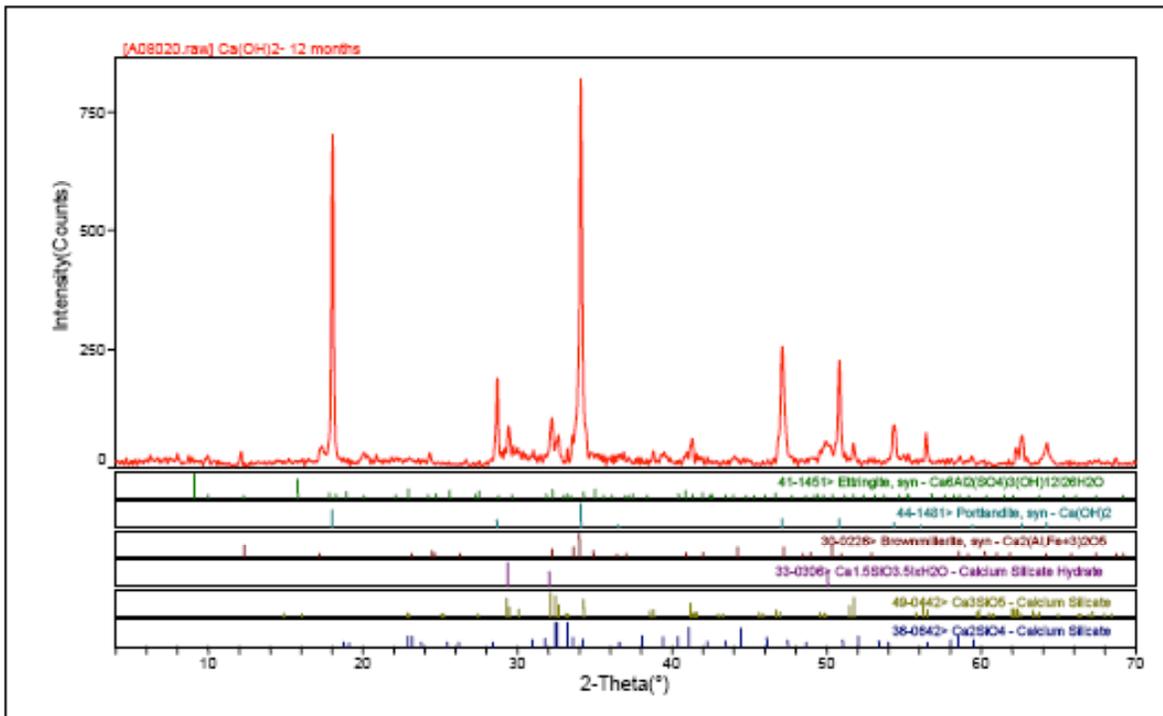


Figure 9 XRD spectrum of specimen conditioned 12 months in Ca(OH)₂.

4.2.5 SEM examination results

The scanning-electron microscope (SEM) examinations performed on specimens after 12 months of conditioning in each of the solutions confirmed the results found by X-ray diffraction. Phosphate-containing crystals were not observed in the specimens even at locations close to the exposed surfaces of the cement paste cubes. Mineralogical phases observed were C-S-H, Ettringite, Portlandite, calcium sulfoaluminates and non-hydrated clinker. These phases are typical of those observed in cement paste specimens that had been cured under control conditions [e.g., in a $\text{Ca}(\text{OH})_2$ solution]. The cement paste did not appear to have been modified as a result of the 12 months of conditioning in the phosphate solutions. Figures 10 – 14 provide SEM results showing typical phases observed in specimens that had been conditioned in the Na_2HPO_4 and MgHPO_4 solutions.

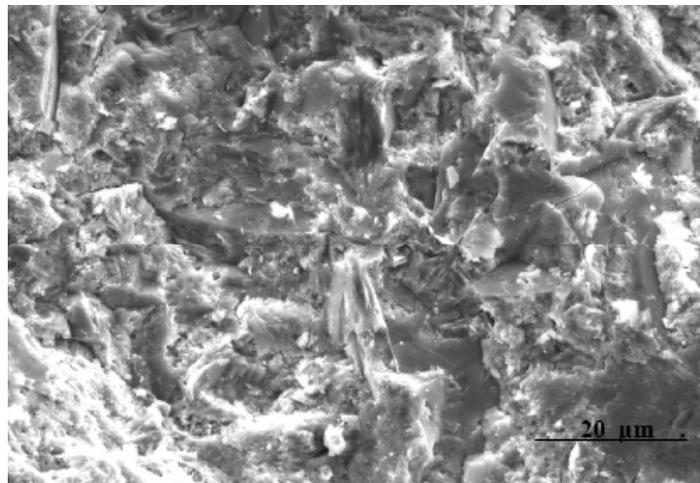


Figure 10 SEM result showing of cement paste – 12 months conditioning in Na_2HPO_4 solution.

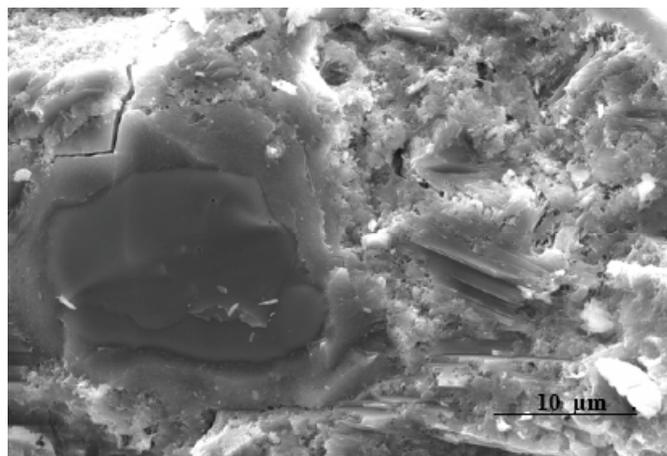


Figure 11 SEM result showing C_3S surrounded by dense layer of C-S-H – 12 months conditioning in Na_2HPO_4 solution [$\text{Ca}(\text{OH})_2$ and calcium sulfoaluminates visible in cement paste].

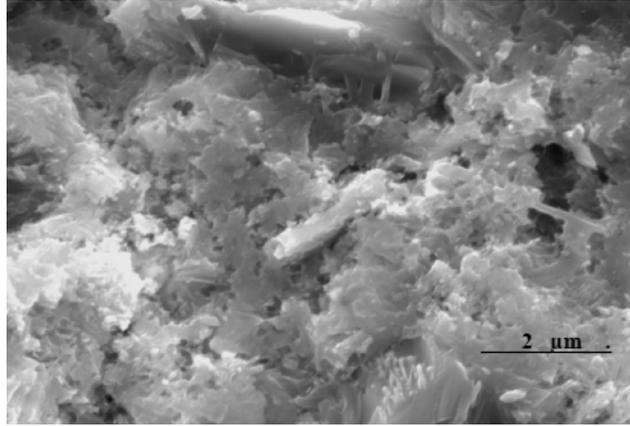


Figure 12 SEM result showing C-S-H and sulfoaluminates – 12 months conditioning in Na_2HPO_4 solution.

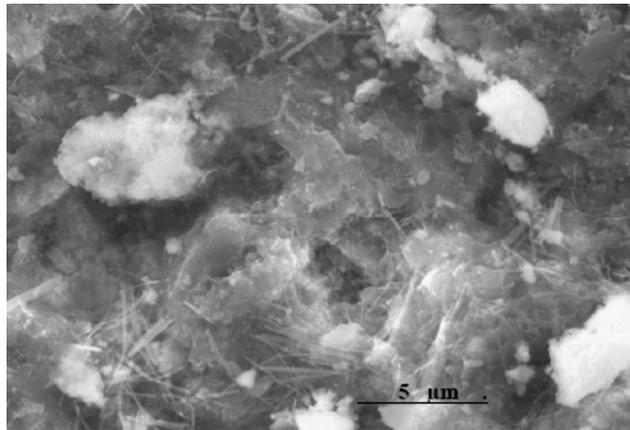


Figure 13 SEM result showing Ettringite in cement paste – 12 months conditioning in MgHPO_4 solution.

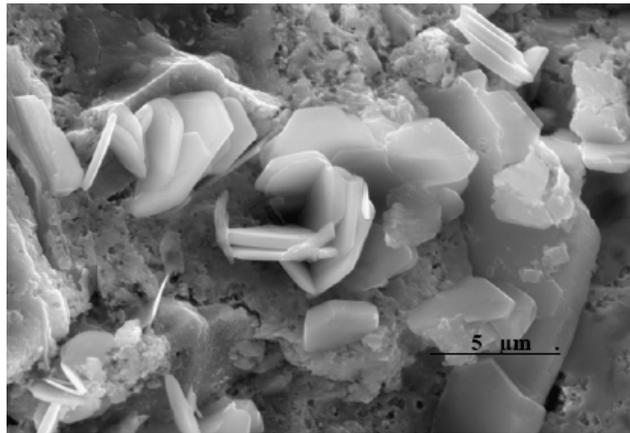


Figure 14 SEM result showing Calcium sulfoaluminates – 12 months conditioning in MgHPO_4 solution.

4.2.6 Future tests

Sufficient numbers of specimens remain that additional testing can be performed. Current plans are to remove the specimens from the three solutions after 18 months of conditioning and repeat the testing performed at 12 months.

5. Conclusions

After 12 months of conditioning in either of the phosphate solutions the specimens exhibited either an equivalent length change (MgHPO_4) or a reduced length change (Na_2HPO_4) relative to that obtained from specimens conditioned in the reference $\text{Ca}(\text{OH})_2$ solution. Weight gains exhibited by specimens conditioned for 12 months in the phosphate solutions were similar, but less than that observed for specimens conditioned in the reference $\text{Ca}(\text{OH})_2$ solution. The weight gain exhibited by specimens conditioned in the Na_2HPO_4 was slightly less than that obtained for specimens conditioned in the MgHPO_4 solution. Compressive strength results obtained for specimens conditioned in the phosphate solutions were comparable to those obtained from specimens conditioned in the reference $\text{Ca}(\text{OH})_2$ solution. X-ray diffraction and scanning-electron microscope results indicate that similar mineralogical phases have been observed for specimens conditioned in the phosphate solutions and the reference $\text{Ca}(\text{OH})_2$ solution. Phosphate-containing crystals have not been observed in specimens conditioned in either of the phosphate solutions. After 12 months of conditioning no sign of deleterious effects of phosphate salts on cement pastes have been observed.

APPENDIX

Tabulation of Results

**LENGHT AND WEIGHT VARIATION FOR THE SPECIMENS
CURED IN Na₂HPO₄**

		1	2	3	4	5	6	7	
To 2/8/2005	Wt (g)	393.29	408.12	409.79	393.73	410.52	403.47	413.07	
	length	940	955	1075	1112	1238	1178	1128	
28d cure 3/1/2005	Wt (g)	393.44	408.37	410.1	394.41	410.69	403.85	413.4	
	length	878	894	997	1060	1159	1116	1064	
1 month	Wt (g)	400.06	413.45	414.41	400.58	415.36	410.09	420.07	
	Δ Wt (g)	6.62	5.08	4.31	6.17	4.67	6.24	6.67	
	Δ Wt (%)	1.7	1.2	1.1	1.6	1.1	1.5	1.6	+ 1.4% average
	length	926	944	1062	1102	1214	1160	1109	
	Δ length	48	50	65	42	55	44	45	
	Δ length (%)	5.5	5.6	6.5	4.0	4.7	3.9	4.2	+ 4.9% average
3 m	Wt (g)	402.78	415.56	416.11	403.31	417.1	412.87	423.04	
	Δ Wt (g)	9.34	7.19	6.01	8.9	6.41	9.02	9.64	
	Δ Wt (%)	2.4	1.8	1.5	2.3	1.6	2.2	2.3	+ 2.0% average
	length	947	964	1078	1119	1241	1182	1128	
	Δ length	69	70	81	59	82	66	64	
	Δ length (%)	7.9	7.8	8.1	5.6	7.1	5.9	6.0	+ 6.9% average
6 m	Wt (g)	404.09	416.4	416.77	404.64	417.77	414.18	424.42	
	Δ Wt (g)	10.65	8.03	6.67	10.23	7.08	10.33	11.02	
	Δ Wt (%)	2.7	2.0	1.6	2.6	1.7	2.6	2.7	+ 2.3% average
	length	956	977	1087	1127	1247	1187	1139	
	Δ length	78	83	90	67	88	71	75	
	Δ length (%)	8.9	9.3	9.0	6.3	7.6	6.4	7.0	+ 7.8% average
9 m	Wt (g)	404.5	416.65	416.86	405.04	417.79	414.55	425.01	
	Δ Wt (g)	11.06	8.28	6.76	10.63	7.1	10.7	11.61	
	Δ Wt (%)	2.8	2.0	1.6	2.7	1.7	2.6	2.8	+ 2.3% average
	length	964	985	1098	1135	1256	1195	1145	
	Δ length	86	91	101	75	97	79	81	
	Δ length (%)	9.8	10.2	10.1	7.1	8.4	7.1	7.6	+ 8.6% average
12 m	Wt (g)	404.71	416.75	416.99	405.37	417.91	414.93	425.24	
	Δ Wt (g)	11.27	8.38	6.89	10.96	7.22	11.08	11.84	
	Δ Wt (%)	2.9	2.1	1.7	2.8	1.8	2.7	2.9	+ 2.4% average
	length	967	992	1104	1143	1265	1200	1152	
	Δ length	89	98	107	83	106	84	88	
	Δ length (%)	10.1	11.0	10.7	7.8	9.1	7.5	8.3	+ 9.2% average

**VARIATION OF LENGTH AND WEIGHT FOR THE SPECIMENS CURED
IN MgHPO₄**

		8	9	10	11	12	13	14	
To	Wt (g)	401.15	413.52	408.48	405.18	399.87	403.83	401.45	
2/8/2005	length	1116	1167	952	957	1136	1052	1030	
28d cure	Wt (g)	401.06	413.32	407.89	405.89	400.07	403.99	401.92	
3/1/2005	length	1038	1081	885	904	1067	968	963	
1 month	Wt (g)	408.18	418.16	416.92	414.58	405.06	408.71	409.68	
	Δ Wt (g)	7.12	4.84	9.03	8.69	4.99	4.72	7.76	
	Δ Wt (%)	1.8	1.2	2.2	2.1	1.2	1.2	1.9	+ 1.7% average
	length	1107	1158	955	969	1134	1049	1034	
	Δ length	69	77	70	65	67	81	71	
	Δ length (%)	6.6	7.1	7.9	7.2	6.3	8.4	7.4	+ 7.3% average
3 m	Wt (g)	410.64	420.4	418.93	416.5	407.4	410.6	411.99	
	Δ Wt (g)	9.58	7.08	11.04	10.61	7.33	6.61	10.07	
	Δ Wt (%)	2.4	1.7	2.7	2.6	1.8	1.6	2.5	+ 2.2% average
	length	1132	1183	986	1000	1162	1082	1060	
	Δ length	94	102	101	96	95	114	97	
	Δ length (%)	9.1	9.4	11.4	10.6	8.9	11.8	10.1	+ 10.2% average
6 m	Wt (g)	412.04	421.38	419.78	417.66	408.58	411.56	413.28	
	Δ Wt (g)	10.98	8.06	11.89	11.77	8.51	7.57	11.36	
	Δ Wt (%)	2.7	2.0	2.9	2.9	2.1	1.9	2.8	+ 2.5% average
	length	1148	1198	998	1012	1177	1095	1077	
	Δ length	110	117	113	108	110	127	114	
	Δ length (%)	10.6	10.8	12.8	11.9	10.3	13.1	11.8	+ 11.6% average
9 m	Wt (g)	412.29	421.6	420.11	417.88	408.99	411.73	413.75	
	Δ Wt (g)	11.23	8.28	12.22	11.99	8.92	7.74	11.83	
	Δ Wt (%)	2.8	2.0	3.0	3.0	2.2	1.9	2.9	+ 2.5% average
	length	1160	1208	1013	1029	1185	1108	1088	
	Δ length	122	127	128	125	118	140	125	
	Δ length (%)	11.8	11.7	14.5	13.8	11.1	14.5	13.0	+ 12.9% average
12 m	Wt (g)	412.59	421.68	420.44	418.12	409.05	412.07	413.96	
	Δ Wt (g)	11.53	8.36	12.55	12.23	8.98	8.08	12.04	
	Δ Wt (%)	2.9	2.0	3.1	3.0	2.2	2.0	3.0	+ 2.6% average
	length	1170	1215	1027	1040	1196	1114	1094	
	Δ length	132	134	142	136	129	146	131	
	Δ length (%)	12.7	12.4	16.0	15.0	12.1	15.1	13.6	+ 13.9% average

**VARIATIONS OF LENGTH AND WEIGHT FOR THE SPECIMENS
CURED IN Ca(OH)₂**

		15	16	17	18	19	20	
To	Wt (g)	411.4	402.53	406.17	403.29	416.1	402.53	
2/8/2005	length	1240	1176	1049	1125	1057	967	
28d cure	Wt (g)	411.6	402.99	406.62	403.32	415.77	402.41	
3/1/2005	length	1167	1112	975	1048	962	896	
1 month	Wt (g)	418.2	412.78	416.26	412.28	422	412.68	
	Δ Wt (g)	6.67	9.79	9.64	8.96	6.23	10.27	
	Δ Wt (%)	1.6	2.4	2.4	2.2	1.5	2.6	+ 2.1% average
	length	1240	1179	1049	1120	1045	970	
	Δ length	73	67	74	72	83	74	
	Δ length(%)	6.3	6.0	7.6	6.9	8.6	8.3	+ 7.3% average
3 m	Wt (g)	420.2	414.62	418.2	414.42	423.85	414.52	
	Δ Wt (g)	8.65	11.63	11.58	11.1	8.08	12.11	
	Δ Wt (%)	2.1	2.9	2.8	2.8	1.9	3.0	+ 2.6% average
	length	1268	1198	1073	1147	1075	998	
	Δ length	101	86	98	99	113	102	
	Δ length (%)	8.7	7.7	10.1	9.4	11.7	11.4	+ 9.8% average
6 m	Wt (g)	423.2	417.43	421.19	416.23	427.39	418.07	
	Δ Wt (g)	11.65	14.44	14.57	12.91	11.62	15.66	
	Δ Wt (%)	2.8	3.6	3.6	3.2	2.8	3.9	+ 3.3% average
	length	1285	1227	1089	1156	1094	1018	
	Δ length	118	115	114	108	132	122	
	Δ length (%)	10.1	10.3	11.7	10.3	13.7	13.6	+ 11.6% average
9 m	Wt (g)	424.4	419.15	422.53	418.06	428.4	419.15	
	Δ Wt (g)	12.89	16.16	15.91	14.74	12.63	16.74	
	Δ Wt (%)	3.1	4.0	3.9	3.7	3.0	4.2	+ 3.7% average
	length	1299	1241	1100	1170	1104	1029	
	Δ length	132	129	125	122	142	133	
	Δ length (%)	11.3	11.6	12.8	11.6	14.8	14.8	+ 12.8% average
12 m	Wt (g)	424.1	418.84	422.21	418.22	428.45	419.29	
	Δ Wt (g)	12.57	15.85	15.59	14.9	12.68	16.88	
	Δ Wt (%)	3.1	3.9	3.8	3.7	3.0	4.2	+ 3.6% average
	length	1304	1247	1111	1178	1109	1038	
	Δ length	137	135	136	130	147	142	
	Δ length (%)	11.7	12.1	13.9	12.4	15.3	15.8	+ 13.6% average

Compressive strength for the specimens cured in Ca(OH)₂

	Wt (t ₀) 2/8/2005	Wt after cure 3/1/2005	1 month exposure		3 months exposure		6 months exposure		9 months exposure		12 months exposure	
			Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive Strength (psi)
37	267.44	268.87	275.3	7170								
38	274.53	275.26			284.1	7190						
39	269.7	270.52			279.4	9600						
40	271.56	271.61			280.8	6740						
41	272.07	272.01	279.4	11230								
42	270.24	270.13	277.5	10640								
43	271.63	271.59										
44	274.07	274.76										
45	274.17	274.42	281.8	6130							287.1	18300
46	267.15	269.32		average							287.02	17060
47	275	277.22		8793							283.91	17600
48	270.04	270.12		sd			281.2	8760				average
49	271.83	271.97		2522								17653
50	271.91	271.9		error								sd
51	273.01	273.2		6260						283.9	18230	622
52	271.1	271.01					282	10840				error
53	273.71	273.92										1543
54	272.58	272.64					283.7	8650		286.5	18950	
weight variation (%)			2.39		3.21		4.10		3.81		4.49	
			2.72		3.29		4.06		4.42		4.59	
			2.69		3.38		4.05		4.60		5.42	
Ca(OH) ₂	average	2.60	average	3.29	average	4.07	average	4.28	average	4.83		
Δ Wt (%)	sd	0.18	sd	0.08	sd	0.03	sd	0.42	sd	0.51		
	error	0.45	error	0.20	error	0.07	error	1.04	error	1.26		

Compressive strength for the specimens cured in Na₂HPO₄

	Wt (g)		1 month exposure		3 months exposure		6 months exposure		9 months exposure		12 months exposure	
	2/8/2005	3/1/2005	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)
1	274.01	275.58	279.26	5840								
2	265.72	265.75	270.42	9780								
3	273.72	273.76	278.29	6630								
4	266.49	266.73		average	273.74	6800						
5	274.52	276.19		7417	281.7	8110						average
6	272.75	274		sd	279.7	10660						19163
7	274.12	274.66		2084			282.46	8840				sd
8	273.09	273.35		error			281.36	8450				893
9	277.27	277.42		5175			284.77	8080				error
10	274.24	274.96						average	282.31	15890		2216
11	270.05	270.78						8457	278.08	17100		
12	274.14	274.25						sd	282.37	18260		
13	264	264.25						380		average	272.72	18730
14	273.54	273.97						error		17083	282.26	20190
15	273.63	274.31						943		sd	281.85	18570
16	275.92	277.35								1185		
17	273.59	274.15								error		
18	276.39	276.85								2942		

Weight variation

(%)		1.34		2.63		2.84		2.67		3.21
		1.76		2.00		2.93		2.70		3.03
		1.65		2.08		2.65		2.96		2.75

Na ₂ HPO ₄	average	1.58	average	2.23	average	2.81	average	2.78	average	2.99
Δ Wt (%)	sd	0.22	sd	0.34	sd	0.14	sd	0.16	sd	0.23
	error	0.55	error	0.85	error	0.36	error	0.40	error	0.57

Compressive strength for the specimens cured in MgHPO₄

			1 month exposure		3 months exposure		6 months exposure		9 months exposure		12 months exposure	
	Wt (to) 2/8/2005	Wt after cure 3/1/2005	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)	Wt (g)	Compressive strength (psi)
19	274.81	276.46			285.28	4830						
20	274.04	274.79			284.28	9920						
21	273.62	275.33			284.28	9680						
22	268.11	268.39				average						
23	273.11	273.53				8143						
24	274.82	275.14				sd						
25	275.65	276.43				2872					285.92	18670
26	274.2	275.14				error					284.93	17990
27	276.81	276.89		error		7130		error			287.43	18080
28	271.39	271.45		423				2233	281.83	16660		average
29	273.51	273.42		sd				sd	283.85	17600		18247
30	269.2	269.19		170				900	280.36	14700		sd
31	273.96	273.85		average			282.57	8160		average		369
32	271.29	271.83		9403			278	7820		16320		error
33	274.38	274.43					283.75	9520		sd		917
34	272.44	272.73	279.79	9390				average		1480		
35	268.72	269.4	274.7	9240				8500		error		
36	270.67	271.29	277.24	9580						3673		
weight variation (%)			2.59		3.19		3.18		3.82		3.43	
			1.97		3.45		2.27		3.81		3.56	
			2.19		3.25		3.40		4.15		3.81	
MgHPO ₄	average	2.25	average	3.30	average	2.95	average	3.93	average	3.60		
ΔWt (%)	sd	0.31	sd	0.14	sd	0.60	sd	0.19	sd	0.19		
	error	0.78	error	0.34	error	1.49	error	0.47	error	0.47		