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# **Evaluation of Stratlingite-Hydrogarnet Glass Cement As a Quick-Setting Patching Material**

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# Contents

Acknowledgments .....	iii
List of Figures .....	vii
List of Tables .....	ix
Abstract .....	xi
Executive Summary .....	1
1 Introduction .....	3
1.1 Purpose and Scope .....	3
1.2 Test Program .....	3
1.3 Technical Background .....	4
1.3.1 S-HG Cements .....	4
1.3.2 Patching Materials .....	5
2 Experimental Procedure .....	6
2.1 Glass Cement Production .....	6
2.2 Compressive Strength Tests .....	6
2.3 Tensile and Bond Strength Tests .....	6
2.4 Shrinkage Tests .....	7
3 Test Data and Discussion - Corning Study .....	9
3.1 Glass Composition Study .....	9
3.2 Microstructure .....	9
3.3 Porosity .....	10
4 Test Data and Discussion - Lehigh Study .....	16
4.1 Compressive Strength of Neat Cements .....	16
4.2 Compressive Strength of Mortars .....	16
4.3 Effect of w/c ratio on Compressive Strength .....	17
4.4 Bonding to Portland Cement Concrete .....	18
4.5 Shrinkage Behaviour .....	18
4.6 Comparison to leading Commercial Patching Materials .....	19

<b>5</b>	<b>Conclusion and Recommendations</b>	<b>41</b>
5.1	Conclusion	41
5.2	Recommendations for Future Work	41
5.3	Summary	42
<b>References</b>		<b>43</b>

## List of Figures

2-1	Briquette Specimen for Bond Strength Test .....	8
3-1	Region of Statlingite-Hydrogarnet Glass (S-HG) Cements .....	12
3-2	SEM (Polished Section) of a Hydrogarnet Cement Paste (Comp. #6) .....	13
3-3	Polished SEM of a Stratlingite Cement Paste (#7) .....	14
3-4	Polished and Etched SEM of a Stratlingite Cement Paste (#7) .....	14
3-5	SEM of Fracture Section of a Cured High Early Strength Cement Paste (Comp #1) .....	15
4-1	Strength Gain Curve Neat Cement Paste: 0.4 w/c ratio .....	33
4-2	Strength Gain Curve Neat Cement Paste: 0.5 w/c ratio .....	34
4-3	Strength Gain Curve Neat Cement Paste: 0.6 w/c ratio .....	35
4-4	W/c Ratio vs. Strength Behaviour for Neat Cement Pastes .....	36
4-5	Strength Gain Curve Sand Mortar : 0.4 w/c ratio .....	37
4-6	Strength Gain Curve Sand Mortar : 0.5 w/c ratio .....	38
4-7	Shrinkage of Blend #1 Mortar .....	39
4-8	Shrinkage of Blend #3 Mortar .....	40

## List of Tables

Table 3-1	Corning Glass Cement Compositions in Percent Weight and Molar Ratio . . . . .	11
Table 4-1	Compressive Strength of Neat Cement Paste #1 . . . . .	20
Table 4-2	Compressive Strength of Neat Cement Paste #2 . . . . .	21
Table 4-3	Compressive Strength of Neat Cement Paste #3 . . . . .	22
Table 4-4	Comparison of Neat Cement and Sand Mortar Strengths . . . . .	23
Table 4-5	Compressive Strength of Sand Mortar #1 . . . . .	24
Table 4-6	Compressive Strength of Sand Mortar #2 . . . . .	25
Table 4-7	Compressive Strength of Sand Mortar #3 . . . . .	25
Table 4-8	Compressive Strength of Sand Mortar #4 . . . . .	26
Table 4-9	Compressive Strength of Sand Mortar #5 . . . . .	27
Table 4-10	Comparison of Effect of w/c ratio on Compressive Strength . . . . .	28
Table 4-11	Tensile and Bond Strength of Blend #1 . . . . .	28
Table 4-12	Tensile and Bond Strength of Blend #3 . . . . .	29
Table 4-13	Tensile and Bond Strength of Blend #4 . . . . .	29
Table 4-14	Tensile and Bond Strength of Blend #5 . . . . .	30
Table 4-15	Comparison of Tensile and Bond Strength Results . . . . .	30
Table 4-16	Shrinkage of Blend #1 and Companion PC Mortar ( $\times 10^{-6}$ ) . . . . .	31
Table 4-17	Shrinkage of Blend #3 and Companion PC Mortar ( $\times 10^{-6}$ ) . . . . .	32



## **Abstract**

**Stratlingite-Hydrogarnet Glass (S-HG) cements, a new type of high alumina cements developed by Corning Glass Works, was evaluated for highway and bridge-deck patching applications. Results of the first phase of the project is reported. Five blends of S-HG cement are tested and two promising blends identified. Data obtained from this preliminary set of tests strongly suggest that S-HG cements can be developed into an excellent high early strength highway patching material.**

## Executive Summary

A new family of stratlingite-hydrogarnet glass (S-HG) glass cements with high early strength and low porosity was discovered and patented by the Corning laboratories. A glass cement study by Corning showed that stratlingite (gehlenite hydrate) could constitute the principal phase of a strong, fast-setting cement. Prior hydration studies by others of  $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$  (C-A-S) glasses have concluded that: (1) activators such as Portland cement clinker, gypsum, or lime were required to produce practical rates of hydration; and (2) stratlingite was only a transient phase in the hydration of these glasses. However, Corning scientists formed stable stratlingite cement pastes directly from glass without the use of activators.

Corning found glasses that hydrated to a mixture of stratlingite and hydrogarnet with initial sets of one to two hours, final sets of three to four hours, and achieved up to 10,000 psi compressive strength in four hours. These cement pastes also displayed higher porosities than the slow-curing pure stratlingite cements, but had much lower porosities than the slow-curing pure stratlingite cements, but had much lower porosities than Portland or other commercial cements. Figure 1 shows the microstructure topography of stratlingite cement paste with dense granular interlocking and minimal voids.

## 1. Introduction

### 1.1 Purpose and Scope

About five years ago researchers at Corning Laboratories developed and patented (Maddowell, 1986a) a new type of hydraulic cement. This new family of cements, Stratlingite Hydrogamet (S-HG), was found to be fast-setting, developed high early strength and had low porosity. Corning Market researchers looking for an application for S-HG cements identified highway and bridge deck patching as a possible area where this material might be used.

The work presented in this report was jointly conducted by Corning Glass Works and Lehigh University, and supported by the Strategic Highway Research Program (SHRP). The purpose of the project is to evaluate S-HG cements as highway patching materials. The goals set for this phase of research was,

- To identify the most promising composition from the family of S-HG cements based on their performance
- To evaluate the potential of this material as a quick-setting patching cement and establish whether the material merits further detailed testing

### 1.2 Test Program

Since this goal of this phase of research was limited to comparing the different blends and to determine viability of the material as a patching material, a few basic properties were identified as being critical to the proposed patching application. The test program was devised to investigate these properties. Initially five compositions, shown by studies at Corning to be promising, were to be studied. After the initial tests, one or two of the better performing blends were to be studied in more detail.

The compressive strength of concrete is often taken as an important index of its quality, and is frequently determined as an index toward the estimation of other characteristics. So compressive strength was identified as the most important criteria. In the patching application a sound bond between the freshly poured concrete and the existing underlying structure is essential. The bond strength with concrete was taken as the next most important criterion. Besides this two other properties such as the shrinkage and freeze-thaw characteristics of the material is also very important because these properties correlate with the durability of the patch. These properties were also incorporated into the test program.

The test program was organised under two broad tasks. The first task focused on evaluating compressive strength of different compositions. Water-to-cement (w/c) ratio and presence of fine aggregate were taken as the principal variables. The development of strength as a function of time after casting was studied under this task. The second task focused on the bond strength of the blends with Portland cement concrete. Bonding tests concentrated only on

mortars and only w/c ratio was taken as a variable. Tensile strength tests were also conducted to put the bond strength tests in perspective. The final bond strengths developed were studied in this task. Besides these tasks other tests such as shrinkage tests were also done on promising blends.

## 1.3 Technical Background

### 1.3.1 S-HG cements

The S-HG cements are a family of strong and durable cements which lie within a small polygonal region in the tripartite diagram of the Calcium AluminoSilicate system. Between 12% and 26% by wt. of  $\text{SiO}_2$ , 22-40% of  $\text{Al}_2\text{O}_3$ , and 45-55% of  $\text{CaO}$ . The addition of less than 10 moles of  $\text{TiO}_2$ ,  $\text{ZrO}_2$  and/or other oxides to the glass batches is also useful in regulating the structure and curing behaviour of the cements.

The principal crystalline hydrates formed during the curing process are Hydrogarnet ( $\text{C}_3\text{AH}_6$ ) and Gehlenite Hydrate ( $\text{C}_2\text{ASH}_8$ ) (or more correctly Stratlingite). Hydrogarnet is the dominant crystalline phase in glass cements containing between 12-15% by wt. of  $\text{SiO}_2$ , while Stratlingite predominates in hydrated glasses with  $\text{SiO}_2$  contents between 17-26%.

The cubic hydrogarnet structure is the only calcium aluminate hydrate stable under ambient conditions. This phase occurs in nature as hydrogrossular and as the final aluminate hydrate phase in commercial high alumina cements. When formed as a result of chemical conversion of hydrate phases such as  $\text{CAH}_{10}$  and  $\text{C}_2\text{AH}_8$ , a structural densification accompanied by substantial weakening in the concretes made from these cements may occur. Because this weakening process may be progressive over time and may impair the structural integrity of high alumina concretes, the use of these materials in load-bearing structural members has been banned throughout the world. (Neville, 1975) The hydrogarnet cements described in this paper, however, do not degrade in this manner because the hydrogarnet phase forms directly during hydration of the glasses. Thus, their use for structural purposes is a real possibility.

Perhaps the most significant result of the glass cement study at Corning was the discovery that Stratlingite (Gehlenite Hydrate) could constitute the principal phase of a strong, fast-setting cement. Locher extensively studied hydration of  $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$  glasses, but concluded (Locher, 1960) that,

- Activators such as Portland Cement clinker, gypsum or lime were required to produce practical rates of hydration.
- Stratlingite was only a transient phase in the hydration of these glasses.

In the Corning study, described by MacDowell, stable Stratlingite cement pastes were formed directly from glass without the use of activators. Furthermore, some of these pastes

displayed high early strength and an unusually dense structure with low porosity. After crystallization of the glass cements, hydration rates for these same compositions decreased dramatically, along with their compressive strengths. Apparently, the dissolution rate of crystalline Gehlenite in water is not sufficient to produce the practical hydration rates found with the amorphous cements.

Although the pure Stratlingite cement pastes were dense, strong, and had very low porosity, their slow setting times (1 to 3 days) eliminated most practical applications. Accelerators were used, but they tended to destroy the desirably dense Stratlingite structure. On the lower  $\text{SiO}_2$  end of the hydraulic glass cement composition region, pure Hydrogarnet formed in less than a minute ! Between these two extremes, however, glasses were found that hydrated to a mixture of Stratlingite and Hydrogarnet with initial setting time of 1-2 hours, final setting time of 3-4 hours and up to 10,000 psi of compressive strength in four hours. These cement pastes also displayed porosities of about 10% , higher than slow-curing pure Stratlingite cements (<5%), but much lower than Portland or other commercial cements (>25%).

### 1.3.2 Patching materials

Evaluating highway patching materials is a difficult task, which defies precise quantification. Many surveys (NTIS, 1977) (NCHRP, 1977) have been done, especially by the state transportation agencies, to evaluate the many patching materials available commercially. Attempts have been made (Spellman, 1972) to formulate a standardized approach towards evaluating patching materials. Surveys conducted among the state transportation agencies emphasize (Fowler, 1983) that the most desired qualities in a patching material are,

- rapid setting capability
- good bonding quality with Portland Cement Concrete
- durability

Adequate strength, quality performance over a wide temperature range and ease of using the material were also emphasized. Material cost was considered a less important factor since it constitutes but a small fraction of the total cost of a patching operation.

## 2. Experimental Procedure

### 2.1 Glass Cement Production

The glass cements were melted at 1600°C for two hours in platinum crucibles and quenched by pouring in cold tap water (drigaging). Batch materials used for the melts were,

1. SILCOSIL 75 Sand from Pennsylvania Glass Sand Co.
2. Low soda A-14  $\text{Al}_2\text{O}_3$  from Alcoa Corp.
3. Calcium Carbonate (Limestone) from the Warner Co.

Drigaged glass was crushed and then ballmilled to achieve an average glass particle diameter of between 8 and 15 microns. Specific surface area (Blaine) measured on selected powders varied between 3000 and 4000  $\text{cm}^2/\text{gm}$ .

### 2.2 Compressive Strength Tests

As per ASTM C109, mixes were cast in 2-inch (50 mm) cubes using bronze gang molds of three cubes each. The molds were cleaned, dried, and coated with wax before using.

Premeasured amounts of cement, sand, and tap water were placed into a 0.125 HP "soil" mixer and run at a speed of 17 cycles/min for 3-4 minutes. After mixing and pouring into three layers into the cube molds (as per ASTM C109), the cubes were covered with plastic bags and left in ambient air to cure. The cubes were stripped from the molds in about three hours after casting and weighed. When the cure exceeded 8 hours, the cast mix was capped with gypsum cement before testing to give the cube faces a smooth finish.

The compressive strength tests were carried out on a 60,000 lb. Universal Testing Machine (UTM) in the highest load range. The smallest division on the scale corresponded to 50 lbs. and the sensitivity of the measuring system is 1/1200. The loading was applied with a strain controlled hydraulic system, the loading rate was 0.1 inch/min. and load at failure was automatically recorded.

### 2.3 Tensile and Bond Strength Tests

Briquette specimens as per ASTM C190 specifications were used in the tensile mode bonding tests to portland cement concrete. Tensile tests were performed according to the specification. In the bonding tests, one-half of the briquette specimen was made out of Portland Cement Concrete (See Fig.2-1 ) and the other half was made out of S-HG cement mortar. The specimens were cast in bronze molds in gangs of three.

Tensile specimens from ordinary Portland Cement Concrete were initially fabricated and cured. Then these specimens were loaded in tension to failure. These halves were wetted and cleaned with a water jet, and then S-HG cement mortar was cast against it. The specimens were

cured in ambient air and tested at three days. These tests were performed on a 120,000 lb. UTM at the lowest load range of 1200 lbs.

## **2.4 Shrinkage Tests**

Specimens 11.25" long and 1" square in cross-section were used in this test. The tests were performed according to ASTM C157. The specimens were cast in bronze molds in gangs of four, two S-HG and two Type III fast setting PC companion specimens, and left in ambient air. One day after casting, the specimens were stripped from the mold and the lengths were measured. The shrinkage measurements were based on this one day length as the base length. Then the specimens were stored in a rack allowing free air passage. The length change was monitored upto four weeks after casting.

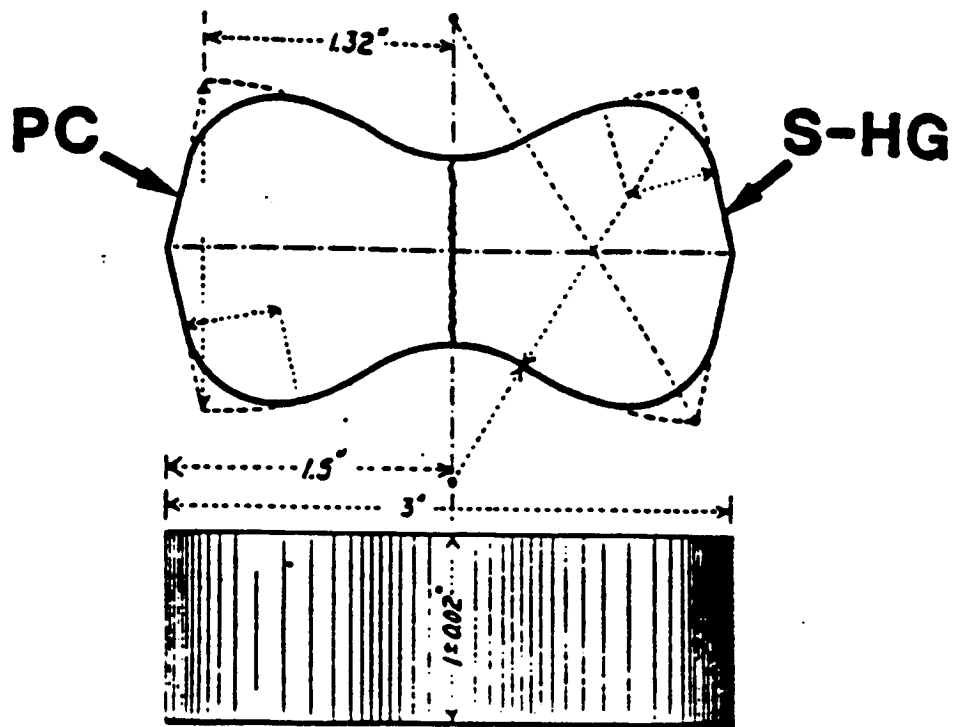


Figure 2-1: Briquette Specimen for Bond Strength Test



### 3. Test Data and Discussion - Corning Study

#### 3.1 Glass Composition Study

Figure 3-1 shows the region of the  $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$  system in which glass cements were found that produced neat pastes measuring greater than about 5000 psi compressive strength. The glass cements which hydrate predominately to hydrogarnet (HG) are fast curing (from less than a minute to 30 minutes), whereas the higher silica stratlingites (S) have curing times ranging from about 30 minutes to over 24 hours.

The small, round, crosshatched area near the center of the subject region delineates the optimum glass composition region for high early strength. Initial setting times of these preferred cement pastes vary from 30 to 90 minutes and final setting occurs between 60 and 180 minutes.

To achieve optimum development of crystallinity and to increase the rate of the final setting process, small amounts of a "nucleating catalyst" such as  $\text{TiO}_2$  or  $\text{ZrO}_2$  are added. Between two and seven mole percent of these oxides added to the glass batch before melting insures that initial and final setting times will fall between the practical limits of 30 and 240 minutes. The role of these minor additives is not well understood, but they seem to retard gel formation (initial set), while enhancing the crystallization (final set). On one hand they delay initial set, but at the same time accelerate the final set.

Table 3-1 lists five compositions (No. 1-5) that were selected for evaluation by the Fritz Engineering Laboratories at Lehigh University. Also listed for comparison are compositions 6 and 7 that hydrate directly to hydrogarnet and to stratlingite, respectively, as sole crystalline phases.

#### 3.2 Microstructure

Figure 3-2 is a scanning electron micrograph (polished section) of a typical hydrogarnet neat cement paste (#6 in Table 1). Note the large amount of open porosity evident.

Figure 3-3 is an S.E.M. of composition #7 (see Table 3-1) showing the relatively tight, non-porous structure of a pure stratlingite paste. Figure 3-4 is the same sample after etching in a mild acid solution, showing a platy, almost micaceous intergranular structure.

Figure 3-5 is a micrograph of composition 1 after polishing and etching the cured paste. Note the radial spherulitic structure of the stratlingite with evidence of occasional porosity, perhaps due to interference of the spherulitic growth by hydrogarnet. Based upon Figure 3-5, it can be postulated that the pure stratlingite composition #7 also consists of bladed spherulites that are intergrown and thus difficult to discern.

A pattern of fine cracks seems to be evident in the micrographs of the stratlingite pastes and probably results from the increase in density between the gel (initial cure) and crystalline (final cure) structures as the curing process proceeds.

S.E.M.s of glass cements 2,3 and 4 also displayed bladed spherulitic structures similar to Blend #1 (Shown in Figure 3-5).

### 3.3 Porosity

The principal difference between hydrogarnet and stratlingite pastes is structure related porosity. Mercury porosimetry has revealed that the cured paste of composition #6 (hydrogarnet) has over 30% porosity, while pure stratlingite (#7 in Table 3-1) has less than 2% ! Mixed S-HG high early strength pastes have measured between 10% and 15% porosity.

Modulus of Rupture (MOR) of the neat pastes (1 week cure) range from pure hydrogarnet (#6) at 6000 psi to over 16000 psi for the pure stratlingite paste (#7). The pattern of fine cracks that appears during the curing of the stratlingite cements (Figures 3-3, 3-4 and 3-5 ) may point to the reason that these relatively dense materials have only moderate strengths. The authors feel confident that if the fine cracks could be reduced or eliminated, MORs and compressive strengths would increase substantially. It seems remarkable that a material literally filled with griffith (greater than critical length) flaws could measure over 16,000 psi compressive strength !

Blend	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	TiO <sub>2</sub>	ZrO <sub>2</sub>
1	15.7 0.8	33.3 1.0	45.8 2.5	5.2 0.2	
2	17.8 0.9	33.5 1.0	46.1 2.5	2.6 0.1	
3	17.5 0.9	33.1 1.0	45.4 2.5		4.0 0.1
4	16.2 0.8	34.4 1.0	45.3 2.4		4.1 0.1
5					
6 (HG)	12.9 0.7	32.9 1.0	54.2 3.0		
7 (S)	16.2 0.8	34.1 1.0	41.5 2.2		8.3 0.2

**Table 3-1: Corning Glass Cement Compositions  
in % wt and Molar Ratio**

12

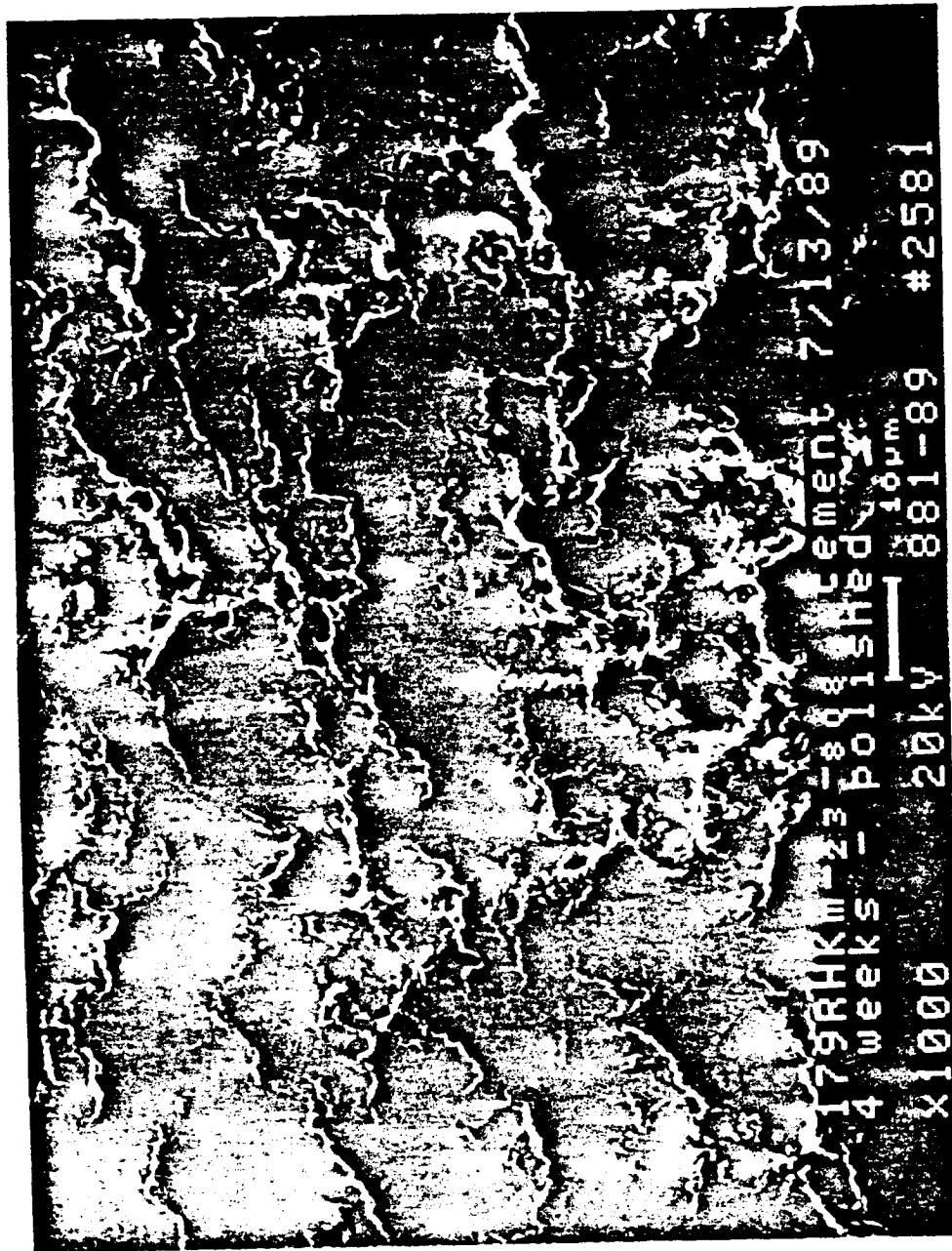


Figure 3-2: S.E.M. (Polished Section) of a  
Hydrogarnet Cement Paste (Comp.#6)



Figure 3-3: Polished S.E.M of a Stratlingite Cement Paste (#7)



Figure 3-4: Polished and Etched S.E.M of a Stratlingite Cement Paste (#7)



Figure 3-5: S.E.M. of Fracture Section of a cured High  
 Early Strength Cement Paste (Comp #1)

## 4. Test Data and Discussion - Lehigh Study

### 4.1 Compressive Strength of Neat Cements

Three compositions (#1 to #3) were tested for compressive strength of neat pastes. Neat cement pastes were used with water-to-cement (w/c) ratio varying from 0.4 to 0.6. All the compositions showed similar responses. The mix consistency for each w/c ratios were quite alike for all the compositions and there was a substantial exotherm one to three hours after casting in all the cases.

All three blends gained strength rapidly as expected and the neat cement cubes showed 5500 to 7000 psi compressive strength in the first three hours and 6000 to 8000 psi in eight hours after casting. The data is presented in Tables 4-1 to 4-3 and the strength gain curves are shown in Figures 4-1 to 4-3.

Paste #1 appeared to have the lowest strength after a 72 hour cure (7600 psi at 0.4 w/c ratio). After final set very fine cracks were observed on the face of the 2" cube specimen. Possibly the heat from the initial reaction was shunted away through the metal mold, causing the surface hydration reaction to trail the interior, thus setting up tensile stresses at the cubes surface. These microcracks could easily have caused the lower strength values. The final setting time for #1 was shortest of the three blends - about 2 hours.

Composition #2 was the strongest blend at this stage, with 8700 psi after 3 days at 0.4 w/c ratio. These cube faces were apparently crack-free. Composition #2 also had the longest final setting time of the three - about 3 1/2 hours.

Blend #3 was marginally stronger than #1 ( about 8000 psi at 3 days), but some cracking was apparent on the cube faces.

### 4.2 Compressive Strength of Mortars

Graded sand according to ASTM specifications C33 and C778 was used in the ratio of two parts sand to one part cement in all the mortar tests. W/c ratios of 0.4 and 0.5 were used (0.6 w/c was eliminated) with the mortar blends. Mortars from five blends (#1 to #5) were tested.

Results of compression tests on sand mortar specimens of the five Coming cement compositions are plotted in Figures 4-5 and 4-6.

While #1 exhibits a very rapid strength build-up to 8000 psi (See Table 4-5 ) in three hours and 10,000 psi in eight hours, blends #2 and #3 (See Tables 4-6 and 4-7 ) develop only 5500 psi to 6500 psi in eight hours, but catch up to #1 in about 24 hours. Comp. #5 was comparatively



weaker (See Table 4-9 ) and developed 4800 psi in four hours, 6000 psi in a day and eventually had a final strength of about 7000 psi in a week. Mortar made with #4 glass cement (See Table 4-8 ) set up even faster than #1, achieving an initial set of 30 minutes and developing a compressive strength of 7000 psi within 2 hours.

When the w/c ratio of #2 mortar was increased to 0.5, strength markedly decreased and on occasion the material failed to cure. Because of this erratic behaviour at high w/c ratios, #2 was not considered further as a pavement repair material without extensive testing to elucidate this sensitivity.

The strength capacity of mortar blends were distinctly higher than that of the neat pastes at all data points. Table 4-4 compares the final strength of the neat with the mortar cubes at 0.4 and 0.5 w/c ratios. "Final" strength is that averaged between 24 and 72 hours. Composition #1 mortar shows a 40% increase in compressive strength over the neat paste, whereas #2 and #3 show an increase of about 25%.

The problems of minute cracks in the cube faces and assymetric, brittle specimen failure frequently encountered with the neat pastes, were virtually absent with the mortars. Presumably, the presence of sand within the mix allowed better packing and redistribution of internal stresses so that large areal stresses could be accomodated locally (around sand grains) at the subcritical stage.

The mass density of the mortar cubes were also considerably higher than for the neat paste specimens. The neat cubes weighed an average of 245.5 gm (0.4 w/c), while the average for mortar specimens was 290.4 gm (0.4 w/c). Thus, the distribution of particles of the sand enabled the mix to achieve better packing, and consequently lower porosity and higher strength.

### 4.3 Effect of w/c ratio on Compressive strength

The effect of w/c ratio on compressive strength was very similar for the three S-HG hydrated glass cements, as previously seen in the Figures 4-1 to 4-3. The data points are combined and plotted in Figure 4-4 as a percentage of strength at the 0.4 w/c ratio. From Fig. 4-4 it can be seen that there is a drop of about 25% of strength as the w/c ratio increases from 0.4 to 0.5. However from 0.5 to 0.6 strength appears to level off.

The sand mortar specimens were tested only at 0.4 and 0.5 w/c ratios. So a similar curve cannot be drawn for the mortar specimens. However the results at these two w/c ratios suggest that the behaviour of sand mortars follow that of the neat cement tests for compositions #1, #2 and #4. Composition #3 on the other hand appear to be comparatively insensitive to w/c ratio changes in this range. And composition #5 actually shows some increase with increased w/c in this region. In all likelihood the increase is nothing but a data fluctuation, but it does indicate the

insensitivity for this composition as well. This is illustrated by the data presented in Table 4-10. Note that the percentage difference between strengths at two w/c ratios is only 2.5% for #3, and -15.9% for #5 mortar specimens, compared to 20-30% for the other blends.

#### 4.4 Bonding to Portland Cement Concrete

A sound bond between the freshly-poured patching mix and the existing Portland concrete substrate is essential for good performance of the repair. Thus, the study of the bond characteristics between Stratlingite-Hydrogamet cements and Portland cement concrete was an integral part of this study. The test data is presented in Tables 4-11 to 4-14.

An improvised bond test based upon ASTM C190 (see Sec. 2.3) was used to measure the bond strength that will develop in actual field patches. Casting mortar against a fractured surface and allowing it to cure in open air simulates the field conditions. Due to the nature of the test itself, a scatter of 20 to 25% of the measured value (Table 4-15) is expected, compared to about 5% for compressive strength tests and 5-10% for tensile strength tests. To achieve statistically valid results, a much larger number of measurements will obviously be required.

In Table 4-15, three-day bond strength results are presented and compared against Type III Portland Cement using mortars of two parts sand and one part cement and w/c ratios of 0.4 and 0.5 for four blends (Blend #2 was omitted). Bond strength test results for Blend #5 was discarded because adequate bonding could not develop in this series of tests because Portland Cement fractured surface was dust coated and unacceptable. Tensile strength test results are also presented to validate the bond strength results. Type III Portland cement mortar with a cement-to-sand ratio of 1:2 and a w/c ratio of 0.4 was used as the basis for comparison.

The tensile tests confirm that S-HG cements are substantially stronger in tension than the bonding interface, and all failures were bond failures. Although S-HG mortars develop 20% to 50% less bonding strength in tension than Type III PC mortar at 0.4 w/c ratio, they are quite comparable (or better) at 0.5 w/c ratio (Table 5). The difference in bond strengths is principally because of flowability of the mixes. Thus, using adaptive formulations, S-HG cement mortars should develop bonding strengths comparable to Type III PC mortar.

#### 4.5 Shrinkage Behaviour

Shrinkage tests were performed on Blends #1 and #3 according to ASTM C157 (See section 2.4). Two specimens from S-HG cement mortar and two companion specimens from Portland Cement Mortar were fabricated, for each set of tests. They were stripped from their molds at one day and their length change was monitored for about a month. The data from these tests is presented in Tables 4-16 and 4-17.

The averaged cumulative shrinkage, taking 1 day lengths as base, is presented in Fig. 4-7

and Fig. 4-8. From the curves it can be easily seen that, S-HG cements show approximately 30% to 50% more shrinkage than fastsetting Type III Portland Cement Mortar. Shrinkage appears to be higher for blend #1 than blend #3. This is expected since blend #1 sets faster.

There is an anomaly in the PC specimen readings around the age of 25 days. This is in all probability due to experimental error introduced by instrument inaccuracy or unaccounted change storage conditions. This, however, does not affect the preliminary shrinkage evaluations of the blends.

Ultimate shrinkage for S-HG cement blend mortars appear to be around  $1300-1700 \times 10^{-6}$ . In comparison, shrinkage for Type III fast-setting Portland Cement Mortars ( $1000 - 1200 \times 10^{-6}$ ) and normal Portland Cement Concrete ( $800 \times 10^{-6}$ ) is somewhat lower. Since cement mortar typically exhibits more shrinkage than concrete, it is anticipated that the shrinkage characteristic of the patching compound using S-HG cement will be comparable to that of Portland Cement products. More refined tests will be needed to ascertain this comparison.

#### 4.6 Comparison to leading Commercial Patching Materials

S-HG cement patching materials seem to compare more than favorably to two well-known commercial patching products. FS-16 PRECRETE is commonly used in patching concrete floors, pavements and highways, and is also used for anchoring rods, dowells, machine bases etc. Manufacturer's literature claims that compressive strength in accordance with ASTM C109-64 is 2,200 psi in 3 hours, 3100 psi in 24 hours, and 4600 psi in one week. S-HG #1 mortar, in comparison, develops 8275 psi in 3 hours, 10,100 in 24, and 11,200 psi in 3 days. Thus S-HG has at least two to four times the early strength of FS-16 PRECRETE mortar.

PYRAMENT, a new product of Lone Star Industries, is being touted as a revolutionary high early strength cement with a variety of potential uses, including highway and architectural. PYRAMENT concrete develops 2000 psi in two hours, 3000 psi in 4 hours, 3400 psi in 8 hours and about 12 hours. Extrapolations from mortar to concrete could lead us to speculate that S-HG could have at least twice the early strength of PYRAMENT.

<b>w/c ratio</b>	<b>Weight gms</b>	<b>Time hrs</b>	<b>Failure Load lbs</b>	<b>Compr. Str. psi</b>
0.4		0	0	0
0.4	246	3	30400	7600
0.4	245	4	26000	6500
0.4	246	5	30200	7550
0.4	246	8	29800	7450
0.4	245	24	33800	8450
0.4		72	30400	7600
0.5		0	0	0
0.5		3	28500	7125
0.5		4	30900	7725
0.5		5	31800	7950
0.5	228	8	28100	7025
0.5	226	24	23400	5850
0.5	227	72	25200	6300
0.6		0	0	0
0.6	216	8	22800	5700
0.6	214	24	23000	5750
0.6	215	72	27100	6775

Table 4-1: Compressive Strength of Neat Cement Paste #1

w/c ratio	Weight gms	Time hrs	Failure Load lbs	Compr. Str. psi
0.4		0	0	0
0.4	244	3	23500	5875
0.4	244	4	22800	5700
0.4	244	5	31300	7825
0.4		8	29700	7425
0.4	246	24	34100	8525
0.4	245	72	33500	8375
0.5		0	0	0
0.5		3	35800	8950
0.5		4	21000	5250
0.5		5	34100	8525
0.5	233	8	28800	7200
0.5	232	24	29500	7375
0.5	230	72	25200	6300
0.6		0	0	0
0.6	222	8	21600	5400
0.6	220	24	21800	5450
0.6	221	72	28800	7200

Table 4-2: Compressive Strength of Neat Cement Paste #2

w/c ratio	Weight gms	Time hrs	Failure Load lbs	Compr. Str. psi
0.4		0	0	0
0.4	247	3	24800	6200
0.4	245	4	26800	6700
0.4	246	5	22300	5575
0.4		8	31300	7825
0.4	249	24	30200	7550
0.4	247	72	33200	8300
0.5		0	0	0
0.5		3	26400	6600
0.5		4	23700	5925
0.5		5	30100	7525
0.5	231	8	26000	6500
0.5	230	24	24000	6000
0.5	230	72	25500	6375
0.6		0	0	0
0.6	220	8	22500	5625
0.6	219	24	24800	6200
0.6	220	72	29300	7325

Table 4-3: Compressive Strength of Neat Cement Paste #3

Blend No.	W/c Ratio	Neat Cement Strength psi	Mortar Strength psi	Percentage Gain
1	0.4	8040	11200	39.3%
2	0.4	8730	10800	23.7%
3	0.4	8130	10050	23.6%
4	0.4		8425	
5	0.4		7250	
1	0.5	5930	7725	30.3%
2	0.5	6700	8600	28.4%
3	0.5	6150	9800	59.4%
4	0.5		6525	
5	0.5		8400	

**Table 4-4: Comparison of Neat Cement & Sand Mortar Strengths**

<b>w/c ratio</b>	<b>Weight gms</b>	<b>Time hrs</b>	<b>Failure Load lbs</b>	<b>Compr. Str. psi</b>
0.4		0	0	0
0.4	289	3	33100	8275
0.4	289	4	35000	8750
0.4	290	5	36100	9025
0.4	290	8	40000	10000
0.4	290	24	40400	10100
0.4	290	72	44800	11200
0.5		0	0	0
0.5	282	3	29100	7275
0.5	281	4	28200	7050
0.5	283	5	29600	7400
0.5	281	8	31300	7825
0.5	282	24	32200	8050
0.5	282	72	30900	7725

Table 4-5: Compressive Strength of Sand Mortar #1



w/c ratio	Weight gms	Time hrs	Failure Load lbs	Compr. Str. psi
0.4		0	0	0
0.4	292	8	21700	5350
0.4	292	24	42200	10550
0.4	292	72	43200	10800
0.5		0	0	0
0.5	280	8	900	225
0.5	280	24	24500	6125
0.5	280	72	34400	8600

Table 4-6: Compressive Strength of Sand Mortar #2

w/c ratio	Weight gms	Time hrs	Failure Load lbs	Compr. Str. psi
0.4		0	0	0
0.4	290	8	27000	6750
0.4	289	24	40400	10100
0.4	289	72	40200	10050
0.5		0	0	0
0.5	284	8	28000	7000
0.5	283	24	36200	9050
0.5	284	72	39200	9800

Table 4-7: Compressive Strength of Sand Mortar #3

w/c ratio	Weight gms	Time hrs	Failure Load lbs	Compr. Str. psi
0.4	289	3	30700	7625
0.4	289	4	33600	8400
0.4	288	5	31400	7850
0.4	289	8	34500	8625
0.4	289	24	31200	7800
0.4	290	72	84300	21075
0.4	286	2	20500	5125
0.4	285	24	32600	8150
0.4	286	24	31400	7850
0.4	286	48	32400	8100
0.4	285	72	33700	8425
0.4	286	168	26300	6575
0.5	283	3	25900	6475
0.5	283	4	25700	6425
0.5	283	5	27900	6975
0.5	287	8	28200	7050
0.5	287	24	25600	6400
0.5	285	72	49600	12400
0.5	286	24	25500	6375
0.5	285	48	32400	6525
0.5	286	168	26300	6500

Table 4-8: Compressive Strength of Sand Mortar #4

w/c ratio	Weight gms	Time hrs	Failure Load lbs	Compr. Str. psi
0.4		0	0	0
0.4	290	4	19400	4850
0.4	291	6	26400	6600
0.4	290	8	27300	6825
0.4	289	24	23300	5825
0.4	289	72	16900	4225
0.4	289	168	29000	7250
0.5		0	0	0
0.5	288	4	10000	2500
0.5	288	6	24500	6125
0.5	288	8	20700	5175
0.5	290	24	23100	5775
0.5	289	72	24000	6000
0.5	289	168	33600	8400

Table 4-9: Compressive Strength of Sand Mortar #5

Blend No.	Type of Mix	Strength at 0.4 w/c psi	Strength at 0.5 w/c psi	Percentage Difference
1	Neat	8040	5930	26.2%
2	Neat	8730	6700	23.3%
3	Neat	8130	6150	24.4%
1	Mortar	11200	7725	31.0%
2	Mortar	10800	8600	20.4%
3	Mortar	10050	9800	2.5%
4	Mortar	8425	6525	22.6%
5	Mortar	7250	8400	-15.9%

Table 4-10: Comparison of Effect of w/c ratio on Compr. Strength

Specimen No.	W/c ratio	Bond Strength psi	Tensile Strength psi
4	0.4	115	515
5	0.4	78	605
6	0.4	65	552
1	0.5	185	455
2	0.5	236	395
3	0.5	260	408

Table 4-11: Tensile and Bond Strength of Blend #1

Specimen No.	W/c ratio	Bond Strength psi	Tensile Strength psi
16	0.4	150	507
17	0.4	124	495
18	0.4	157	429
7	0.5	160	480
8	0.5	325	419
9	0.5	260	428

Table 4-12: Tensile and Bond Strength of Blend #3

Specimen No.	W/c ratio	Bond Strength psi	Tensile Strength psi
10	0.4	105	538
11	0.4	129	477
12	0.4	118	475
13	0.5	245	465
14	0.5	184	440
15	0.5	145	506

Table 4-13: Tensile and Bond Strength of Blend #4

Specimen No.	W/c ratio	Bond Strength psi	Tensile Strength psi
19	0.4		533
20	0.4		520
21	0.4		480
22	0.5		422
23	0.5		425
24	0.5		480

Table 4-14: Tensile and Bond Strength of Blend #5

Blend No.	W/c Ratio	Tensile Strength psi	Bond Strength psi	Standard Deviation % Bond St.
1	0.4	557	86	24.6%
3	0.4	477	144	9.9%
4	0.4	497	117	8.4%
5	0.4	511		
1	0.5	419	227	13.8%
3	0.5	442	248	27.3%
4	0.5	470	191	21.5%
5	0.5	442		
PC III	0.4	533	172	21.5%

Table 4-15: Comparison of Tensile and Bond Strength Results

Time After Casting days	Specimen No. 1	Specimen No. 2	PC Spec No. 1	PC Spec No. 2
1	0	0	0	0
2	489	720	382	329
3	658	1502	604	533
4	729	1671	702	604
7	836	1778	791	818
11	1031	1929	1049	969
16	1058	2036	1360	1253
22	1067	2053	996	924
26	1209	2178	1111	1031
33	1244	2204	1129	1013

Table 4-16: Shrinkage of Blend #1 and Companion PC Mortar (  $\times 10^{-6}$  )

Time After Casting days	Specimen No. 1	Specimen No. 2	PC Spec No. 1	PC Spec No. 2
1	0	0	0	0
2	329	364	187	293
3	596	560	471	489
4	622	622	551	640
7	889	862	738	711
11	1138	1084	836	844
16	1138	1120	916	880
22	1191	1182	889	889
26	1262	1298	960	942
33	1316	1316	987	1013

Table 4-17: Shrinkage of Blend #3 and Companion PC Mortar (  $\times 10^{-6}$  )



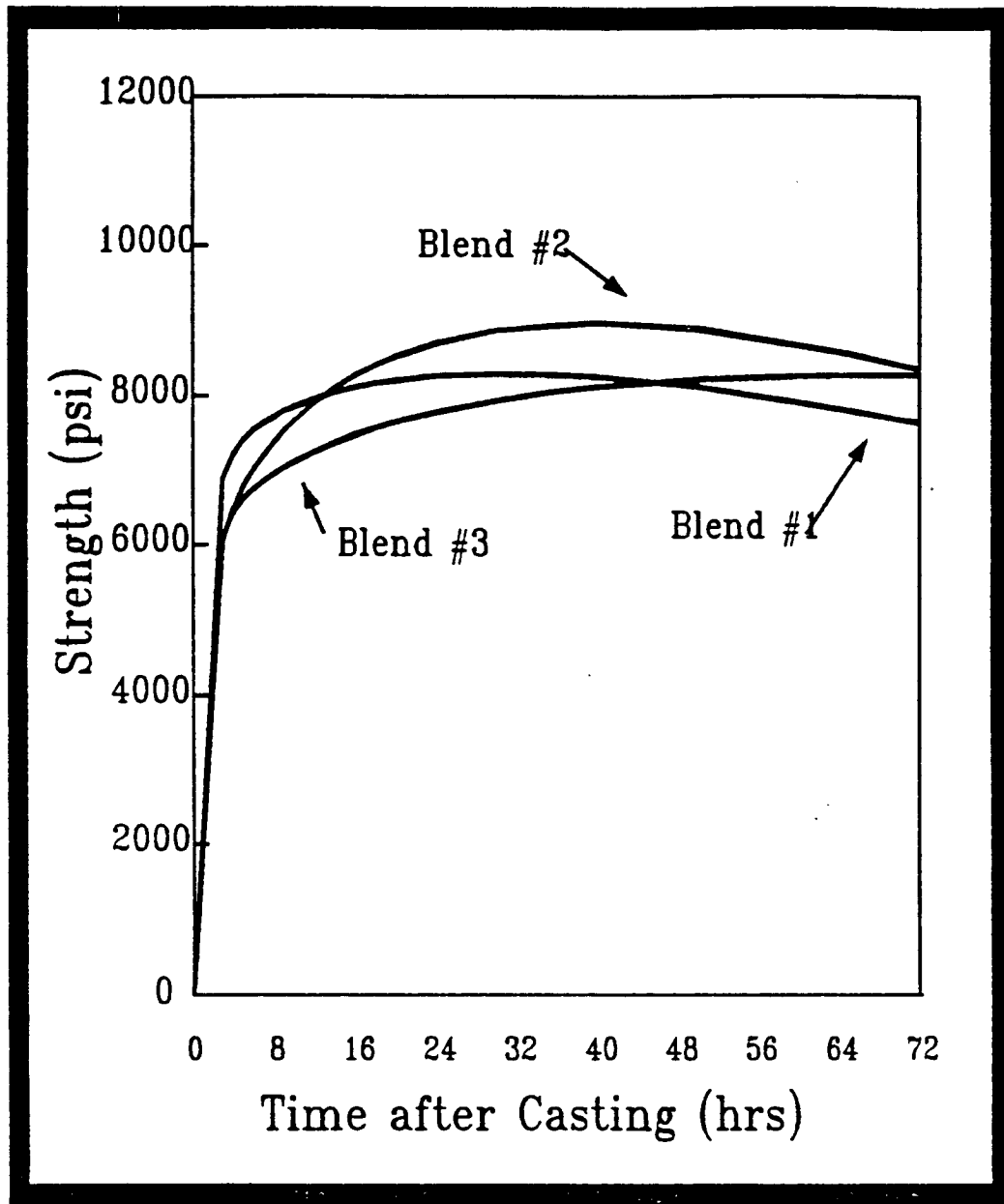


Figure 4-1: Strength Gain Curve Neat Cement Paste : 0.4 w/c ratio

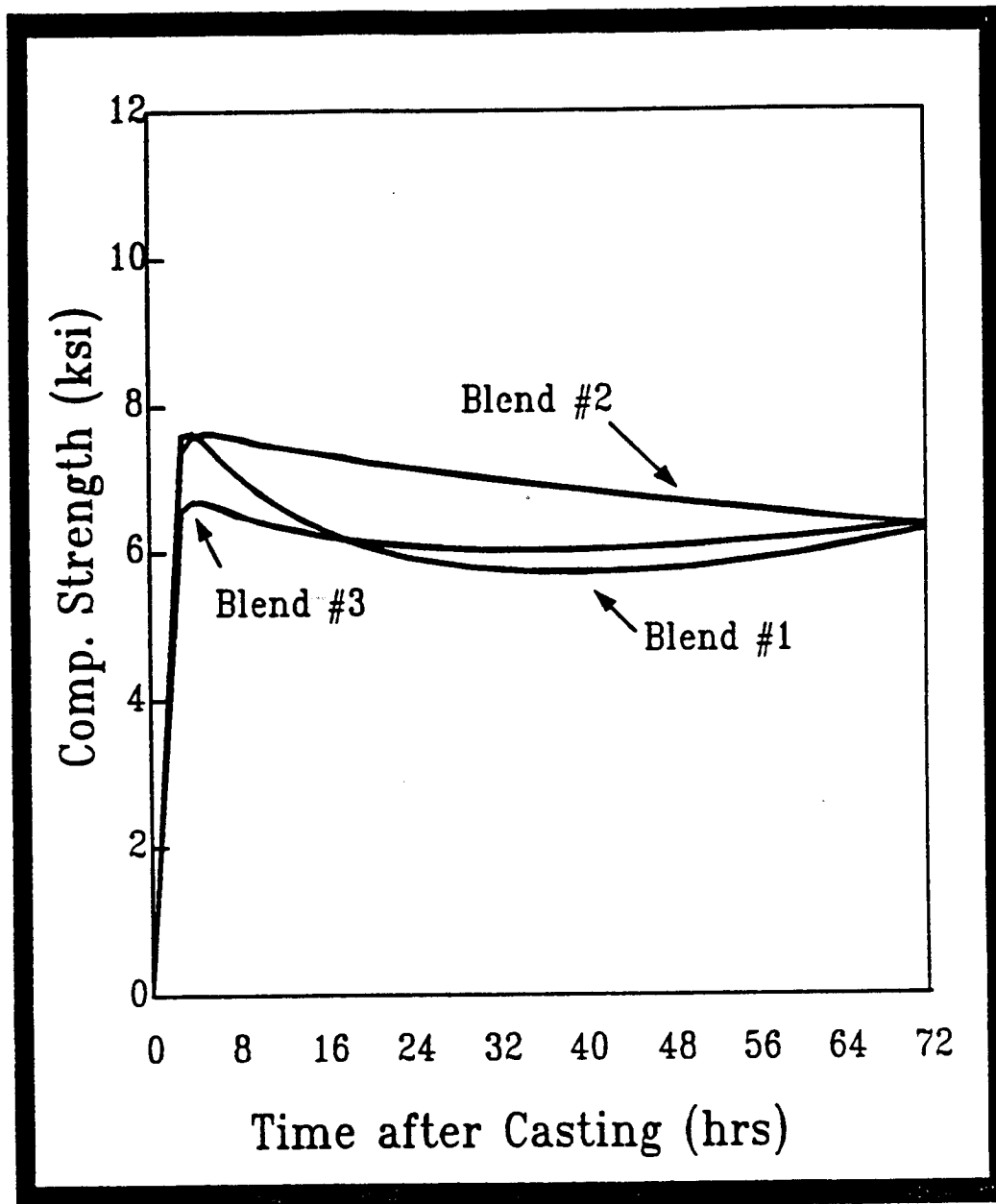


Figure 4-2: Strength Gain Curve Neat Cement Paste : 0.5 w/c ratio

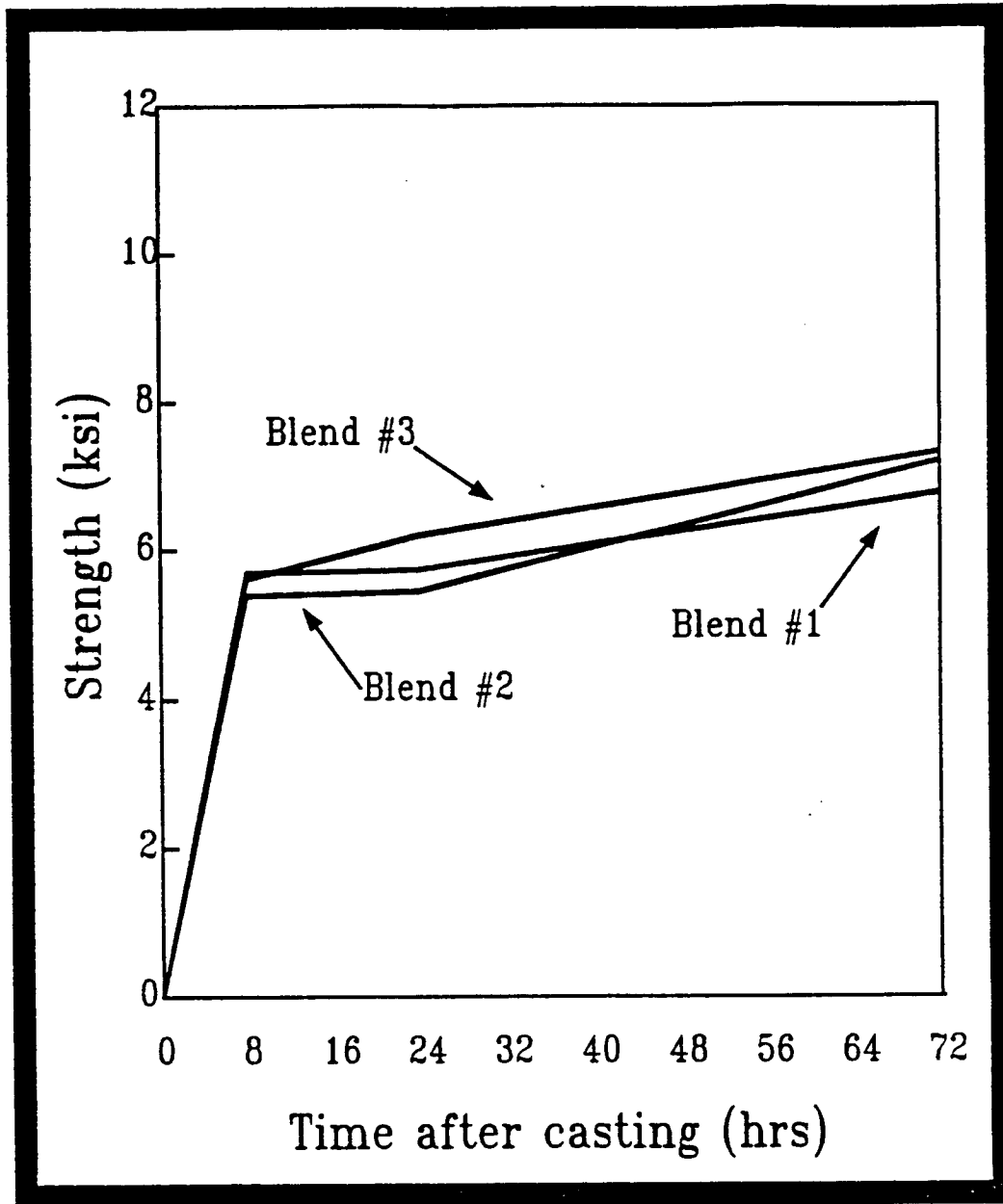


Figure 4-3: Strength Gain Curve Neat Cement Paste : 0.6 w/c ratio

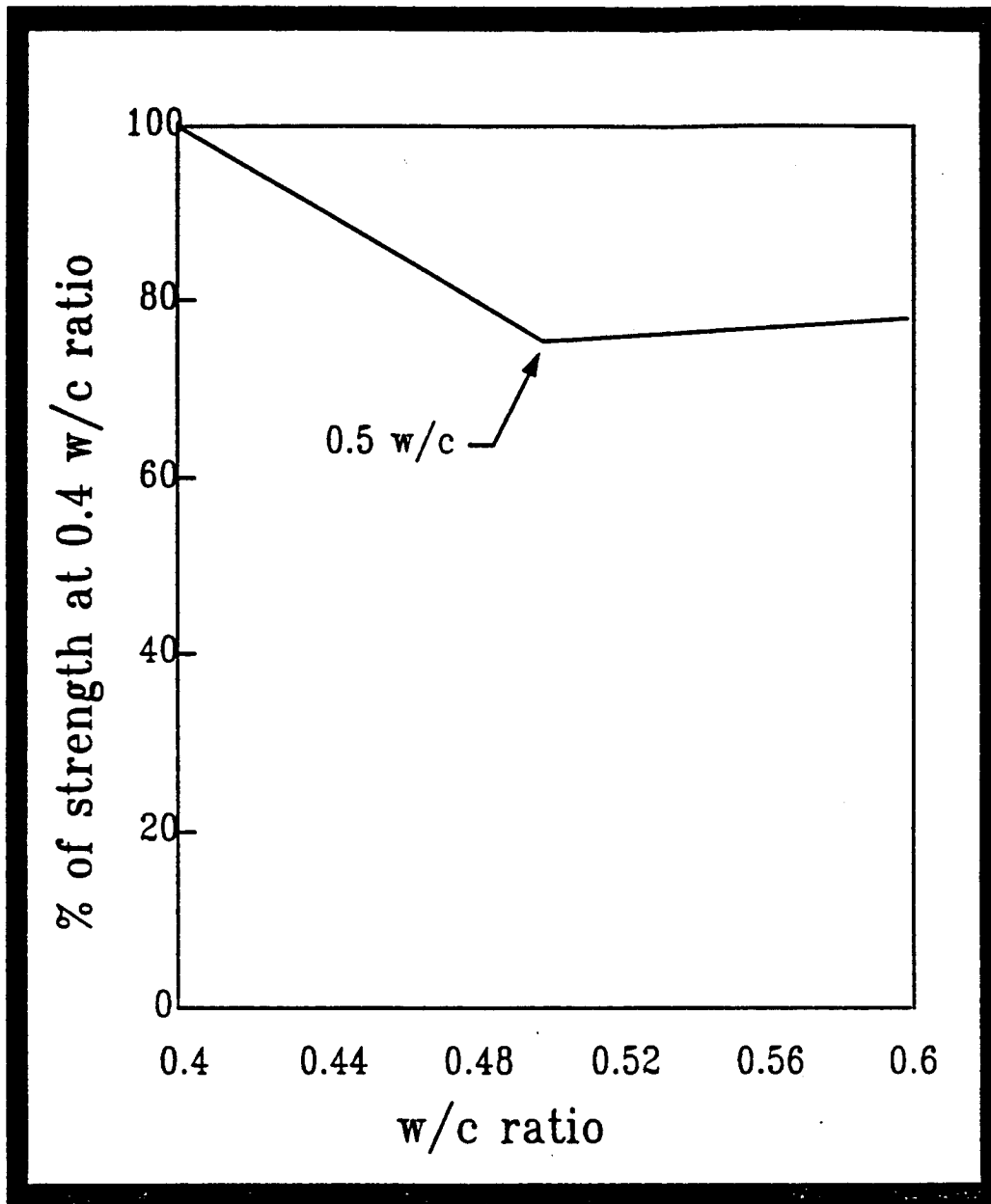


Figure 4-4: W/c Ratio Vs. Strength Behaviour for Neat Cement Pastes

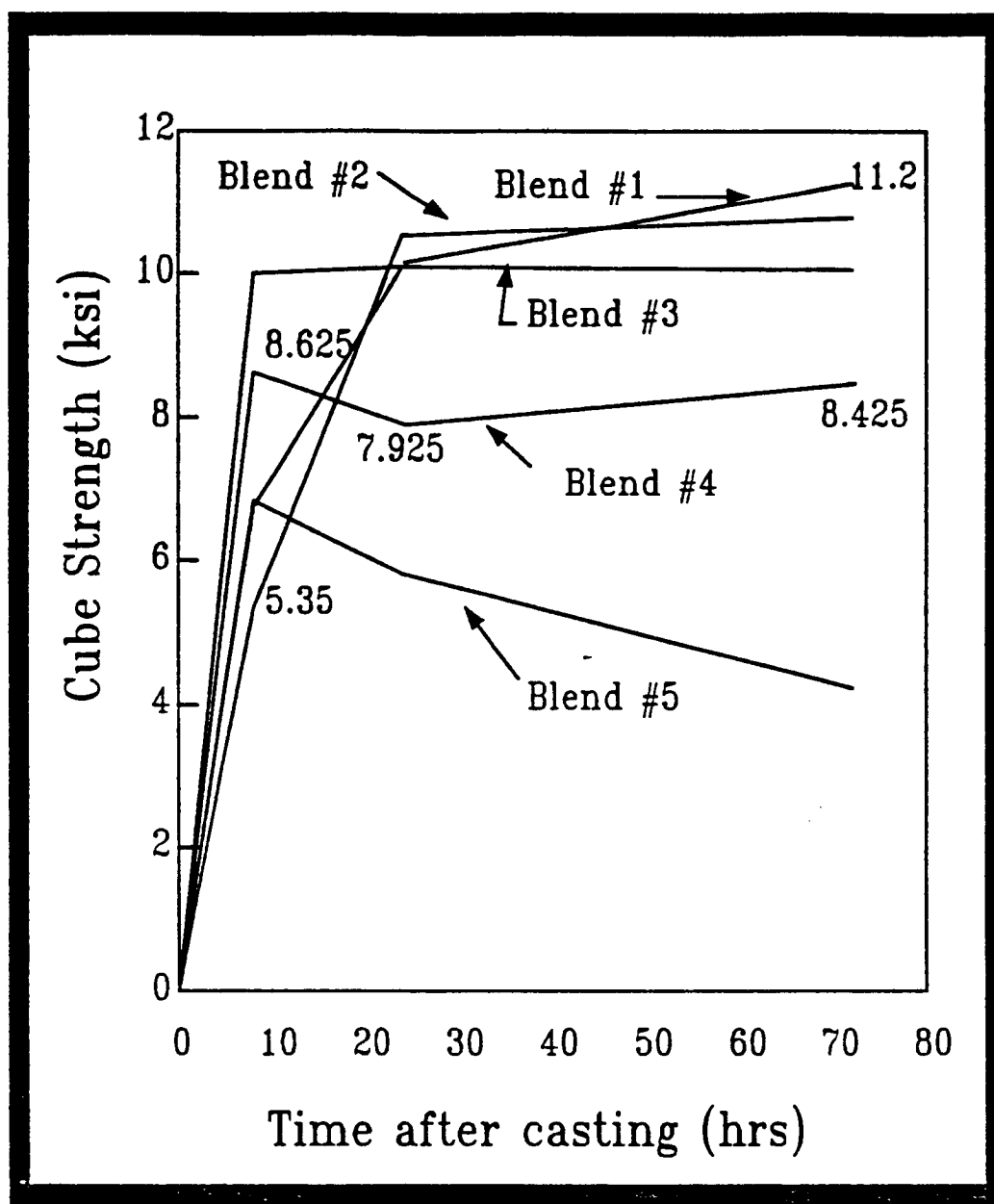


Figure 4-5: Strength Gain Curve Sand Mortar : 0.4 w/c ratio

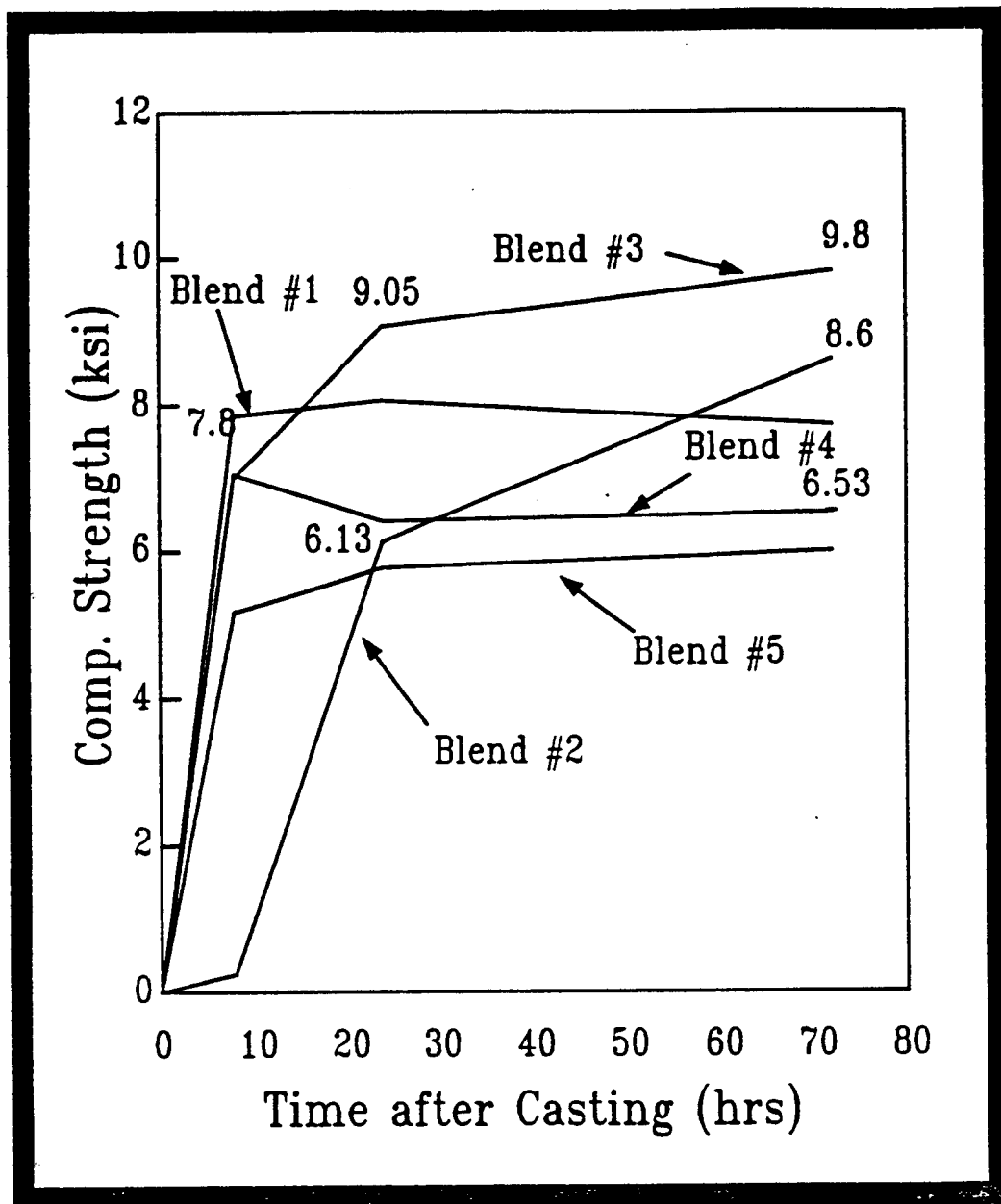


Figure 4-6: Strength Gain Curve Sand Mortar : 0.5 w/c ratio

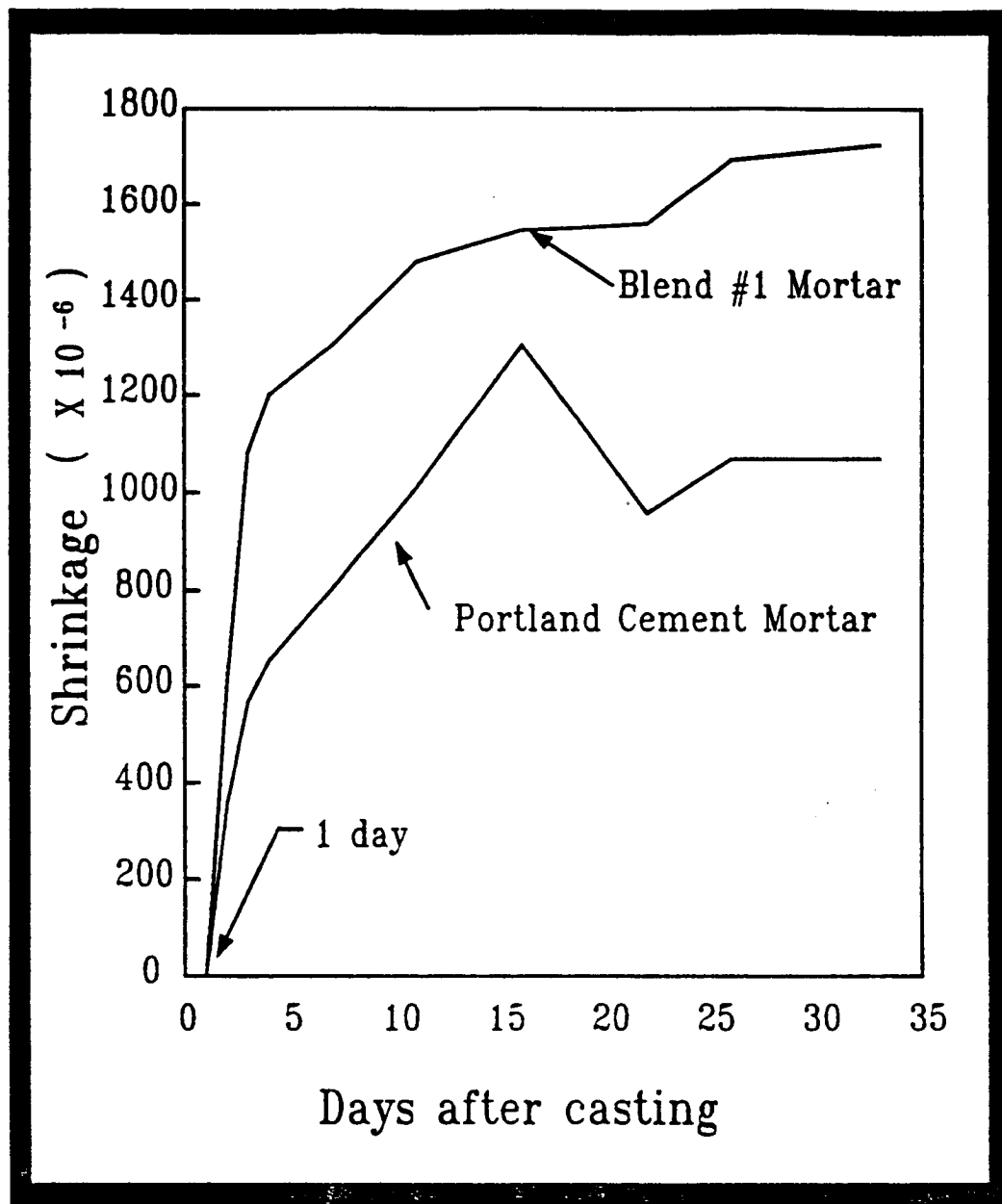


Figure 4-7: Shrinkage of Blend #1 Mortar

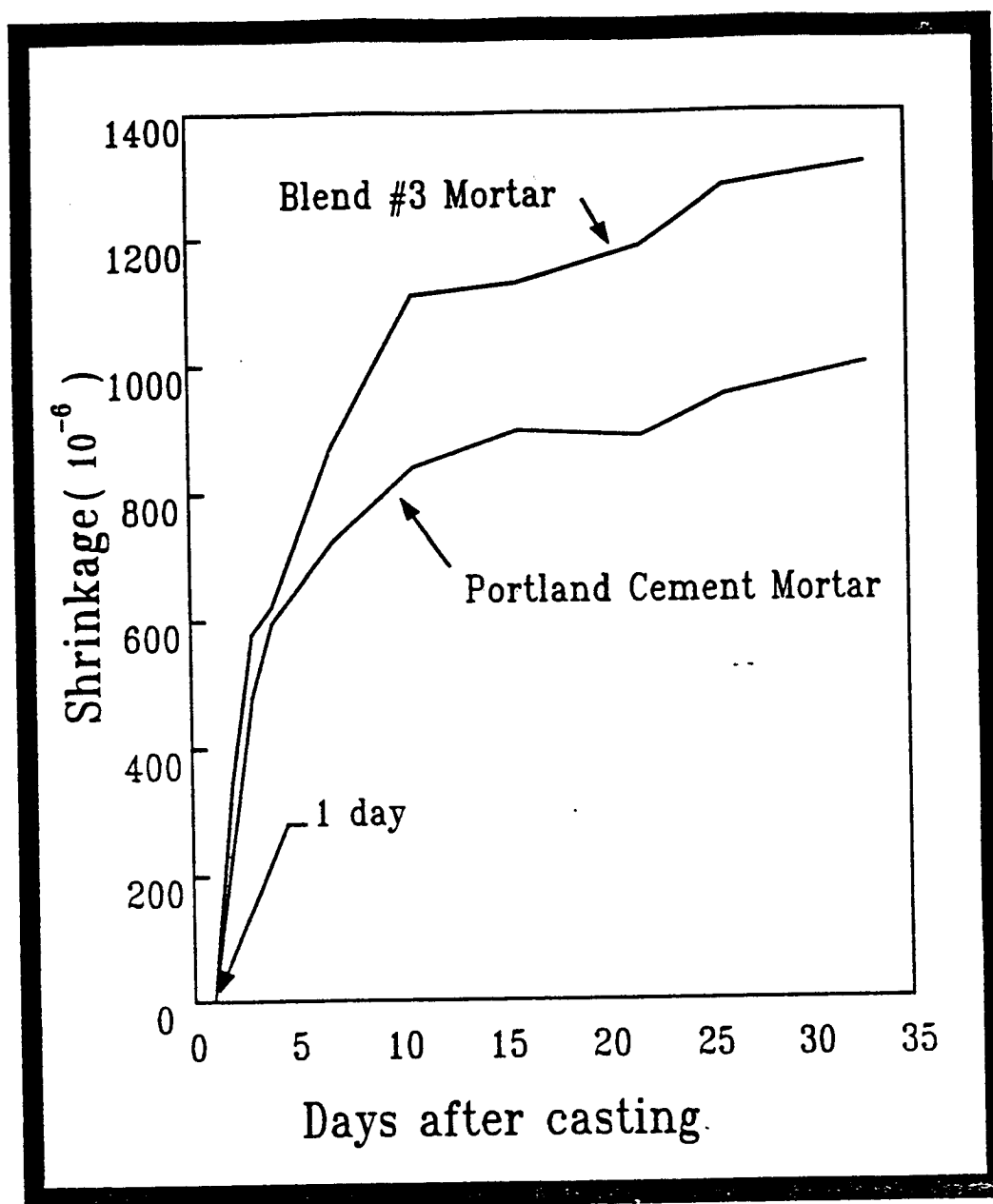


Figure 4-8: Shrinkage of Blend #3 Mortar



## 5. Conclusion and Recommendations

### 5.1 Conclusion

The data obtained from this initial research, strongly indicate that Stratlingite-Hydrogamet based cements can be developed into an excellent high-early-strength patching material.

- There is a substantial variation in compressive strength ( 5500 to 11000 psi mortar strength at 0.4 w/c ratio ) between different compositions of S-HG cement. However almost all of the blends appear to have adequate compressive strength for highway and bridge deck patching use. So the choice of the optimum composition is governed more by the other qualities than strength alone.
- S-HG cement sand mortar specimens have higher compressive strength and higher specific weight than neat cement specimens. This is due to better packing. This indicates that careful concrete mix design maximizing the density of the material may enhance the strength characteristics even more.
- In general S-HG cement blend compressive strengths are sensitive to w/c ratio changes and typically the strength drops 25% from 0.4 to 0.5 w/c ratio. But mortar compressive strength of some of the blends (Notably compositions #3 and #5 ) are not significantly affected by w/c ratio changes in this range.
- Bond strength of S-HG cement mortar to Portland Cement Concrete is comparable to that of Type III fast-setting Portland Cement Mortar. Bond strength is lower for lower w/c ratio (0.4) mixes than for higher (0.5) w/c ratio mixes, possibly because of their reduced flowability.
- Tensile strength of the material is about 7-10% of its compressive strength. It is higher than the bonding strength to Portland Cement Concrete.
- S-HG cement mortars show 30-50% more shrinkage than Type III fast-setting Portland Cement (PC) mortars in the first month. The difference between the ultimate shrinkages is possibly somewhat lesser, because PC mortars continue to shrink beyond the first month.

### 5.2 Recommendations for future work

A substantial amount of research is still necessary to develop this material into a usable product stage. Detailed shrinkage behaviour, properties of these cements in concrete, freeze-thaw behaviour, workability vs. strength with and without water reducers are of critical importance for many applications. Perhaps more importantly studies to determine concrete strength as a function of time and temperature must be conducted. Studies to develop optimised curing procedures and application techniques are also required.

Other properties of interest are thermal expansion behaviour, rebar corrosion studies using controlled chloride contamination and durability of S-HG cement concretes in chemical solutions such as sulfates, acid, and bases.

S-HG cements are a versatile family of materials which need not be limited to highway patching uses. Other applications of the material may range from tunneling to high performance structural members. Glass fiber reinforcing of S-HG cement concrete may also prove to be

interesting. Different blends of S-HG cement present substantially different properties. Eventually different compositions of this material may possibly be individually tailored to suit the particular needs of a given application. Different application of this material represent another possible area of investigation.

### 5.3 Summary

Stratlingite-Hydrogarnet Glass cements are a promising new family of "hydroceramics" that may have great utility as highway patching materials. Their inherently higher cost (due to the glass\_melting step in their manufacture), however, will narrow the field of application to those demanding higher early strength and lower porosity than currently available products. Other advantages (or disadvantages) of these materials may emerge only through extensive applications testing.

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