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Dr. James H. Deatherage, Major Professor

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AN INVESTIGATION OF THE EFFECTS OF SUPERPLASTICIZERS IN STEAM CURED CONCRETE

A Thesis
Presented for the
Master of Science Degree

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Raulston Lee Travis

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ABSTRACT

The ever increasing use of precast and prestressed concrete as structural elements has caused a demand for further research and development in the steam curing process which is used by the precast concrete industry in order to produce structural precast members in short periods of time. The rate of temperature rise in the steam chamber and maximum temperature are critical elements in the process of steam curing concrete. The rate of temperature rise should be controlled and should reach its maximum temperature as quickly as possible without adversely affecting the long-term or short-term strength of the concrete. The maximum temperature should be limited to a temperature that will minimally decrease the 28 day strength of the concrete. Using the results and conclusions from previous research, this investigation examines the effect that an admixture such as a superplasticizer may have on the strengths of the concrete in the steam curing process.

A 6000 psi mix design for a mix with a water-cement ratio of 0.40 was used and the w/c ratio was varied to test the effects on different strengths of concrete. The specimens were fabricated in standard 6 x 12 inch molds and each batch was tested at 24 hours, 3 days, 7 days, and 28 days. There were four batches of 24 cylinders each produced for testing.

The use of a superplasticizer in steam cured concrete was found to be beneficial in the strength of the concrete and the rate at which the concrete gains strength between the ages of 7 and 28 days. It was also found to have no adverse effects on the strength of the concrete in comparison to steam cured concrete without a superplasticizer. The early strength of the steam cured concrete did not appear to be any different than the strengths reported in previous investigations.

TABLE OF CONTENTS

CHAPTER ONE		**INTRODUCTION**	
1.1		Purpose	1
1.2		Background	
	1.2.1	Precast Concrete	1
	1.2.2	Superplasticizers	2
CHAPTER TWO		**LITERATURE REVIEW**	
2.1		Introduction	6
2.2		Article Reviews	
	2.2.1	Shideler and Chamberlin	6
	2.2.2	Saul	11
	2.2.3	Higginson	15
	2.2.4	Hanson	18
	2.2.5	Oluokun, Burdette, & Deatherage	22
CHAPTER THREE		**TESTING PROCEDURE**	
3.1		Introduction	24
3.2		Test Program	
	3.2.1	Materials	24
	3.2.2	Fabrication of test cylinders	27
	3.2.3	Curing process	27
	3.2.4	Testing procedure	29

CHAPTER FOUR		**DISCUSSION OF RESULTS**	
4.1		Introduction	30
4.2		Test Results	
	4.2.1	Batch 1	31
	4.2.2	Batch 2	34
	4.2.3	Batch 3	38
	4.2.4	Batch 4	41
	4.2.5	Comprehensive	44
4.3		Cost Analysis	46
CHAPTER FIVE		**CONCLUSIONS**	48
LIST OF REFERENCES			50
VITA			53

LIST OF TABLES

TABLE		PAGE
2.1	Compressive strength of 6 x 12 in. cylinders - first series (13)	7
2.2	Compressive strength of 6 x 12 in. cylinders - second series (13)	9
2.3	Compressive strength of 6 x 12 in. cylinders - third series (13)	10
2.4	Curing treatments and test results (12)	13
2.5	Curing treatments and test results (12)	14
2.6	Mix data and properties of moist cured concrete (2)	19
2.7	Compressive strength of steam and moist cured concrete (2)	20
2.8	Summary of test results (9)	23
3.1	Mix designs per cubic yard	25
3.2	Actual mixed proportions for 24 cylinders	26
3.3	Slump values and superplasticizer dosage	27
4.1	Batch 1 results	32

TABLE		PAGE
4.2	Batch 2 results	36
4.3	Batch 3 results	39
4.4	Batch 4 results	42
4.5	Cost Analysis	47

LIST OF FIGURES

FIGURE		PAGE
1.1	Schematic diagram of the effect of water reducers on fresh and hardened concrete. (10)	3
1.2	Water-reduction obtained by adding a superplasticizer. (10)	4
1.3	Effect of dosage of superplasticizer on the slump of concrete. (10)	5
1.4	Effect of delayed addition of a super-plasticizer on the slump of concrete. (10)	5
2.1	Delay period prior to steam curing. (13)	10
2.2	Compressive strength of steam cured concrete; 5 sacks per cu yd. (3)	16
2.3	Compressive strength of steam cured concrete; 7 sacks per cu yd. (3)	17
2.4	Relative compressive strength of steam cured concrete. (2)	21
3.1	Steam curing cycle.	28
4.1	Batch 1 results.	33
4.2	Batch 1 results.	33
4.3	Batch 2 results.	37

FIGURE		PAGE
4.4	Batch 2 results.	37
4.5	Batch 3 results.	40
4.6	Batch 3 results.	40
4.7	Batch 4 results.	43
4.8	Batch 4 results.	43
4.9	Rate of strength gain.	44
4.10	Superplasticizer dosage vs. 28 day moist cured strength.	45
4.11	Superplasticizer dosage vs. 28 day moist cured strength.	45

CHAPTER ONE
INTRODUCTION

1.1 PURPOSE

The research that is presented in this thesis was performed because of the possibility of future use of superplasticizers in the production of precast concrete. The literature reviewed and discussed in Chapter Two does not include any testing of steam cured concrete with a superplasticizer admixture. However, it is relevant to this research because of the comparison that is made between the strength effects of steam cured concrete both with and without the use of a superplasticizer. The possible use of a superplasticizer in the production of precast concrete could be advantageous from both an economical standpoint as well as the increase in concrete strength.

1.2 BACKGROUND

1.2.1 Precast Concrete

Structural precast concrete elements such as slabs, beams, girders, columns, and wall panels are cast and cured in industrial plants, then transported to the job site and erected. Precasting of concrete offers many advantages over sitecasting of concrete. The production of precast concrete elements is carried out conveniently at ground level and, after proper curing, transported to the job site for erection. The mixing and pouring operations are often highly complicated and mechanized which generally produces better products than if cast on the construction site.

Precast concrete elements are usually steam cured. The steam curing process furnishes heat to accelerate the curing of the concrete, and moisture for full hydration. Steam curing enables a precasting plant to

produce a sufficiently cured structural element in 24 hours. The steam curing process used by most plants incorporates a mix design which produces a compressive strength of at least 4000 psi within 24 hours after pouring. This can be achieved by an infinite number of mix designs, with the use of many different types of admixtures. However, the use of a high-range water reducing admixture, also known as a superplasticizer, is not typically used in the production of precast concrete. This study tests the effects that a superplasticizer has on the strength of steam cured concrete of various water-cement ratios.

1.2.2 Superplasticizers

The use of high range water-reducing admixtures known as superplasticizers was first introduced in Japan and later in Germany. Superplasticizers are organic compounds that transform a stiff concrete mix into a free-flowing liquid. They are used either to facilitate placement of concrete under difficult circumstances or to reduce the water content of a concrete mix to increase its strength. There are basically three types of uses for water-reducers. One reason for using a water-reducer in a concrete mix would be to increase strength, a second reason would be to save cement, and a third reason might be to increase workability. These different uses are shown schematically in Figure 1.1. [10]

A normal water reducer has the capability of reducing the water requirement for a given mix design by approximately 15%. The use of a superplasticizer in the same mix could reduce the water content by 30% (see Figure 1.2) [10], thereby producing a significantly stronger concrete. Using a higher dosage of a normal water reducer would also achieve this further water reduction but would also have various undesirable effects on air content, bleeding, segregation and hardening of the concrete. The use of a superplasticizer produces a concrete which has a high workability for easy placement and will also be of considerably higher strength.

Superplasticizers' capability to increase the slump of concrete depends on various conditions. For example, the type of plasticizer used, the dosage and time the plasticizer was introduced into the mixture, the w/c

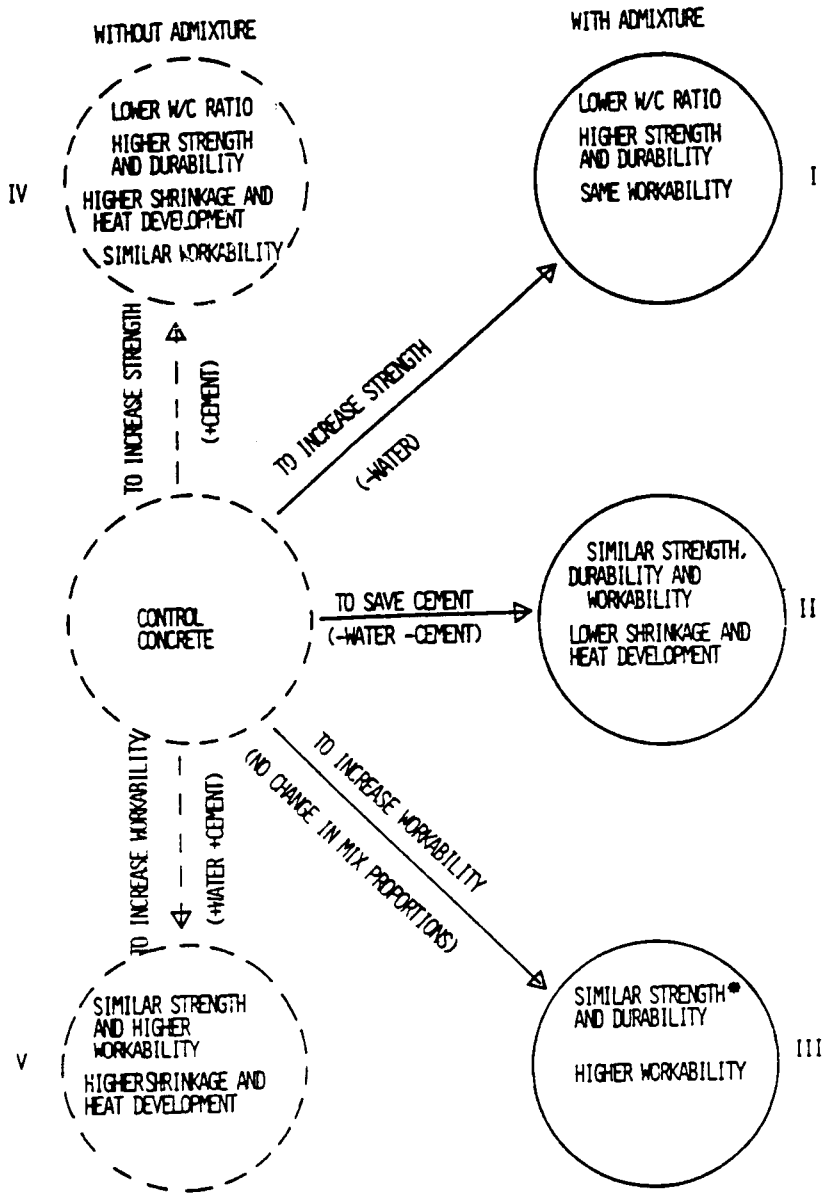


FIGURE 1.1: Schematic diagram of the effect of water reducers on fresh and hardened concrete.

Source: Ramachandran, V.S., (1984). *Concrete Admixtures Handbook*, Noyes Publications, p. 117.

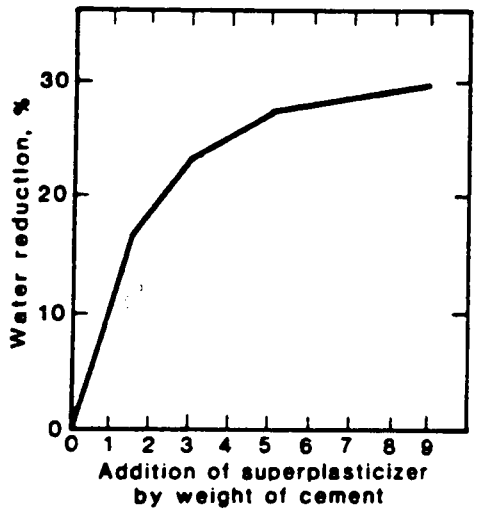


FIGURE 1.2 Water-reduction obtained by adding a superplasticizer.
Source: Ramachandran, V.S., (1984). *Concrete Admixtures Handbook*, Noyes Publications, p. 236.

ratio of the concrete, type and amount of cement used, and curing temperature are examples. The precast concrete industry generally produces a concrete mixture with a 6-inch slump for the production of precast concrete. Therefore, the process which was used in the production of the concrete cylinders for this study was to add the required dosage of superplasticizer to obtain a 6-inch slump for the given mix design. The amount of superplasticizer added depended on the initial slump and w/c ratio. A mix with a low slump required a higher dosage to obtain the 6-inch slump. However, the effectiveness of the superplasticizer is greatly reduced with higher and higher dosages, see Figure 1.3. [10]. The effectiveness of the superplasticizer also depends on the time at which it is added to the mixture. If added at the same time as the water is added, then the slump is increased considerably. However, an even higher slump value can be achieved when the superplasticizer is added a few minutes after the water has been added. But, after a few minutes, the longer the period between the water and superplasticizer addition, the larger the decrease in the effectiveness of the admixture as shown in Figure 1.4 [10]. Typically, the superplasticizer was added within ten minutes after the water was added in this particular study.

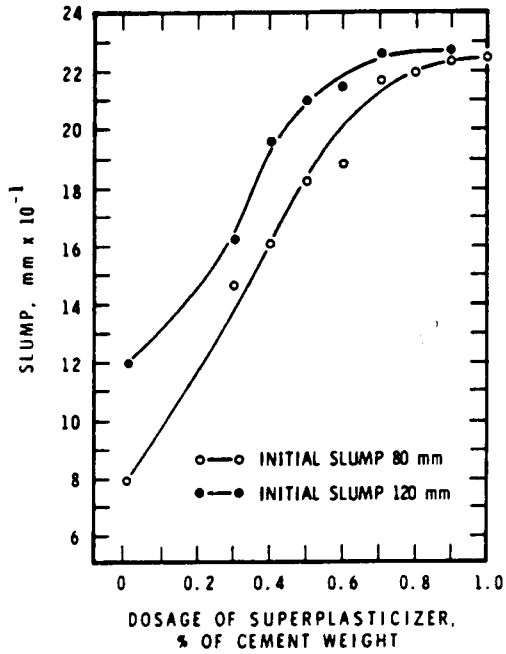


FIGURE 1.3 Effect of dosage of superplasticizer on the slump of concrete.

Source: Ramachandran, V.S., (1984). *Concrete Admixtures Handbook*, Noyes Publications, p. 228.

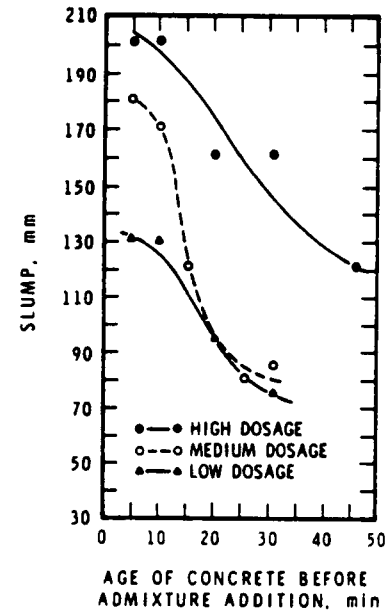


FIGURE 1.4 Effect of delayed addition of a superplasticizer on the slump of concrete.

Source: Ramachandran, V.S., (1984). *Concrete Admixtures Handbook*, Noyes Publications, p. 229.

1.2.3 Scope of Work

The scope of the work presented in this thesis pertains specifically to the testing of 96 standard 6 x 12 inch concrete cylinders. The testing performed on the specimens was limited to compressive strength tests of 48 steam cured specimens and 48 moist cured companion specimens. There were four batches of 24 specimens, 12 moist cured and 12 steam cured, produced and 3 cylinders from both the moist and steam cured specimens were tested at ages of 1 day, 3 days, 7 days, and 28 days. A 6000 psi mix design was used for a 0.40 w/c ratio and the amounts of water and fine aggregate was varied to produce mixes with 0.35 and 0.45 w/c ratios for the other batches. Three of the four batches were cured using the same curing procedure. This procedure, which is common to the precast industry, consisted of a pre-steam period of 5 hours and a rise rate of 40 degrees per hour to a maximum temperature of 160 degrees. The fourth batch was cured using a pre-steam period of 5 hours and a rise rate of 80 degrees per hour to a maximum temperature of 180 degrees.

CHAPTER TWO
LITERATURE REVIEW

2.1 INTRODUCTION

There has been a considerable amount of research done on the various effects that steam curing has on different characteristics of concrete. There have been numerous tests performed and many articles published on the effect that steam curing has on various properties of concrete such as permeability, freezing and thawing, sulfate resistance, modulus of elasticity, poisson's ratio, and modulus of rupture, to name a few. There have been tests performed to study the effect of varying rise rates and maximum temperatures. However, the most important tests were those which studied the effect that steam curing has on the compressive strength of concrete. This particular study is taking this procedure one step further and studying the effect that the addition of a superplasticizer has on the compressive strength of steam cured concrete.

This chapter presents a chronological review of a few of the articles by various authors which seem pertinent to this study. Some of the earliest work by pioneers of steam cured concrete tests is reviewed as well as some recent studies performed.

2.2 ARTICLE REVIEWS

2.2.1 Shideler and Chamberlin (1949) --- (Ref. 13)

The study published by Joseph J. Shideler and Wilbur H. Chamberlin was performed for the Bureau of Reclamation for use in determining a specification for the process of steam curing precast units such as irrigation pipe. They obtained the results from the testing of 990 standard 6 x 12 in. concrete cylinders that had different steam cycle

periods as well as various maximum temperatures. There were three different series of tests performed as described below.

The first series of testing was performed on 390 cylinders cast from 15 different mix designs. The cylinders were subjected to immediate steam curing cycles of 3 to 7 days and cured at one of five different steam room temperatures ranging from 100 to 195 degrees fahrenheit. The test results, shown in Table 2.1 [13], show that specimens steam cured at temperatures higher than 165 degrees gain strength slower than specimens cured at lower temperatures. Shideler and Chamberlin concluded that there was no appreciable difference in strength between cylinders steam cured for 24 hours at 130 and 165 degrees and that these two temperatures produced higher strengths than specimens cured at higher or lower temperatures. However, some swelling and cracking near the ends of the cylinders was noticed for cylinders cured at 185 degrees and higher.

TABLE 2.1 Compressive strength of 6 x 12 in. cylinders - first series (Shideler and Chamberlin).

Source: Shideler and Chamberlin, "Early Strength of Concrete as Affected by Steam Curing Temperature," *Journal of the American Concrete Institute*, Vol. 46, No. 6, p. 278.

Time cured	Compressive strength (psi)†								
	Fog-cured control cylinders 70 F			Steam cured at 100 F			Steam cured at 130 F		
	Type I	Type II	Type V	Type I	Type II	Type V	Type I	Type II	Type V
3 hr	—	—	—	—	—	—	280	180	40
6 hr	—	—	—	190	140	110	780	560	280
12 hr	280§	280	140	640	640	510	1520	1120	720
1 day	920	850	500	1300	1320	1060	2020	1590	1220
2 days	1780	1510	1070	1960	1880	1510	2400	1930	1830
3 days	2250	1980	1500	2180	2180	1830	2720	2360	2100
4 days	—	—	—	2300	2490	1980	—	—	—
7 days	3170	2940	2350	2670	2890	2390	—	—	—
28 days	4680	4740	4060	—	—	—	—	—	—
	Steam cured at 165 F			Steam cured at 185 F			Steam cured at 195 F		
	Type I	Type II	Type V	Type I	Type II	Type V	Type I	Type II	Type V
3 hr	670	420	120	660	560	360	780	590	90
6 hr‡	1220	860	490	1040	820	660	1160	880	340
12 hr	1750	1310	1000	1420	1280	1060	1640	1080	620
1 day	2070	1600	1340	1710	1500	1240	1580	1300	610
2 days	2480	2010	1780	1800	1730	1500	1880	1560	700
3 days	2880	2240	1960	1760	1740	1580	1880	1550	860
7 days	2750	2300	2030	1960	1790	1810	1790	1620	840

†Average of two cylinders.
‡185 F specimens steam cured 5 hours.
§Average of 10 cylinders.

The second series of tests that Shideler and Chamberlin performed consisted of 130 cylinders that were steam cured immediately after casting, same as the first series, but for periods of 6, 24, and 72 hours and then were fog cured at 70 degrees until tested. The data compiled from this series of testing, Table 2.2 [13], show that steam curing at low temperatures followed by moist curing produces a concrete strength almost the same as the continuously moist cured. However, the specimens steam cured at 165 degrees had 28-day strengths of approximately 75% of that of the continuously moist cured, and specimens steam cured at 185 degrees had strengths about 50% of the moist cured specimen. Therefore, one of the conclusions that Shideler and Chamberlin noted from this series of testing was that higher curing temperatures produces lower 28-day strengths.

The third and final series of tests were performed on 176 cylinders, and it is this series that is most pertinent to the testing and results presented in this study. The specimens of this series were subjected to an initial curing period prior to steam curing. This initial curing period ranged from immediate steam curing, as in the previous series of tests, to 12 hours. After the initial curing period, the specimens were then steam cured to an age of 24 hours. The data obtained from these tests, Table 2.3 [13], show that the use of the initial curing period prior to steam curing produces higher strengths at 24 hours, although still weaker in 28-day strength than the continuously moist cured specimens. The results also show that higher steam curing temperatures require longer initial curing periods to produce maximum strengths as shown in Figure 2.1 [13]. Figure 2.1 also shows that a delay of approximately 4 to 6 hours prior to steam curing at a maximum temperature of 165 degrees produced maximum strengths.

In conclusion, Shideler and Chamberlin suggested that further testing be performed on the subject of steam curing, particularly the steam curing with an initial curing cycle. They noted that steam curing accelerates the early strength development of concrete but adversely effects the 28-day strength. They stated that the optimum steam room temperature was between 130 and 165 degrees and recommended an

TABLE 2.2 Compressive strength of 6 x 12 in. cylinders - second series (Shideler and Chamberlin).

Source: Shideler and Chamberlin, "Early Strength of Concrete as Affected by Steam Curing Temperature," *Journal of the American Concrete Institute*, Vol. 46, No. 6, p. 279.

Time specimens subjected to steam and fog curing	Age at test	Compressive strength (psi)*									
		100 F†			130 F			165 F		185 F	
		Type I	Type II	Type V	Type I	Type II	Type V	Type I	Type II	Type I	Type II
6-hour steam cure	6 hours	130	120	140	280	400	390	620	740	880	1010
1-day steam cure	1 day	1090	1280	1210	1400	1620	1430	1550	1990	1420	1660
3-day steam cure	3 days	2010	2460	2220	2620	2780	2530	2450	2840	2000	2160
6-hour steam cure plus 7-day fog cure	7 days	2460	2770	2680	2470	2730	2390	2200	2210	1720	1680
6-hour steam cure plus 28-day fog cure	28 days	3510	4640	4200	3920	4490	4000	2820	3380	2220	2310
1-day steam cure plus 6-day fog cure	7 days	2550	2960	2450	2700	3220	2680	2700	2950	1670	1670
1-day steam cure plus 27-day fog cure	28 days	3760	4450	4220	3750	4270	3830	3200	3370	2080	2340
3-day steam cure plus 4-day fog cure	7 days	2660	2960	2580	2970	3330	3050	2830	2930	2320	2180
3-day steam cure plus 25-day fog cure	28 days	3460	4260	4030	3710	4250	3980	2800	3550	1920	2290

Fog-cured control cylinders 70 F

Time cured	Age	Compressive strength (psi)		
		Type I‡	Type II‡	Type V§
1-day	1 day	540	680	600
3-day	3 days	1680	1890	1560
7-day	7 days	2640	3010	2350
28-day	28 days	4070	4810	4100

*Average of two cylinders.
†Steam room temperature.
‡Average of eight cylinders.
§Average of four cylinders.

TABLE 2.3 Compressive strength of 6 x 12 in. cylinders - third series (Shideler and Chamberlin).

Source: Shideler and Chamberlin, "Early Strength of Concrete as Affected by Steam Curing Temperature," *Journal of the American Concrete Institute*, Vol. 46, No. 6, p. 281.

Specimens fog cured for period indicated, then steam cured to age of 24 hours	Compressive strength (psi) at age of 1 day							
	100 F (steam temp)		130 F (steam temp)		165 F (steam temp)		185 F (steam temp)	
	Type I	Type II	Type I	Type II	Type I	Type II	Type I	Type II
0 hours	1070*	1190	1360	1500	1520	1600	1350	1630
½ hour	1060	1200	1400	1600	1680	1640	1310	1380
1 hour	1150	1260	1320	1600	1660	1500	1380	1360
2 hours	1280	1390	1520	1860	1600	1740	1280	1600
4 hours	1190	1200	1720	1830	1950	1990	1970	2060
6 hours	1120	1120	1540	1720	1900	2050	2020	2260
8 hours	1050	1070	1550	1660	1850	1950	1900	2160
12 hours	940	980	1420	1480	1710	1830	1880	2040

Fog-cured control cylinders 70 F

Continuously fog-cured at 100 percent R.H. 70 F	Compressive strength (psi)	
	Type I	Type II
1 day	520†	680
2 days	1220	1300
7 days	2760	2800

*Average of two cylinders.
†Average of eight cylinders.

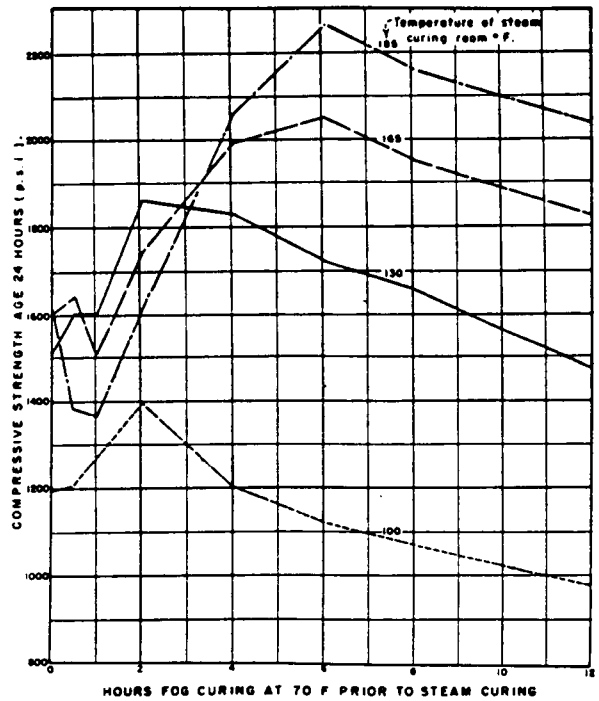


FIGURE 2.1 Delay period prior to steam curing.

Source: Shideler and Chamberlin, "Early Strength of Concrete as Affected by Steam Curing Temperature," *Journal of the American Concrete Institute*, Vol. 46, No. 6, p. 281.

initial curing period of 2 to 6 hours prior to steam curing. Finally, they remarked that steam room temperatures greater than 165 degrees and rapid rise rates are extremely detrimental to the strength of the concrete.

2.2.2 Saul (1951) — (Ref. 12)

In March of 1951 the *Magazine of Concrete Research* published an article by A. G. A. Saul which summarized the conclusions of his study carried out at the Cement and Concrete Association Research Station. Saul studied the effects that various characteristics of steam curing have on the compressive strength of concrete. He compared his test results to the "maturity" of the concrete which he defined as the concrete's age multiplied by the average temperature above freezing that the concrete has maintained and is expressed in degrees C-hours. Using this as a basis, a normal moist curing cycle of 24 hours would produce a concrete with a maturity of 400 degrees C-hours and a maturity of 2800 and 11,200 degrees C-hours are produced for 7 and 28 days, respectively. Saul uses this method for his comparison of steam cured specimens to that of moist cured and compares the effects that steam curing has on the "maturity" of the concrete.

The curing chamber used by Saul limited the amount of specimens to be steam cured simultaneously to 24; however, 24 specimens were the most that could conveniently be produced in the laboratory that was used. Therefore, he produced 12 specimens for steam curing and 12 for moist curing. The steam curing chamber used was made of two 36" diameter concrete pipes that lay end to end to produce two unequal compartments. The larger of the two compartments was used to hold the specimens for steam curing and the smaller to hold 16 gallons of water which was heated to produce the steam. A total of 1176 specimens were tested in Saul's experiment. He used one batch of 12 control specimens to compare a number of batches of experimental specimens. He justified the use of only one batch of control specimens per mix by using exactly the same mix design for a varying number of experimental batches as was used in the production of the control specimens. In total, he produced 90 experimental batches of 12 specimens each and 8 control batches of 12. The results of

a portion of his testing are shown in Tables 2.4 and 2.5 [12].

Saul states in his article that time and temperature are major factors influencing the rate at which concrete gains strength. This is because the chemical reaction between the cement and water is practically nonexistent at about the freezing point of water and is greatly stimulated at extremely high temperatures. During normal curing cycles, concrete will gain strength rapidly at first and slower as it ages. The early strength gain can be increased with higher and higher temperatures at early ages but can be damaging if subjected to temperatures too high too soon or for extended periods of time.

As stated above, Saul introduces the concept of maturity for concrete. He also suggests a natural law of the gain of strength of concrete with its maturity by stating that a concrete with the same mix at the same maturity has approximately the same strength no matter its age. His testing determined that concrete will obey this law unless its temperature reaches 50 degrees Celsius before it has cured for 2 hours or if it reaches 100 degrees Celsius before 5 to 6 hours of curing. If subjected to a more rapid temperature rise than that just stated, the concrete will not obey this law. Instead, it will gain strength much faster during the first few hours but will be adversely affected in its long term strength.

Saul touches on many points and offers a number of suggestions for the production of steam cured concrete throughout his paper; however, only a few are pertinent to this study. He proved that after approximately 10 to 12 days, the moist cured specimens surpassed the strength of the steam cured concrete and at 28 days is perceptibly stronger than the steam cured specimens. He also shows that for a test method with a slow initial rise rate to a maximum temperature of about 40 to 45 degrees Celsius, the gain of strength in relation to maturity is at first slower than with normally cured concrete, but afterwards is greater. This phenomenon suggests that normal curing temperatures may not necessarily provide optimum curing conditions. With Saul's study, the adverse effect of a rapid early temperature rise is seen to be greater as the water/cement ratio increases. In his conclusions he states that the most important factor in steam curing is the rise rate of temperature and that higher temperatures and prolonged

TABLE 2.4 Curing treatments and test results; w/c ratios 0.35 and 0.50 (Saul).

Source: Saul, A.G.A., "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure," *Magazine of Concrete Research*, Vol. 2, No. 6, p. 136.

Ordinary Portland cement. (Mix 1 : 3 by weight ; water-cement ratio 0·35) (Mix 1 : 5·5 by weight ; water-cement ratio 0·50)

1	Number of experiment	8	11	6	4	3	1	10	9	2	5	7	Control
2	Time from mixing to start of treatment (hr-min)	1–00	1–00	1–10	1–30	1–40	1–50	4–00	1–40	2–00	1–40	0–40	
3[a]	Time from mixing to reach 50°C (hr-min)	1–43 (1–37)	2–20 (2–35)	5–10 (5–10)	5–00 (5–10)	5–30 (5–30)	5–10 (5–10)	6–00 (6–00)	2–50 (3–00)	4–30 (4–30)	3–05 (3–15)	0–50 (0–45)	
4[a]	Time from mixing to reach maximum temperature (hr-min)	4–00 (3–55)	6–30 (6–30)	6–10 (5–10)	6–20 (5–50)	7–10 (6–30)	6–50 (7–05)	9–00 (9–30)	6–20 (6–50)	6–30 (6–30)	5–15 (5–25)	1–20 (1–45)	
5[a]	Maximum temperature (°C)	100+ (100)	90 (76)	63 (51)	70 (62)	82 (75)	100+ (100)	100+ (100)	93 (77)	100+ (100)	100+ (100)	100+ (100)	16·6°C for
6[a]	Duration of maximum temperature (hr-min)	1–40 (1–40)	0–50 (0–50)	0 (0–50)	0 (0)	0 (0–40)	1–00 (0–40)	2–00 (1–00)	1–00 (0–30)	3–30 (3–30)	9–00 (9–00)	11–30 (11–00)	3 days
7[a]	Duration of cooling period (hr) ..	Nom (0)	Nom (0)	18 (18)	17½ (18)	17½ (17½)	17 (17)	13 (13½)	16½ (16½)	14 (14)	9½ (9½)	11 (11)	
8[a]	Temperature at end of cooling period (°C)	12 (12)	12 (12)	38 (16)	43 (28)	44 (32)	56 (24)	45 (31)	52 (32)	46 (34)	65 (47)	60 (44)	
9	Time after cooling until tested (hr) ..	18½	18½	0	0	0	0	0	0	0	0	0	
10[a]	Maturity (°C–hr)	737 (622)	851 (727)	993 (732)	1127 (886)	1384 (1138)	1498 (1097)	1535 (1322)	1673 (1284)	1721 (1514)	2059 (1874)	2164 (1986)	1200
11[b]	Compressive strength at 24 hr (lb per sq. in.)	3860 2290	4460 2520	4260 2450	4950 2940	5004 2820	5175 3103	4895 3210	5365 3330	5250 3150	5350 3540	4045 2375	4805[c] 3160
12[b]	Compressive strength at 7 days (lb per sq. in.)	4630 2910	5550 3820	5730 3640	5406 3780	5680 3456	5350 3653	5687 3620	5620 3700	5516 3206	5570 3600	3776 2350	5678 3865
13[b]	Compressive strength at 28 days (lb per sq. in.)	6250 4030	6810 4645	6500 5012	6600 4578	6800 4780	6660 4640	6895 4960	7085 5075	6800 4200	6870 4579	5575 3240	7067 5286

[a] Upper figures refer to concrete, lower figures (in brackets) to curing chamber.

[b] Upper figures refer to low water-cement ratio cubes, lower figures to high water-cement ratio cubes.

[c] Control specimens tested at 3 days (1200°C-hr) in lieu of 24 hr.

100+ means slightly above 100°C.

TABLE 2.5 Curing treatments and test results; w/c ratio 0.275 (Saul).

Source: Saul, A.G.A., "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure," *Magazine of Concrete Research*, Vol. 2, No. 6, p. 140.

Ordinary Portland cement. (Mix 1 : 2·5 by weight ; water-cement ratio 0·275)

1	Number of experiment	53	56	51	55	57	52	59	49	50	58	54	Control
2	Time from mixing to start of treatment (hr-min)	1·0	0·45	0·30	0·30	0·40	0·40	0·35	0·30	0·30	0·45	0·40	
3[a]	Time from mixing to reach 50°C (hr-min)	2·10 (2·30)	2·10 (2·20)	1·50 (1·40)	2·05 (2·25)	2·35 —	— —	1·40 (1·40)	1·10 —	— —	1·15 (1·0)	0·50 (0·45)	
4[a]	Time from mixing to reach maximum temperature (hr-min)	5·50 (7·00)	6·30 (6·30)	5·20 (5·00)	4·00 (4·00)	3·0 (3·0)	1·15 (1·15)	4·40 (4·30)	2·0 (2·0)	0·50 (0·40)	2·45 (2·30)	2·0 (2·0)	
5[a]	Maximum temperature (°C)	100+ (98)	100+ (96)	100 (93)	70 (59)	55 (48)	40 (35)	100 (93)	60 (47)	40 (40)	100 (93)	100+ (94)	at 16·6°C
6	Duration of maximum temperature (hr)	1½	1	2½	4	4	6	—	2	4½	4	5	
7	Duration of cooling period (hr) ..	17	16½	16	16	17	17	19	20	18½	17	17	
8[a]	Temperature at end of cooling period (°C)	55 (41)	41 (30)	41 (31)	18 (16)	17 (15)	21 (20)	32 (23)	22 (17)	17 (17)	38 (26)	40 (32)	
9	Maturity after 24 hr (°C-hr)	1918	1590	1598	1063	823	747	1449	875	662	1581	1715	400
10[b]	Compressive strength (lb per sq. in.) at ages: 3 hr	—	—	—	—	—	—	—	—	—	—	3010	
	5 hr	—	—	3635	—	—	—	—	—	—	—	—	
	7 hr	4600	4715	—	4205	2810	2365	4950	2810	2060	4630	4545	350
	24 hr	6425	6180	6165	5570	4806	4750	6260	4145	3930	5835	5820	3060
	2 days	6895	—	(5675)	6200	—	(5280)	6510	(4750)	(4762)	5980	—	5390 (4990)
	3 days	(6320)	—	(6110)	6180	5620	—	—	(5185)	—	—	—	5930 (5760)
	5 days	—	—	—	—	—	(6815)	—	—	(6040)	—	—	
	7 days	(6530)	7160	(6570)	6780	6680	(6910)	7140	(6225)	(7320)	6450	(6070)	7220 (7270)
	14 days	—	7820	—	—	7610	—	—	—	—	—	(6240)	8020 (7990)
	28 days	(8070)	7910	(7980)	7980	8160	(8675)	8280	(7575)	(8100)	7585	(7060)	8720 (8580)
	91 days	—	9710	—	—	—	—	9420	—	—	8400	—	9580 (9520)

[a] Upper figures refer to concrete, lower figures (in brackets) to curing chamber.

[b] Figures in brackets refer to specimens stored in curing tank and tested wet. Figures without brackets refer to specimens stored in moist cupboard and tested relatively dry.

100+ means slightly above 100°C.

steaming are costly and should be used only when the resulting saving of time justifies such a procedure.

2.2.3 Higginson (1961) --- (Ref. 3)

This particular study by Elmo C. Higginson is an extension of the investigations reported by Shideler and Chamberlin. The study presented by Higginson is merely the concluding experiments that extended over 11 years in the Bureau of Reclamation Laboratories, continuing work which Shideler and Chamberlin began. The results presented by Higginson include the effect of steam temperatures from 100 degrees to 160 degrees, length of steam curing from 6 to 48 hours, and of a 1 and 3 hour pre-steam period. He used the results from 2330 test specimens to present effects on the compressive strength of the concrete, modulus of elasticity, durability, permeability, volume change, resistance to abrasion, and resistance to sulfate attack. Of the 2330 specimens, there were 768 produced for compressive strength tests. Although all the properties that were studied by Higginson are important, only the compressive strength tests are reviewed here.

The 768 cylinders fabricated for compressive strength tests were used to study the effect of time in steam curing on the strength of the concrete, the effect of temperature, and the effect of a pre-steam period. The steam cured cylinders were tested at 1/2, 1, 2, 7, 28, and 90 days, and the control specimens were tested at 2, 7, 28, and 90 days. The effect of time in steam curing was determined by curing the specimens for 6, 12, 24, and 48 hours in the steam chamber. As shown by Figures 2.2 and 2.3 [3], with an increase in the curing time of the steam period, there was also an increase in the compressive strength of the concrete. The effect that temperature had on the strength was presented by using a 100, 130, and 160 degree maximum curing temperature, and it was found that the higher the maximum temperature then the higher the compressive strength at early ages. However, this also produced lower 28 day strengths than the specimens cured at lower temperatures. As presented by both of the earlier articles reviewed in this chapter, the moist cured concrete developed higher 28 day strengths than any of the steam cured cylinders. The effect

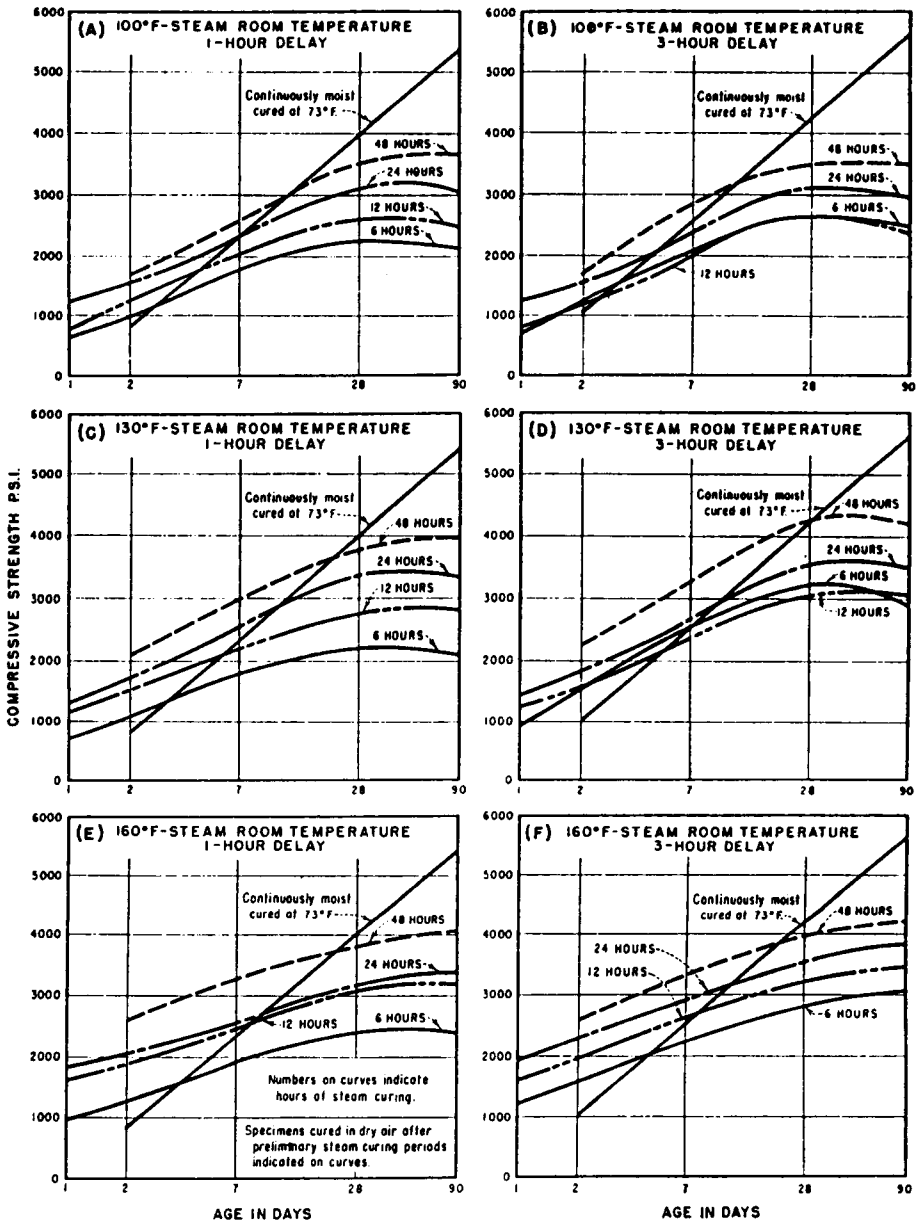


FIGURE 2.2 Compressive strength of steam cured concrete, 5 sacks per cy.

Source: Higginson, Elmo C., "Effect of Steam Curing on the Important Properties of Concrete," *Journal of the American Concrete Institute*, Vol. 58, No. 3, p. 285.

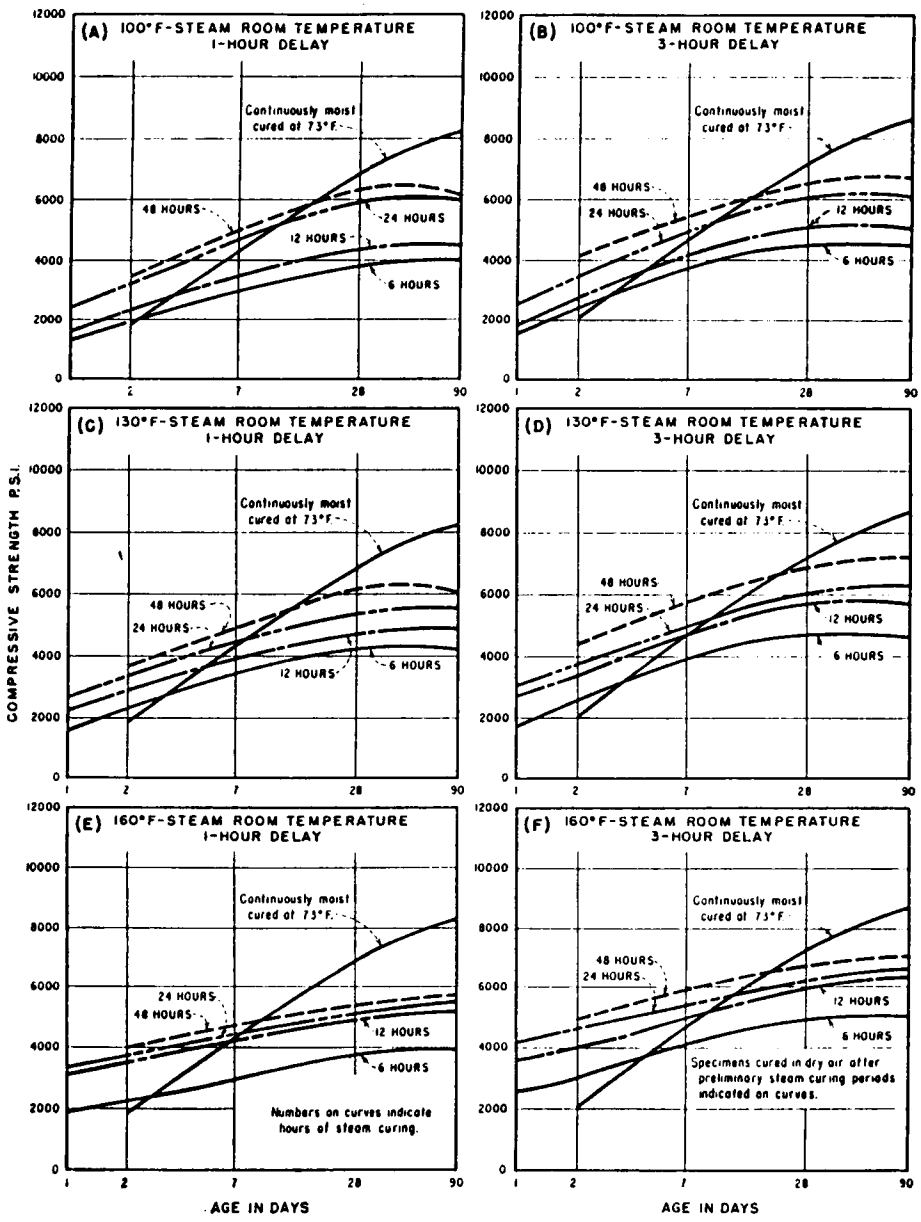


FIGURE 2.3 Compressive strength of steam cured concrete; 7 sacks per cy.
Source: Higginson, Elmo C., "Effect of Steam Curing on the Important Properties of Concrete," *Journal of the American Concrete Institute*, Vol. 58, No. 3, p. 286.

of a pre-steaming period was studied by using a 1 hour and a 3 hour delay prior to steam curing. It was shown that a 1 hour pre-steam period developed lower strengths than those in specimens subjected to a 3 hour pre-steam period. Higginson concluded that in general, steam cured concrete is not as good as concrete that has been moist cured. However, moist curing after steam curing does improve the quality of steam cured concrete.

2.2.4 Hanson (1963) --- (Ref. 2)

An investigation of the optimum steam curing procedure for precast, prestressed concrete plants is presented by J.A. Hanson in the Journal of the American Concrete Institute's January 1963 issue. The study emphasized steam curing procedures compatible with that of precast plants. Hanson mentions that many structural precast plants operate on a 24 hour cycle, with approximately 6 hours used for the stripping, cleaning and reassembling forms and the other 18 hours of the cycle set aside for the curing period. The curing period he referred to includes any presteam period plus the rise time and maximum curing periods. Hanson recognized the previous studies by Saul, Shideler and Chamberlin, and by Higginson and their indications that an initial pre-steam period is beneficial to the compressive strength of the concrete and incorporated their conclusions into his investigation.

The primary purpose of Hanson's study was to find optimum conditions for steam curing concrete. He notes that the strength of the precast concrete must reach 3500 to 4000 psi prior to form removal. Hanson used these characteristics of steam curing in his testing and varied several properties of the curing process to come to his conclusions. His tests used maximum temperatures of 125, 150, and 175 degrees with rise rates of 20, 40, 60, and 80 degrees per hour. Presteam periods of 1, 3, 5, and 7 hours were used. To coincide with the precast industry, Hanson incorporated an 18 hour cycle which included the presteam period, the rise time, and the maximum temperature curing time. Compressive strength tests were performed at 18 hours, 7 days, and 28 days, and the mixes were

designed to produce a 6000 psi, 28-day moist cured strength; see mix data in Table 2.6 [2]. As shown in both the test results of Table 2.7 [2] and test graphs of Figure 2.4 [2], Hanson showed that the early strength of the steam cured specimens increases as the presteaming period increases from 1 to 5 hours and begins a slight decrease for more than a 5 hour presteaming period. The later tests of the 7 and 28 day strengths reached a maximum with a presteam period ranging from 5 to 7 hours. As shown by Shideler and Chamberlin, as well as Higginson. the loss of potential compressive strength due to steam curing is in the range of a 5-20% decrease in the 28 day strength. With this in mind, Hanson's test results generally exhibit an optimum initial curing period of 5 hours prior to steam curing.

Hanson's data concerning rise rate and maximum temperature show that compressive strengths increase quickly with rising maximum temperatures to approximately 150 degrees and only a very slight increase in strength resulting from temperatures higher than 150. He also showed an optimum rise rate of 40 degrees per hour with a minor change in

TABLE 2.6 Mix data and properties of moist cured concrete.
Source: Hanson. J. A., "Optimum Steam Curing Procedure in Precasting Plants." *Journal of the American Concrete Institute*. Vol. 60, No. 1. p. 80.

Cement type	No. of batches	Fine aggregate, percent by volume	Quantities per cu yd of concrete						Gravimetric air, percent	Plastic unit weight, lb per cu ft	Slump, in.
			Water		Cement		Aggregate, lb				
			Gal	Lb	Bags	Lb	Fine	Coarse			
I	61	37.8	30.7	256	8.44	793	1077	1769	6.1	144.3	1.9
III	93	38.6	28.8	240	6.56	617	1159	1848	6.8	143.1	2.1

— PROPERTIES OF CONTINUOUSLY MOIST-CURED CONCRETE

Cement type	Compressive strength				Modulus of elasticity				Tensile strength	
			28 day				28 day		28 day	
	18 hr psi	7 day psi	psi	C.V.* percent	18 hr 10^6psi	7 day 10^6psi	10^6psi	C.V.* percent	psi	C.V.* percent
I	1960	4820	5950	5.0	2.23	3.56	4.14	4.2	—	—
III	2090	5350	6140	5.0	2.37	3.50	3.93	3.9	510	7.6

*Coefficient of variation.

TABLE 2.7 Compressive strength of steam and moist cured concrete.

Source: Hanson, J. A., "Optimum Steam Curing Procedure in Precasting Plants," *Journal of the American Concrete Institute*, Vol. 60, No. 1, p. 84.

Steam rate, F per hr	Presteam period, hr	Steam period, hr	Compressive strength, psi				Modulus of elasticity, 10^6 psi			
			Steam cured			Moist	Steam cured			Moist
			18 hr	7 day	28 day	28 day*	18 hr	7 day	28 day	28 day*
			Maximum temperature, 125 F							
20	7	11	3000	4620	5480		2.84	3.74	4.02	
	5	13	2980	4490	5180		3.03	3.63	3.72	
	3	15	2960	4420	52.0		3.16	3.58	3.85	
	1	17	2940	4290	5000	5960	2.93	3.64	3.82	4.14
40	15	3	2230	4480	5220		2.35	3.72	3.80	
	13	5	2400	4400	4960		2.52	3.71	4.08	
	11	7	2600	4500	5220		2.81	3.63	4.08	
	9	9	2960	4480	5230	5780	2.92	3.68	3.95	4.18
	7	11	3140	4790	5620		2.82	3.47	4.13	
	5	13	3160	4660	5340		2.93	3.69	3.95	
	3	15	3170	4420	5180		3.00	3.48	3.94	
	1	17	2950	4200	5090	6020	2.97	3.52	3.97	4.21
60	7	11	3040	4790	5440		3.00	3.91	4.01	
	5	13	3040	4560	5070		3.06	3.64	3.82	
	3	15	3020	4140	4980		3.00	3.62	4.03	
	1	17	2710	4030	4670	5980	2.72	3.54	3.74	4.07
80	7	11	3260	4700	5580		3.02	3.85	3.86	
	5	13	3030	4420	5080		2.89	3.66	3.74	
	3	15	3040	4170	4870		2.98	3.53	3.75	
	1	17	2300	3160	4080	6000	2.49	3.01	3.52	4.14
			Maximum temperature, 150 F							
20	7	11	3200	4670	5380		2.77	3.66	4.14	
	5	13	3300	4720	5340		3.05	3.64	4.06	
	3	15	3430	4550	5150		3.22	3.58	4.02	
	1	17	3530	4470	4910	6290	3.20	3.60	3.86	4.26
40	15	3	2190	4420	5140		2.21	3.67	4.10	
	13	5	2540	4310	5100		2.46	3.62	3.73	
	11	7	2850	4520	5260		2.74	3.66	3.98	
	9	9	3240	4600	5340	5910	2.97	3.66	3.98	4.04
	7	11	3680	5120	5720		3.26	3.72	4.34	
	5	13	3860	5040	5640		3.32	3.72	4.34	
	3	15	3920	4980	5640		3.52	3.60	4.32	
	1	17	3570	4390	5280	6310	3.38	3.70	4.37	4.30
60	7	11	3540	4830	5460		3.13	3.74	4.34	
	5	13	3540	4690	5400		3.16	3.70	4.37	
	3	15	3660	4540	5340		3.42	3.58	4.20	
	1	17	2830	3390	3980	6320	2.96	3.46	3.78	4.54
80	7	11	3440	4560	5120		3.04	3.62	3.68	
	5	13	3440	4620	5100		3.14	3.66	3.81	
	3	15	3390	4420	4880		3.23	3.55	3.80	
	1	17	2300	2900	3590	5930	2.56	2.78	3.26	4.04
			Maximum temperature, 175 F							
20	7	11	3260	4560	5100		3.04	3.52	3.75	
	5	13	3430	4520	4980		3.18	3.53	3.89	
	3	15	3350	4380	4820		3.26	3.69	3.74	
	1	17	3520	4320	5000	5820	3.40	3.72	3.82	4.07
40	15	3	2000	4160	4840		2.04	3.48	3.74	
	13	5	2630	4180	4880		2.52	3.40	3.67	
	11	7	2990	4300	4920		2.88	3.44	3.72	
	9	9	3210	4470	5130	5920	2.95	3.46	3.83	4.02
	7	11	3660	4720	5280		3.34	3.62	3.88	
	5	13	3760	4780	5270		3.46	3.68	3.86	
	3	15	3650	4540	5020		3.38	3.58	3.91	
	1	17	3320	3930	4530	5700	3.30	3.30	3.71	4.08
60	7	11	3480	4440	5060		3.24	3.62	3.71	
	5	13	3650	4600	5010		3.02	3.47	3.87	
	3	15	3420	4240	4760		3.11	3.64	3.90	
	1	17	2530	2680	3410	5710	2.02	2.65	3.04	3.94
80	7	11	3560	4620	5180		3.03	3.61	3.88	
	5	13	3450	4420	4850		3.15	3.70	3.80	
	3	15	3780	4640	5180		3.13	3.84	3.98	
	1	17	2220	2720	3170	5780	2.06	2.73	2.81	4.05

*Daily average of specimens cured 73 ± 2 F and 100 percent relative humidity.

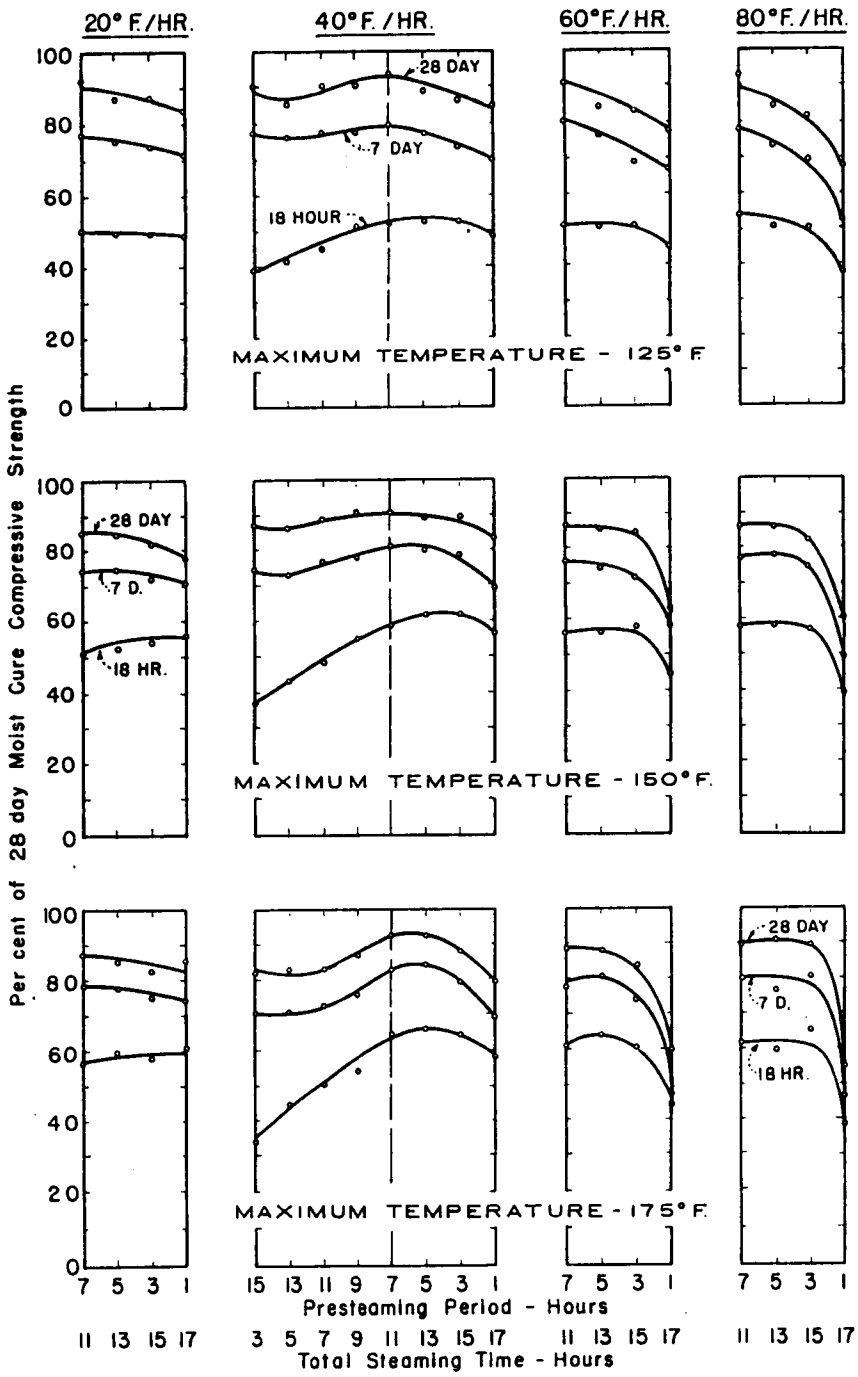


FIGURE 2.4 Relative compressive strength of steam cured concrete.

Source: Hanson, J. A., "Optimum Steam Curing Procedure in Precasting Plants," *Journal of the American Concrete Institute*, Vol. 60, No. 1, p. 86.

strength for other rise rates, whether higher or lower. One of the more interesting findings by Hanson was the substantial amount of horizontal cracking and extreme reduction in strength due to the early application of steam, particularly within 1 hour of casting. He recommended that this practice of early introduction to steam be avoided if at all possible.

In conclusion, Hanson went on to suggest that maximum temperatures higher than 150 be avoided with the exception of the possibility of using higher temperatures for extremely large members. However, if a higher maximum temperature is used, he suggested maintaining a 40 degree rise rate or less. Finally, the optimum steam curing procedure was found to be that with a 5 hour initial curing period, a 40 degree rise rate, and a 150 degree maximum temperature.

2.2.5 Oluokun, Burdette, and Deatherage (1990) --- (Ref. 9)

One of the more recent studies published on the effects that steam curing has on the various properties of concrete was performed by Francis A. Oluokun, Edwin G. Burdette, and J. Harold Deatherage. The purpose of the investigation was to determine the causes of early age cracking in steam cured precast, prestressed concrete. The investigation studied the effect that steam curing has on the elastic modulus, tensile strength, and compressive strength of the concrete. The test procedure fabricated 6 x 12 in. test specimens from a precast, prestressed concrete producer mix design that would provide a 28-day compressive strength of approximately 6000 psi. All specimens were cast from a single batch of concrete which produced specimens for both moist and steam curing. The steam curing procedure used was that practiced by typical prestressing plants. This process included a presteaming period of 5 hours, a rise rate equal to 40 degrees per hour up to a maximum temperature of 130 degrees. The test specimens were subjected to steam for a total of 15 hours including the rise time. Moist cured companion specimens were cured at standard conditions according to ASTM C 192.

The summary of test results shown in Table 2.8 [9] indicates that the moist cured specimens developed stronger 3-day strengths than did the

TABLE 2.8 Summary of test results.

Source: Oluokun, burdette, and Deatherage, "Concrete Physical Property Development at Early Ages: the Influence of Steam Curing," *Transportation Research Record,* No. 1284, 1990, p. 33.

Age	Steam fc (psi)	Moist fc (psi)	Steam Ec (10^6 psi)	Moist Ec (10^6psi)	Steam ft (psi)	Moist ft (psi)	Steam ν	Moist ν
8 Hrs	1,957	1,548	2.4586	2.2677	243	177	0.1438	0.1374
14 Hrs	3,259	2,942	3.3438	3.2875	336	289	0.1841	0.1876
24 Hrs	4,025	3,596	4.2926	3.7994	346	366	0.1815	0.1839
2 Days	4,111	3,979	4.3537	4.0057	391	405	0.1805	0.1834
3 Days	4,029	4,339	4.4744	4.1840	398	420	0.1807	0.1862
7 Days	4,904	5,176	4.5816	4.5960	444	507	0.1906	0.1948
28 Days	6,198	6,720	4.7224	5.1316	534	597	0.1961	0.1875

steam cured specimens. The compressive strength results reported in this study agree with the earlier results obtained by researchers such as Higginson, Hanson, and others that have previously been reviewed. It was also determined that the steam curing procedure, while beneficial to the elastic modulus and compressive strength up to about 3 days, was beneficial to the tensile strength only up to about an age of 14 hours. Afterwards, the process proved to be detrimental to the tensile strength. It was reported that this detrimental effect on the tensile strength of the concrete could possibly be responsible for the early age cracking that has recently been reported. In conclusion, the researchers suggested that further research be performed to establish a possible optimum steam curing procedure which will equally benefit the tensile strength, elastic modulus, and compressive strength of concrete.

CHAPTER THREE
TESTING PROCEDURE

3.1 INTRODUCTION

The experiments presented in this thesis used material proportions which varied according to the w/c ratio used. A mix design using a w/c ratio of 0.40 was designed to produce a 28-day moist cured compressive strength of approximately 6000 psi. This mix was then altered to produce the desired w/c ratios for the testing program. Each mix design's quantities shown in Table 3.1 are those for mixing a cubic yard of concrete. However, each batch mixed was proportioned to fabricate 24 cylinders. There were 12 cylinders used for moist curing and 12 used for steam curing from each batch of concrete. Each batch mixed also contained an amount of superplasticizer which was added during mixing. Each batch was mixed in accordance with ASTM C 192 and immediately tested for slump. After the slump was determined, the superplasticizer was added until the mix obtained a 6 inch slump. The mix proportioning for each batch is shown in Table 3.2. There were a total of four batches used, each of which tested three moist cured specimens and three steam cured specimens at ages of 1 day, 3 days, 7 days, and 28 days.

3.2 TEST PROGRAM

3.2.1 Materials

The materials used in the fabrication of the test cylinders consisted of standard cement and aggregates used in the construction industry today. The cement used was a Type I portland cement. The aggregates used consisted of ASTM No. 67 course aggregate which had 100% of the

TABLE 3.1 Mix designs per cubic yard

0.45 w/c ratio	
Material	**Amount per cy**
type I portland cement	752 lb.
water	338 lb.
course aggregate	1730 lb.
fine aggregate	1113 lb.

0.40 w/c ratio	
Material	**Amount per cy**
type I portland cement	752 lb.
water	301 lb.
course aggregate	1730 lb.
fine aggregate	1215 lb.

0.35 w/c ratio	
Material	**Amount per cy**
type I portland cement	752 lb.
water	263 lb.
course aggregate	1730 lb.
fine aggregate	1317 lb.

TABLE 3.2 Actual mixed proportions for 24 cylinders.

Batch 1: 0.45 w/c ratio

Material	Amount
type I portland cement	153.1 lb.
water	68.9 lb.
course aggregate	352.3 lb.
fine aggregate	226.6 lb.
Rheobuild 1000	50 mL

Batch 2: 0.40 w/c ratio

Material	Amount
type I portland cement	153.1 lb.
water	61.3 lb.
course aggregate	352.3 lb.
fine aggregate	247.4 lb.
Rheobuild 1000	350 mL

Batch 3: 0.35 w/c ratio

Material	Amount
type I portland cement	153.1 lb.
water	53.6 lb.
course aggregate	352.3 lb.
fine aggregate	268.2 lb.
Rheobuild 1000	350 mL

Batch 4: 0.40 w/c ratio

Material	Amount
type I portland cement	153.1 lb
water	61.3 lb.
course aggregate	352.3 lb.
fine aggregate	247.4 lb.
Rheobuild 1000	360 mL

stone less than 1 inch and 90% to 100% less than 3/4 inch. The fine aggregate used in this study was crushed limestone. The high range water reducer (superplasticizer) used was Rheobuild 1000 which is produced by Master Builders. Rheobuild 1000 meets the requirements of ASTM C 494 for Type A and Type F chemical admixtures in concrete.

3.2.2 Fabrication of Test Cylinders

After the concrete had been mixed in accordance with ASTM C 192, the concrete was tested for slump in accordance with ASTM C 143. After determining the initial slump of the batch, a trial and error method of adding the superplasticizer to the mix was incorporated until the desired 6" slump was attained. Table 3.3 represents the initial slump values and required dosage of superplasticizer to attain a resulting 6" slump for each batch. The cylinders were then cast in accordance with ASTM C 192 using three layers of equal depth with each layer being consolidated with 25 roddings per layer using a 5/8" diameter rod.

Immediately after casting, the cylinders were placed in the moist room for the initial curing period. After placing in the moist room, the cylinders were covered with wet burlap and a polyethylene sheet to minimize water evaporation.

3.2.3 Curing Process

Once all 24 cylinders had been fabricated and placed in the moist room, they were allowed an initial curing period of 5 hours, and then 12 of

TABLE 3.3 Initial slump and superplasticizer dosage

Batch #	Initial Slump	Superplasticizer	Final Slump
#1 (0.45 w/c)	5-1/4"	50 mL (1.7 oz.)	6-1/2"
#2 (0.40 w/c)	2-3/4"	350 mL (11.8 oz.)	6"
#3 (0.35 w/c)	3/4"	850 mL (28.7 oz.)	6-1/4"
#4 (0.40 w/c)	2-1/2"	360 mL (12.2 oz.)	6"

the 24 cylinders were moved to the steam chamber to begin the steam curing process. As shown in Figure 3.1, the cylinders of batches 1,2, and 3 were subjected to a set rise rate of 40 degrees per hour until reaching a maximum temperature of approximately 160-165 degrees. The cylinders of batch 4 were subjected to a set rise rate of 80 degrees per hour until reaching a maximum temperature of approximately 180-185 degrees. Once they reached the maximum temperature, the cylinders were subjected to this maximum temperature until reaching an age of 21 hours. Then, the specimens were removed from the steam chamber and allowed to cool for one hour; at this time, all cylinders having reached an age of 22 hours, molds were stripped from all cylinders, and the cylinders were either placed in the moist room for continued curing or air-dried and prepared for capping. The cylinders prepared for capping were then capped in accordance with ASTM C 617 with a proprietary sulfur-based capping compound. The cylinders were now ready for their 24-hour testing. This process of air-drying and capping was used for the 3 day, 7 day, and 28 day tests as well.

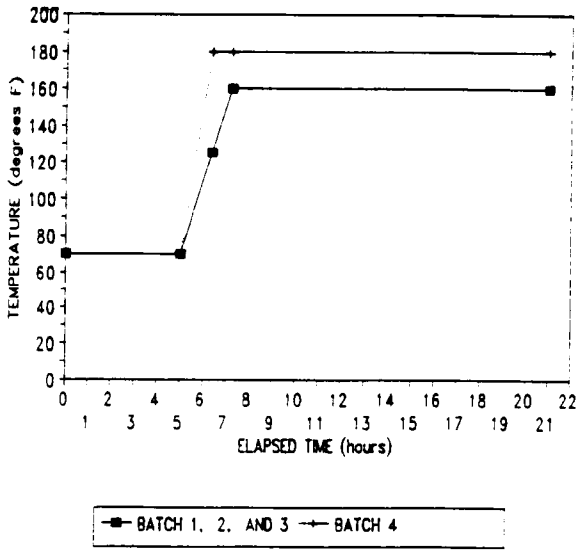


FIGURE 3.1 Steam Curing Cycle

3.2.4 Testing Procedure

As noted earlier, three moist cured specimens and three steam cured specimens from each batch were tested at ages of 1 day, 3 days, 7 days, and 28 days. The testing was performed on a 300,000 pound capacity testing machine that has a loading rate of 20 to 50 psi/sec in accordance with ASTM C 39, and all cylinders were tested to failure. The load at failure was recorded for each specimen and the resulting compressive strength was calculated.

CHAPTER FOUR
DISCUSSION OF RESULTS

4.1 INTRODUCTION

The reason for the research reported in this thesis is the possibility of the future inclusion of a superplasticizer in the mix designs of precast, prestressed concrete. The investigation studied the effect that a superplasticizer would have in steam cured concrete, if any, compared to the conclusions drawn from previous research. The study consisted of the testing of a total of 96, 6 x 12 inch cylinders. The following sections present and discuss the results of the testing and attempt to make a comparison to previous studies on similar topics.

The testing consisted of three batches of 24 cylinders each with w/c ratios of 0.45, 0.40, and 0.35 that underwent the same curing procedure. Of the 24 cylinders of each batch, 12 were steam cured and 12 were moist cured for companion specimens. The steam cured specimens were subjected to a presteam period of 5 hours and then introduced to a steam curing cycle that consisted of a 40 degree per hour rise rate to a maximum temperature of 160 degrees. The total steam cycle including the rise time equalled 16 hours. Later, a fourth batch was added to the experiment to study the effect that a superplasticizer would have if cured at the maximum allowable rise rate and highest allowable maximum temperature that is permitted in the production of precast, prestressed concrete. This fourth batch also had an initial curing period of 5 hours, but was then subjected to a rise rate of 80 degrees per hour until reaching a maximum temperature of 180 degrees. The total steam cycle again was 16 hours. With the addition of this fourth batch, the total number of cylinders tested in this study totals 96 specimens.

4.2 TEST RESULTS

4.2.1 Batch 1 Results

As noted earlier, Batch 1 had a w/c ratio of 0.45 and contained a 50 mL dosage of Rheobuild 1000 to obtain a 6" slump. As shown in Table 4.1 and Figures 4.1 and 4.2, the results from the testing of Batch 1 were as expected. The compressive strength of the concrete was accelerated by the steam curing process in the early ages and detrimental in the 28 day strength. However, the 28 day strength of the steam cured specimens was 93.9% of the moist cured specimens. As reported by Shideler and Chamberlin, specimens that are steam cured at temperatures above 150 degrees have compressive strengths about 75% of moist cured companion specimens. Therefore, it appears that the addition of the superplasticizer may have a significant benefit in the 28 day strength of the steam cured specimens.

Figures 4.1 and 4.2 indicate that the 24 hour strength is significantly increased by the steam curing process. There was, however, a drastic decline in the rate of strength gain in the steam cured specimens after the 24 hour testing and the moist cured specimens continued at a high rate of gain as expected. As reported in many of the previous investigations on steam curing, the moist cured cylinders eventually developed a higher compressive strength than did the steam cured specimens. As shown in Figure 4.1, the "crossover" age was approximately 7 days after casting. This "crossover" age coincides with that reported by Shideler and Chamberlin as well as Higginson. However, the results of Oluokun, Burdette, and Deatherage show a "crossover" age of approximately 3 days. The testing performed by Oluokun, Burdette, and Deatherage used a maximum steam room temperature of only 130 degrees, which would cause this earlier "crossover" age. Therefore, the results obtained from the testing of Batch 1 show no significant benefit from the use of a superplasticizer in the steam curing of concrete except for the slight increase in the percentage of 28 day moist cured strength that the steam cured specimens produced.

TABLE 4.1 Batch 1 test results.

BATCH 1 RESULTS: Moist Cured Specimens (0.45 w/c)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.45 - 1.1 M	75,000 lb.	2653	
0.45 - 1.2 M	80,000 lb.	2829	**2759**
0.45 - 1.3 M	79,000 lb.	2794	
0.45 - 3.1 M	121,000 lb.	4280	
0.45 - 3.2 M	119,000 lb.	4209	**4221**
0.45 - 3.3 M	118,000 lb.	4173	
0.45 - 7.1 M	143,000 lb.	5058	
0.45 - 7.2 M	140,000 lb.	4952	**4916**
0.45 - 7.3 M	134,000 lb.	4739	
0.45 - 28.1 M	170,000 lb.	6013	
0.45 - 28.2 M	171,000 lb.	6048	**5977**
0.45 - 28.3 M	166,000 lb.	5871	

BATCH 1 RESULTS: Steam Cured Specimens (0.45 w/c)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.45 - 1.1 S	128,000 lb.	4527	
0.45 - 1.2 S	125,000 lb.	4421	**4468**
0.45 - 1.3 S	126,000 lb.	4456	
0.45 - 3.1 S	132,000 lb.	4669	
0.45 - 3.2 S	131,000 lb.	4633	**4621**
0.45 - 3.3 S	129,000 lb.	4562	
0.45 - 7.1 S	146,000 lb.	5164	
0.45 - 7.2 S	137,000 lb.	4845	**4881**
0.45 - 7.3 S	131,000 lb.	4633	
0.45 - 28.1 S	152,000 lb.	5376	
0.45 - 28.2 S	161,000 lb.	5694	5612
0.45 - 28.3 S	163,000 lb.	5765	

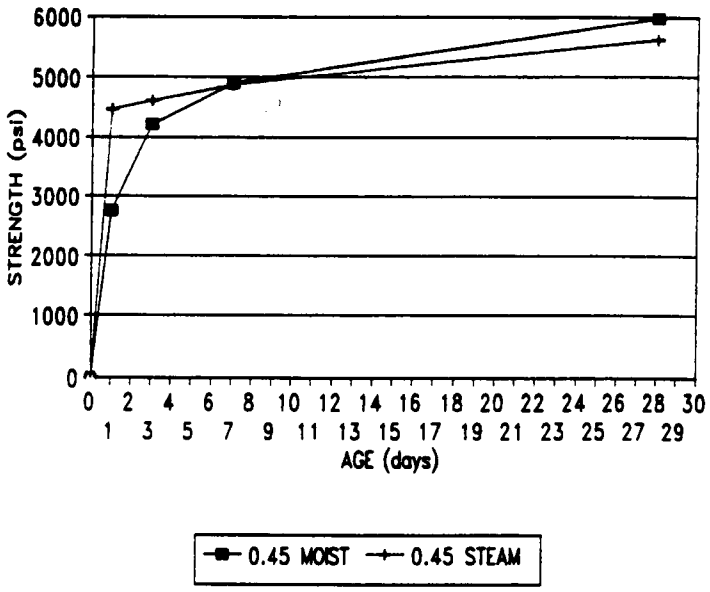


FIGURE 4.1 Batch 1 results.

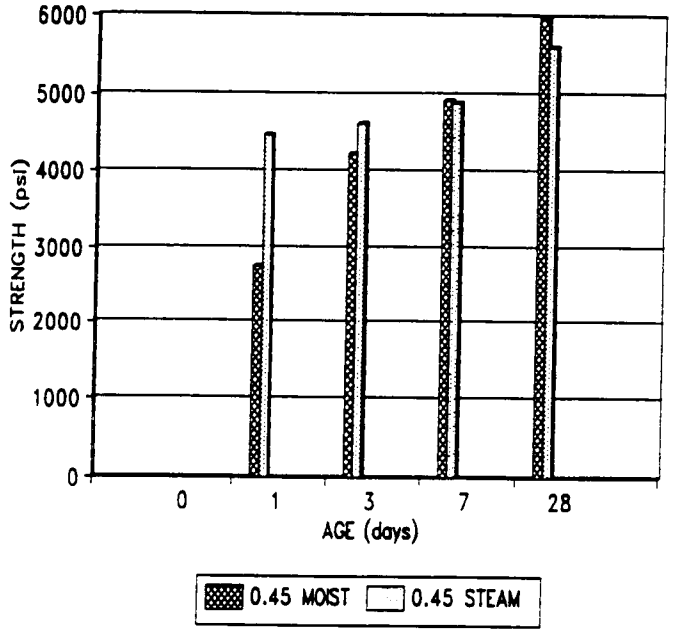


FIGURE 4.2 Batch 1 results.

4.2.2 Batch 2 Results

The results from the testing of Batch 2 are shown in Table 4.2 and Figures 4.3 and 4.4. These particular results were a bit more unexpected than were the results from Batch 1. The results of Batch 2 show a later "crossover" age and a higher percentage of the 28 day moist cured strength for the steam cured specimens.

Figure 4.3 shows that the apparent "crossover" age is approximately 15 days, which is greater than any reported by any of the investigations reviewed in this thesis. The steam cured specimens developed a significantly higher 24 hour strength than the moist cured specimens as expected, but continued to gain strength after the 24 hour test. The strength gain between the 24 hour test and the 3 day test was very minimal; however, the strength gain from 3 to 7 days, as shown by Figure 4.4, almost coincides with the strength gain of the moist cured specimens. Even more unexpected was the rate of strength gain in the steam cured specimens up to the 28 day test. The moist cured specimens had a rate of strength gain of approximately 73 psi per day from the 7 day test to the 28 day test. The steam cured specimens produced a rate of strength gain of about 60 psi per day which allowed the moist cured cylinders to produce a slightly higher 28 day strength. In comparison, the rate of strength gain of steam cured specimens that were cured under similar conditions but did not contain a superplasticizer were much less. Hanson's results indicate that the steam cured specimens cured at 175 degrees for 13 hours with a presteam period of 5 hours had a rate of strength gain between the 7 and 28 day test of only 23 psi per day. Hanson's specimens cured at 150 degrees only had a rate of strength gain of about 29 psi per day and those cured at 125 degrees had 32 psi per day. Therefore, it appears that the superplasticizer increases the rate at which steam cured concrete gains strength at later ages.

The increased percentage of the 28 day moist cured strength again can be accounted for by the addition of the superplasticizer. The steam cured specimens achieved an average 28 day strength of 6561 psi which is 97.46% of that achieved by the moist cured cylinders. Therefore, the

addition of the superplasticizer appears to be beneficial to the strength achieved by steam cured concrete at 28 days in relation to the lower percentages reported by earlier investigations.

As noted in chapter 3, Batch 2 had a w/c ratio of 0.40 and contained 350 mL of Rheobuild 1000. It appears that the increase in the dosage of superplasticizer needed to obtain a 6" slump caused the 28 day strength of the steam cured specimens to increase from the expected 75 to 80 percent up to about 97.5 percent of the 28 day moist cured strength.

TABLE 4.2 Batch 2 test results.

BATCH 2 RESULTS: Moist Cured Specimens (0.40 w/c)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.40 - 1.1 M	124,000 lb.	4386	
0.40 - 1.2 M	116,000 lb.	4103	**4209**
0.40 - 1.3 M	117,000 lb.	4138	
0.40 - 3.1 M	146,000 lb.	5164	
0.40 - 3.2 M	139,000 lb.	4916	**4928**
0.40 - 3.3 M	133,000 lb.	4704	
0.40 - 7.1 M	147,000 lb.	5199	
0.40 - 7.2 M	150,000 lb.	5305	**5199**
0.40 - 7.3 M	144,000 lb.	5093	
0.40 - 28.1 M	191,000 lb.	6755	
0.40 - 28.2 M	188,000 lb.	6649	**6732**
0.40 - 28.3 M	192,000 lb.	6791	

BATCH 2 RESULTS: Steam Cured Specimens (0.40 w/c)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.40 - 1.1 S	141,000 lb.	4987	
0.40 - 1.2 S	137,000 lb.	4845	**4940**
0.40 - 1.3 S	141,000 lb.	4987	
0.40 - 3.1 S	142,000 lb.	5022	
0.40 - 3.2 S	142,000 lb.	5022	**5057**
0.40 - 3.3 S	145,000 lb.	5128	
0.40 - 7.1 S	148,000 lb.	5235	
0.40 - 7.2 S	149,000 lb.	5270	**5294**
0.40 - 7.3 S	152,000 lb.	5376	
0.40 - 28.1 S	186,000 lb.	6578	
0.40 - 28.2 S	* * *	*	6561
0.40 - 28.3 S	185,000 lb.	6543	

*** NOTE: These cylinders sustained a capping failure.

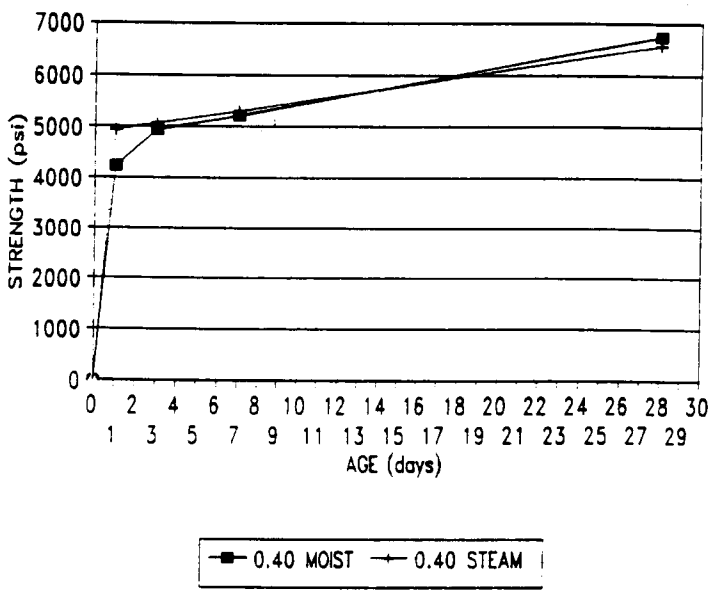


FIGURE 4.3 Batch 2 results.

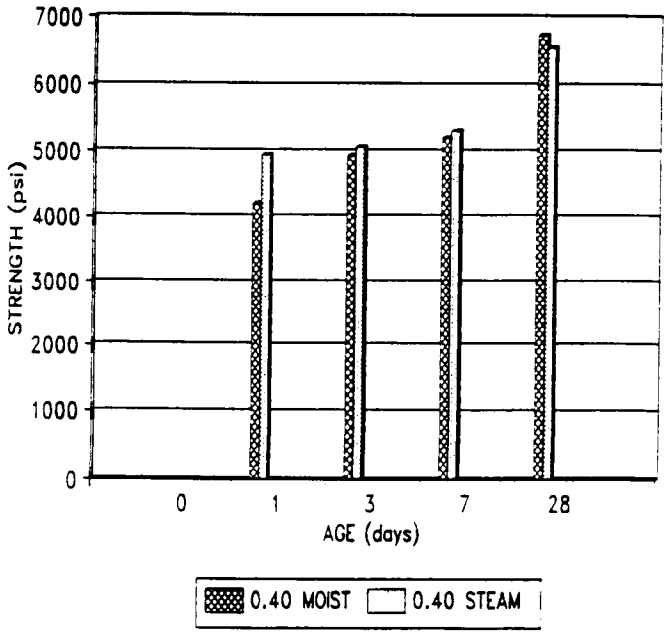


FIGURE 4.4 Batch 2 results.

4.2.3 Batch 3 Results

The results of Batch 3, as presented in Table 4.3 and Figures 4.5 and 4.6 were surprising. As one can see in Figure 4.5, Batch 3 never achieved a "crossover" age; the steam cured specimens achieved a greater 28 day strength than did the moist cured specimens. This phenomenon did not occur in any of the investigations that were reviewed in this thesis; in fact, the closest that the steam cured specimens' 28 day strength got to the moist cured specimens' 28 day strength was that reported by both Hanson and by Oluokun, Burdette, and Deatherage. In both cases, however, the curing process consisted of very low maximum temperatures and low rise rates, which would produce this higher percentage. In the case of Batch 3 tested in this study, the curing process did not consist of the low maximum temperature and the low rise rate. Therefore, the addition of the superplasticizer in this batch of concrete apparently aided in the production of a steam cured concrete with a greater 28 day strength than the companion moist cured specimens.

Batch 3 contained 850 mL of Rheobuild 1000 and had a w/c ratio of 0.35. The lower w/c ratio explains the higher moist cured strengths, but the higher dosage of superplasticizer needed to obtain a 6" slump is the only apparent reason for the steam cured specimens achieving a higher compressive strength than the moist cured. As seen in Figure 4.5 and Table 4.3, there was a very small increase in strength from 1 to 3 days and a slightly higher increase from 3 to 7 days. The increase from 7 to 28 days, however, was quite significant. This rate of strength gain of about 65 psi per day is much greater than the 33 psi per day experienced by the moist cured specimens. The decline in strength gain rate of the moist cured specimens from those of Batch 2 can be attributed to the higher strength of the concrete since higher strength concretes tend to "flatten off" at earlier ages than concretes of lower strengths. The addition of a substantial amount of Rheobuild 1000 appears to produce beneficial effects on the later strengths of steam cured concrete.

TABLE 4.3 Batch 3 test results.

BATCH 3 RESULTS: Moist Cured Specimens (0.35 w/c)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.35 - 1.1 M	158,000 lb.	5588	
0.35 - 1.2 M	154,000 lb.	5447	**5400**
0.35 - 1.3 M	146,000 lb.	5164	
0.35 - 3.1 M	182,000 lb.	6437	
0.35 - 3.2 M	184,000 lb.	6508	**6473**
0.35 - 3.3 M	* * *	* *	
0.35 - 7.1 M	* * *	* *	
0.35 - 7.2 M	187,000 lb.	6614	**6667**
0.35 - 7.3 M	190,000 lb.	6720	
0.35 - 28.1 M	204,000 lb.	7215	
0.35 - 28.2 M	217,000 lb.	7675	**7357**
0.35 - 28.3 M	203,000 lb.	7180	

*** NOTE: These cylinders sustained a capping failure

BATCH 3 RESULTS: Steam Cured Specimens (0.35 w/c)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.35 - 1.1 S	196,000 lb.	6932	
0.35 - 1.2 S	201,000 lb.	7109	**6997**
0.35 - 1.3 S	196,500 lb.	6950	
0.35 - 3.1 S	198,000 lb.	7003	
0.35 - 3.2 S	197,000 lb.	6968	**7003**
0.35 - 3.3 S	199,000 lb.	7038	
0.35 - 7.1 S	201,000 lb.	7109	
0.35 - 7.2 S	203,000 lb.	7180	**7109**
0.35 - 7.3 S	199,000 lb.	7038	
0.35 - 28.1 S	246,000 lb.	8701	
0.35 - 28.2 S	236,000 lb.	8347	**8465**
0.35 - 28.3 S	236,000 lb.	8347	

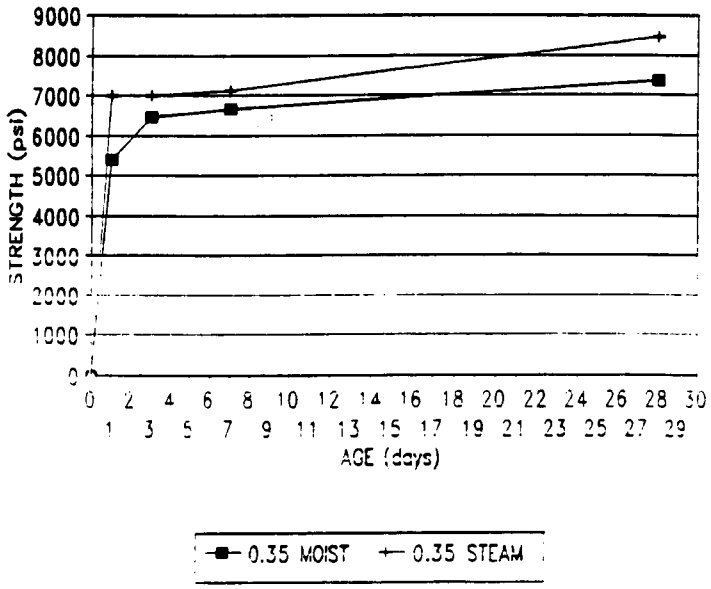


FIGURE 4.5 Batch 3 results.

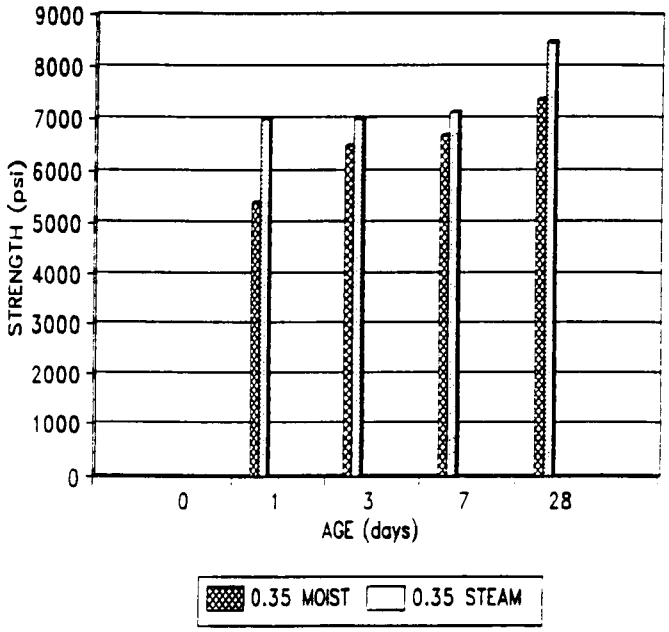


FIGURE 4.6 Batch 3 results.

4.2.4 Batch 4 Results

Batch 4 was added in the later stages of this investigation to study the effects that a superplasticizer has on steam cured concrete when cured at the maximum curing conditions used in the prestress industry. These conditions, as stated earlier, consisted of a rise rate of 80 degrees per hour and a maximum temperature of 180 degrees. The results, shown in Table 4.4 and Figures 4.7 and 4.8, are not as surprising as those found in batches 2 and 3.

Batch 4 contained 360 mL of Rheobuild 1000 and had a w/c ratio of 0.40. Batch 4 was identical to Batch 2 with the only change being that of the curing process. Steam cured specimens of Batch 4 produced a 28 day compressive strength equal to about 92% of the moist cured companion specimens' 28 day strength. In comparison, the corresponding percentage for the steam cured specimens of Batch 2 were 97.5%, indicating that the higher maximum temperature and faster rise rate are detrimental to the long term strength gain of steam cured concrete and also to the effect that the superplasticizer has on the 28 day strength. The rate of strength gain also suffered a decrease as a result of the higher temperature and rise rate. The rate of strength gain from 7 to 28 days was about 46 psi per day compared to that of Batch 2 of 60 psi per day.

TABLE 4.4 Batch 4 test results.

BATCH 4 RESULTS: Moist Cured Specimens (0.40 w/c - 180d max)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.40 - 1.1 M - 180	119,000 lb.	4209	
0.40 - 1.2 M - 180	120,000 lb.	4244	**4173**
0.40 - 1.3 M - 180	115,000 lb.	4067	
0.40 - 3.1 M - 180	140,000 lb.	4952	
0.40 - 3.2 M - 180	141,000 lb.	4987	**4940**
0.40 - 3.3 M - 180	138,000 lb.	4881	
0.40 - 7.1 M - 180	147,000 lb.	5199	
0.40 - 7.2 M - 180	149,000 lb.	5270	**5152**
0.40 - 7.3 M - 180	141,000 lb.	4987	
0.40 - 28.1 M - 180	188,000 lb.	6649	
0.40 - 28.2 M - 180	185,000 lb.	6543	**6649**
0.40 - 28.3 M - 180	191,000 lb.	6755	

BATCH 4 RESULTS: Steam Cured Specimens (0.40 w/c - 180d max)

Cylinder designation	Load at failure	f'_c (psi)	avg. f'_c (psi)
0.40 - 1.1 S - 180	131,000 lb.	4633	
0.40 - 1.2 S - 180	135,000 lb.	4775	**4716**
0.40 - 1.3 S - 180	134,000 lb.	4739	
0.40 - 3.1 S - 180	136,000 lb.	4810	
0.40 - 3.2 S - 180	137,000 lb.	4845	**4786**
0.40 - 3.3 S - 180	133,000 lb.	4704	
0.40 - 7.1 S - 180	145,000 lb.	5123	
0.40 - 7.2 S - 180	149,000 lb.	5270	**5164**
0.40 - 7.3 S - 180	144,000 lb.	5093	
0.40 - 28.1 S - 180	174,000 lb.	6154	
0.40 - 28.2 S - 180	176,000 lb.	6225	**6131**
0.40 - 28.3 S - 180	170,000 lb.	6013	

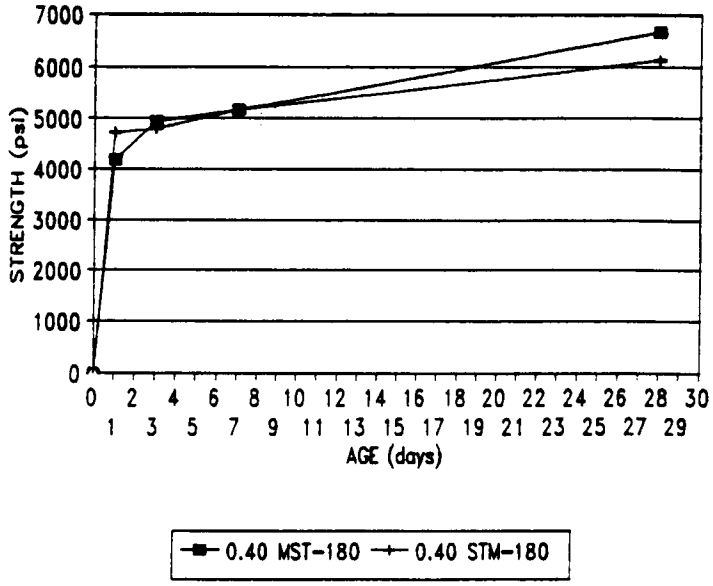


FIGURE 4.7 Batch 4 results.

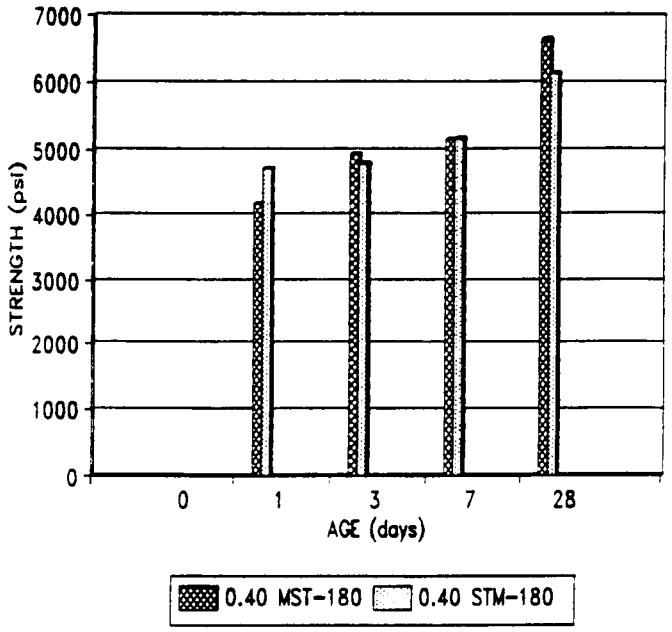


FIGURE 4.8 Batch 4 results.

4.2.5 Comprehensive Discussion

The results of the investigation of the influence of various amounts of superplasticizer in steam cured concrete is presented and discussed in this thesis. The results appear to be favorable for the future use of a superplasticizer in precast, prestressed concrete. As presented in the previous sections, the use of a superplasticizer in batches 1, 2, and 3 appear to have been beneficial in the rate of strength gain between the 7 and 28 day tests; see Figure 4.9. It was shown to be very beneficial in the lower w/c ratio concretes due to the required larger dosage of superplasticizer to obtain the same slump. It was also shown, however, to be less beneficial in batch 4 because of the higher curing temperature and faster rise rate.

Figures 4.10 and 4.11 represent the percentage of the 28 day moist cured strength versus the amount of superplasticizer dosage. As shown, the percentage increased with an increasing dosage of superplasticizer. Batch 4, however, did not show this increase, producing a strength of about 92% of the moist cured strength. This is believed to be due to the curing conditions that the batch 4 specimens were subjected to. The dosage of 360 mL of batch 4 only produced 92% in comparison to the 97.5% that the 350 mL of batch 2.

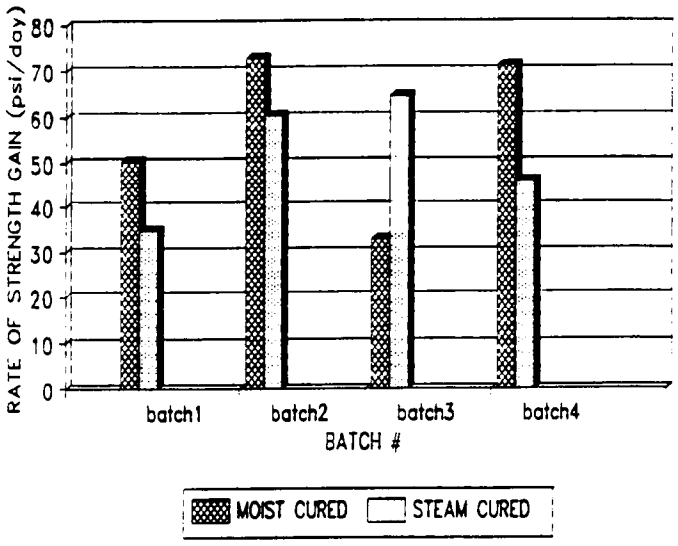


FIGURE 4.9 Rate of strength gain between 7 and 28 days

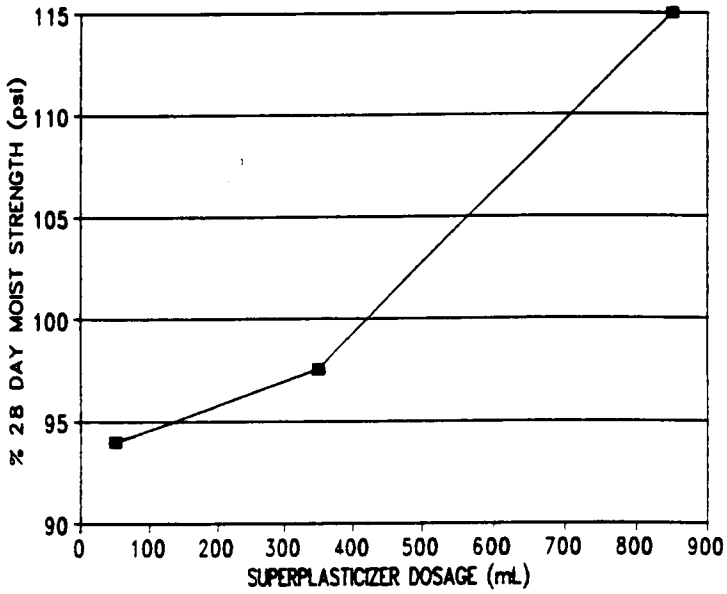


FIGURE 4.10 Superplasticizer dosage versus % of 28 day moist cured strength.

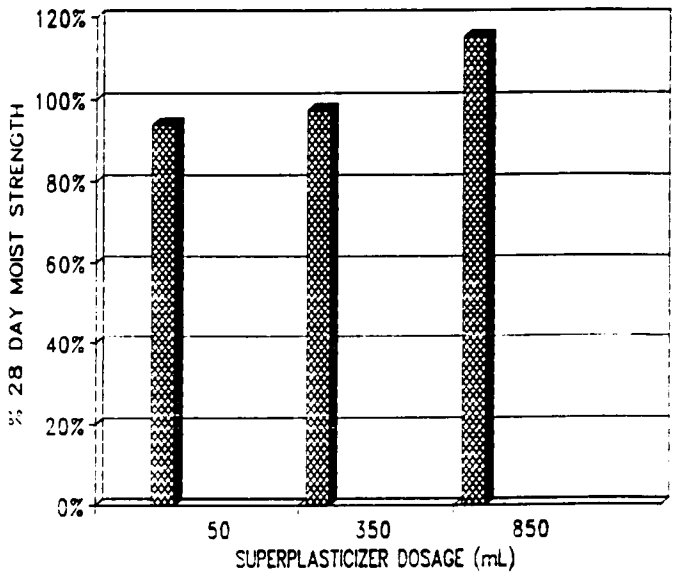


FIGURE 4.11 Superplasticizer dosage versus % of 28 day moist cured strength.

4.3 COST ANALYSIS

After the results of this investigation were determined to be potentially significant, a cost analysis was done to determine the approximate price increase per cubic yard for the addition of a superplasticizer in the production of precast, prestressed concrete. The cost analysis was based on current prices for Rheobuild 1000 if bought in large quantities, specifically in 55 gallon drums. However, if bought in small quantities, there would be a very minimal increase in price per cubic yard of concrete.

As shown in Table 4.5, it was found that a fairly significant increase of approximately $7.70 per cy would be added to the cost of the concrete for a large dosage of Rheobuild 1000 as used in Batch 3. The increase in price per cubic yard was found to be approximately $3.20 when used in Batches 2 and 4, and only about $0.50 per cubic yard in Batch 1. This cost analysis would seem to lead to the more economical use of the superplasticizer and still maintain a high percentage of the moist cured 28-day strength as shown in Batches 1,2 and 4.

TABLE 4.5 Cost Analysis.

Current price of Rheobuild 1000 from Master Builders, Inc. as of July 15, 1993:

Purchase of large quantity ——— $6.99 per gallon
Purchase of small quantity ——— $7.86 per gallon

CALCULATIONS: (1 fluid ounce = 29.57353 mL)

$6.99 per gallon = 5.46 cents per ounce

BATCH 1 —— 50 mL = 1.691 oz. x $0.0546 = $0.09
BATCH 2 —— 350 mL = 11.835 oz. x $0.0546 = $0.65
BATCH 3 —— 850 mL = 28.742 oz. x $0.0546 = $1.57
BATCH 4 —— 360 mL = 12.173 oz. x $0.0546 = $0.66

Each batch = 0.196 cf per cylinder x 28 cylinders per batch = 5.498 cf

5.498 cf / 27 cf per cy = 0.2036 cy per batch

BATCH 1 (0.45 w/c ratio) —— 50 mL = $0.44 per cy increase
BATCH 2 (0.40 w/c ratio) —— 350 mL = $3.19 per cy increase
BATCH 3 (0.35 w/c ratio) —— 850 mL = $7.71 per cy increase
BATCH 4 (0.40 w/c ratio) —— 360 mL = $3.26 per cy increase

$7.86 per gallon = 6.14 cents per ounce

BATCH 1 —— 50 mL = 1.691 oz. x $0.0614 = $0.10
BATCH 2 —— 350 mL = 11.835 oz. x $0.0614 = $0.73
BATCH 3 —— 850 mL = 28.742 oz. x $0.0614 = $1.76
BATCH 4 —— 360 mL = 12.173 oz. x $0.0614 = $0.75

Each batch = 0.196 cf per cylinder x 28 cylinders per batch = 5.498 cf

5.498 cf / 27 cf per cy = 0.2036 cy per batch

BATCH 1 (0.45 w/c ratio) —— 50 mL = $0.51 per cy increase
BATCH 2 (0.40 w/c ratio) —— 350 mL = $3.57 per cy increase
BATCH 3 (0.35 w/c ratio) —— 850 mL = $8.67 per cy increase
BATCH 4 (0.40 w/c ratio) —— 360 mL = $3.67 per cy increase

CHAPTER FIVE
CONCLUSIONS

A research program was conducted to determine the effect that the addition of a superplasticizer would have in the production of steam cured precast, prestressed concrete. The investigation consisted of the fabrication of 96 standard size cylinders to perform compressive tests at the ages of 1 day, 3 days, 7 days, and 28 days. A curing procedure similar to that which is used in the production of precast, prestressed concrete was used. A comparison of the results to previously reported investigations of steam cured concrete without the use of a superplasticizer was used to determine the effect, if any, that the superplasticizer had on the strength of the specimens at various ages.

Based on the results of the tests performed in this investigation, the following conclusions can be drawn:

1. The use of a superplasticizer in steam cured concrete appears to have no apparent adverse effects on the early strength of the concrete in comparison with previous investigations reported.

2. The use of a superplasticizer in steam cured concrete appears to produce a 28 day strength that is greater than that of steam cured concrete without the use of a superplasticizer. This increased strength is dependent on the amount of superplasticizer added. For low w/c ratios, an increased dosage of superplasticizer is required to achieve the same slump and, therefore, produces a higher percentage of the 28 day moist cured strength.

3. The effect of the superplasticizer tends to be less significant at higher maximum temperatures and higher rise rates.

4. The use of a superplasticizer in steam cured concrete appears to have a beneficial effect on the rate that the concrete gains strength from 7 to 28 days, particularly in higher strength concretes.

5. The future use of a superplasticizer in the production of precast, prestressed concrete appears to have potential benefits to both the precast, prestressed industry as well as to the construction industry. It would produce stronger products at early ages without greatly reducing the long-term strength of the concrete.

6. Further investigations should be conducted to study the effects of a superplasticizer in steam cured concrete on other properties of concrete that might be affected by the steam curing process.

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