TRC 98

Early Strength of Concrete

by

Thomas J. Parsons

Final Report

Highway Research Project TRC - 98

Conducted For

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PREFACE

The maturity and pullout methods of determining the compressive strength of concrete is potentially useful in highway projects where portland cement is used. The College of Engineering, Agriculture and Applied Sciences of Arkansas State University (ASU) under contract to the Arkansas Highway and Transportation Department (AHTD), has performed a research program entitled "Early Strength of Concrete." The information contained in this report was collected and developed during this research project to assist engineers and contractors in determining the early age compressive strength of concrete by the pullout and maturity methods. This report provides only the state of the art technology related to early age testing procedures using the maturity and pullout methods.

ASU was awarded the AHTD research contract in 1985 to investigate the usefullness of early age strength determination techniques in highway projects where portland cement is used. The engineering department has conducted this research with major emphasis on data analysis, and has reviewed relevant literature and assessed the progress and achievements of similar research. Indications are that the maturity and pullout test methods of determining the early age compressive strength of concrete will be reliable and useful to the highway department. These methods could be used to estimate the in-place strength of concrete in the field without having to perform any field related laboratory test.

FINDINGS AND CONCLUSIONS

The research conducted during this project resulted in a means of establishing the in-place strength of concrete at early ages, 24 hrs to 7 days. Two procedures were investigated; maturity and pullout. Maturity was used to develop prediction models which established concrete strengths that were independent of curing temperatures. Also, an investigation into the selection of the datum temperature was conducted and an optimum datum temperature was established (-4°C). The maturity model developed establishes the percentage of the ultimate compressive strength present in the sample for a given maturity. This percentage is multiplied by the ultimate compressive strength in order to find the estimated concrete compressive strength. The selection of ultimate strength is critical, for its value is dependent upon the curing temperatures. This selection is done by comparing the samples maturity to the maturity obtained by constant curing temperatures and selecting the corresponding compressive strength to use. A good correlation was obtained between the compressive strengths from outdoor cured cylinders and cores and the estimated compressive strengths by the maturity model.

A pullout prediction model was developed. It was not possible to obtain a model that was independent of curing temperatures. However, the model developed is designed to predict the minimum concrete compressive strength for a given pullout force. Comparisons were made between the estimated strength by the pullout force with the core and cylinder compressive strengths subjected to outdoor curing conditions. A good correlation was obtained, which shows that the model would be useful in establishing the in-place strength of field cured concrete.

Site visits were made to study the implementation of the tests in the field. It was concluded that it would be easy to implement these tests in the field at a minimal cost. It is estimated that the equations could be developed for approximately $5000. A set of equations would have to be developed for each mix produced by the different suppliers since the equations are supplier dependent. The development costs could be spread over several jobs. In the field, a maturity meter could be used to monitor the concrete and they cost approximately $500. The pullout equipment cost is approximately $750 and the inserts cost approximately $1.50 each and could be reused. From the low equipment costs and the long life of the equipment, the application of the tests in the field is low.

The principal conclusion of the research is that the maturity and pullout tests could be used to establish the in-place strength of concrete in the field. The could be used to establish form removal time and loading times. This would give the contractor more control over the project and should help to reduce construction times and costs.

The laboratory test procedure required to establish the maturity and pull-out models is given in Appendix C.

IMPLEMENTATION

The cylinder strength estimates by the maturity and pullout tests should be performed together. The maturity model should be used to estimate the minimum strength. Once the minimum strength has been established, the pullout test should be performed to confirm the maturity restults.

To establish the concrete strength by maturity, the temperature of the concrete has to be monitored by a maturity meter. This meter records the time temperature history of the concrete. The prediction model can be used to establish the maturity at which the required concrete strength will be obtained. Once this maturity is reached in the field, the pullout test would be performed to verify the maturity results.

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CHAPTER 1

INTRODUCTION

1.1 THE PROBLEM

The construction rate of concrete structures is regulated by the requirement of maintaining forms and falsework in-place while the concrete gains strength. This strength gain is affected by the mix designs, curing conditions, material properties and other factors. A method for determining and accurately measuring the early strength of concrete would allow for optimum form and falsework removal, i.e. a construction schedule which would permit the earliest form removal with minimal damage to the structure. Such a method is applicable to areas of highway work where portland cement is used, such as bridge and culvert work. By optimizing form work removal a reduced construction cost as well as cost to the public such as reducing travel delays and obstructions should be obtained.

1.2 PROJECT OBJECTIVES

The research project consisted of three major objectives.

1. To investigate and determine a method of early determination of concrete compressive strength.

2. Review current construction techniques dictated by the Highway Department's current "Standard Specifications".

3. Make recommendations which will include the use of early determination of concrete strengths within the construction techniques and specifications used by the Highway Department.

1.3 METHODOLOGY

In order to obtain the objectives of this research the following procedure was observed.

Objective 1 - The investigation and determination of a method of early determination of concrete compressive strength was obtained in the following manner:

1. A literature review was conducted in order to determine the latest research involving the maturity and pullout procedures.
2. Concrete test data was obtained from NIOSH. This data investigated twelve mix designs subjected to four curing conditions. This would permit an investigation into the maturity and pullout methods ability to predict concrete behavior under field conditions.
3. Maturity and Pullout test procedures were investigated. Procedures were developed that estimated early age concrete strengths. The results of these procedures were compared to compressive strengths obtained from specimens cured outdoors.

Objective 2 - The review of the current construction techniques dictated by the Highway Department's current "Standard Specifications" - was achieved in the following manner:

1. The "Standard Specifications" was reviewed to determine where concrete curing times were addressed.
2. Field trips were made to construction sites to review construction procedures and discuss the early age strength determination with the contractors.

3. Discussions were made with the Highway Department to discuss possible places where the early age strength .etermination could be used.

Objective 3 - Recommendations of appropriate changes were made after reviewing the results of objectives 1 and 2.

1.4 LITERATURE REVIEW

The maturity concept, as applied to concrete behavior was investigated by Nurse [1] and Saul [2]. This resulted in the following equation to record the time-temperature history of concrete.

$$M = [T(t) - T_o]dt \qquad (1.1)$$

where:

M = maturity at time t

$T(t)$ = temperature of the concrete at time t

T_o = datum temperature - The temperature at which concrete will not set.

This concept is based upon the idea that for a given mix of concrete, once a specified maturity is achieved, a specific concrete strength will be achieved, regardless of the curing conditions. Other research efforts have shown that the maturity concept is a useful means of approximating the concrete strength as a function of curing temperature and age [3-12]. However, it has been shown that this method is dependent upon curing temerature [13]. In a paper by Carino [14] a method of expressing the concrete compressive strength in terms of maturity was introduced which minimized the effects of curing temperature. In this approach the concrete strength (S) is expressed as a percent of the ultimate strength (SU). However, the ultimate strength (SU) is a function of the curing temperature.

The pullout method was first investigated in North America by Malhotra [15,16] and Richards [17]. This method is related to the shear strength of hardened concrete which then relates to the concrete's compressible strength. A summary of recent pullout research is as follows: An optimization program using pullout testing has been introduced by Brinkley [18,19]. Large scale pullout tests along with an investigation into the effects of cone shapes has been conducted by the National Bureau of Standards [20,21]. An ASTM standard has been established for pullout testing [22], and recent work by Parsons and Naik has shown that the pullout tests are dependent upon the curing temperature [23]. Lastly, Brinkley has introduced a technique which would determine the number of tests required in order to obtain accurate results [24].

The pullout test consists of placing a steel insert into the concrete and measuring the force required to pull a cone of concrete out of the sample being tested. In order to perform this test, the location of the insert must be pre-determined and placed on the edge of the form prior to the placement of the concrete. Therefore, the number and location of the pullout tests must be pre-planned.

1.5 NIOSH DATA

The National Institute for Occupational Safety and Health contracted with Dr. Tarum Naik at the University of Wisconsin, Milwaukee to conduct a research program into the early age behavior of concrete subjected to different curing temperatures. The following laboratory procedure and experiment design was observed.

A variety of concrete mixes were selected for study. Two types of cement, Types 1 or 2 portland cement, and two types of coarse aggregates, gravel or crushed limestone, were used in the concrete specimens. Water-cement ratios of 0.5, 0.6 and 0.7 were used. This resulted in 12 mixes. These mixes were subjected to 4 curing conditions, constant curing temperatures at 37°, 55°, and 73°F and outdoor curing.

Approximately 24 hr before a scheduled mixing period, fine and coarse aggregates were weighed. The quantites of materials required for each batch were then adjusted to compensate for the actual aggregate moisture content. The materials were mixed in the concrete laboratory in a drum mixer in batches of approximately 5.5 cu ft. Due to capacity limitations of the mixer, two batches were required to cast the cylinder and pullout specimens needed for each curing temperature. The ambient air temperature in the laboratory was maintained at 73° ± 5°F (23.8°C ± 2.8°C).

Half of the cylinders and one slab were cast from each batch. The slab measured 24 x 24 x 7 1/4 inches (610 x 610 x 184 mm). The slab form was completely filled, vibrated with an internal vibrator, leveled and troweled. In each slab twelve pullout anchors embedded, three per side. Also, six cores were drilled from the interior of the slab and the temperature was monitored at the center of the slab.

Sixteen 4 x 8 in (100 x 200 mm) cylinders were also cast from each batch by filling steel molds in a single lift and consolidated by external vibration. A brass tube was cast into one cylinder for the purpose of monitoring the concrete temperature.

The concrete specimens subjected to constant curing temperatures were cured at room temperatures of 37° (2.8°C), 55° (12.8°C) and 73°F (23.8°C) with a 3°F (1.7°C) variation. A large walk-in cooler was used for the 37°F (2.8°C) and 55°F (12.8°C) curing environments and a large walk-in 100% relative humidity room was used to maintain the 73°F (23.8°C) environment.

Cylinders were stored underwater in a 300-gallon curing tank in each curing room. The room temperature and water temperatures were constantly monitored throughout the project duration. The water bath temperature was maintained within 1°F (0.6°C). The remaining specimens were subjected to the outdoor enviornment of Milwaukee, Wisconsin during spring and fall seasons.

Each slab was cast on a cart, immediately covered with plastic and rolled into the appropriate curing room or outside. At approximately 11 hr after casting, the side forms of the slab were removed. At this time, the plastic cover was also removed from the slabs in the 100% humidity room. The slabs in the walk-in cooler or outside remained covered with plastic and were sprinkled regularly to minimize any moisture loss. At each test age, slabs were rolled into the testing area of the laboratory, then immediately returned after the tests.

After each cylinder was cast, a plastic bag was placed over the cylinder mold and secured with a rubber band. The cylinders, including those with temperature probes, were then taken into their respective environments. Cylinders tested 12 and 18 hr after casting were removed from the water tank approximately 30 minutes prior to the test, capped and tested. Twenty to twenty-two hours after casting, the remaining cylinders were removed from the tank, demolded, capped, and returned to the tank or the outdoor environment.

The cylinders cured at 55°F (12.8°C), 73°F (23.8°C), or outdoors were capped with a hot sulfur mortar. The cylinders cured at 37°F (2.8°C) were capped with a cold mixed, high-strength, rapid-setting grout to avoid the temperature shock of the hot sulfur mortar.

Cylinder compressive strength and pullout forces were obtained at various ages within the first seven days of curing. In order to observe the behavior of the different concrete mixes, six cylinders compression tests and pullout tests were performed at 12 hours; three cylinder compression tests and pullout tests were performed at 18, 24, and 36 hours and 2, 3, and 7 days; and three cylinder compression tests only were performed at 5 days. Also, three core samples were taken from the slabs at 2, 3, 5, and 7 days.

The cylinders were all tested in a 400,000 lb force capacity testing machine. The pullout strength of the hardened concrete was determined using an insert of the type shown in Appendix A, which was fastened to the side form of the slab prior to casting the concrete. A hydraulic ram was used to pull the insert from the concrete. The pullout force was monitored by using an electronic load cell and recorded. An X-Y plotter was used to monitor the loading rate which was maintained at about 100 lb (445N) force per second.

Six, 4-in (100 mm) diameter cores were drilled from each of the two slabs. Cores were capped with a hot sulfur mortar and tested in compression.

The slabs and cylinders maturity was determined by one of two recording instruments: 1) A maturity meter which monitors the temperature of the concrete and computes the concrete maturity using the Nurse-Saul maturity law, Equation (1.1), or 2) a six-channel temperature recorder. The temperature and time data from the recorder was then used with the Nurse-Saul maturity equation to compute the concrete maturity.

The mix designs will be referenced by the following code - A B C D or B C D where:

A - 1 = 37°F curing
    2 = 55°F curing
    3 = 73°F curing
    4 = outdoor curing

B - 1 = gravel aggregate
    2 = limestone aggregate

C - 1 = type 1 cement
    2 = type 2 cement

D - 1 = w/c of 0.5
    2 = w/c of 0.6
      = w/c of 0.7

For example, a concrete mix composed of limestone aggregate, type 2 cement and having a water to cement ratio of 0.5 cured outdoors will be coded as 4221. This coding system is used in the following text and in the tables.

CHAPTER 2

MATURITY

2.1 INTRODUCTION

By recording the conrete's time temperature history one can estimate the concrete strength. This is achieved by using maturity as expressed by equation 1.1.

This concept assumes that samples of the same concrete will have equal strengths at equal maturities. This implies that the concrete should yield the same compressive strengths when the maturities are equal, and that curing conditions have no effects on the strengths. The maturity equation contains a datum temperature constant, or temperature at which concrete will not set. The datum temperature in North American practice has been accepted as -10°C [4].

The maturity concept was applied to the NIOSH Data and it was found that the following model best predicted the strength gain of cylinders [13]

$$\text{Cylinder Strength} = A + B(\ln \text{Maturity}) \qquad (2.2)$$

However, this research showed that the model was dependent upon the curing temperature, and the model's behavior was affected by the selection of the datum temperature.

2.2 ESTABLISHING THE DATUM TEMPERATURE

Research conducted by the National Bureau of Standards showed that using a datum temperature other than -10°C[14] affected the results in estimating the concrete strength. The research on mortar indicated the datum temperature should be -4°C. Plots of cylinder strength vs. ln of maturity for the 12 mixes subjected to the different curing conditions are given in Appendix B.

To establish the datum temperature which best predicted the cylinder strength in terms of maturity, the following procedure was followed: The datum temperature was varied from -10°C to 0°C by 2°C increments. To monitor what effect this had on the model, a stastical test was performed which would determine if the prediction equations were independent of curing temperature. The test was the F test. This test would determine if it was by chance or behavior if the models for different curing temperatures were the same. The F value was obtained by the following equation:

$$F = \frac{RT - RI}{RI} \quad \frac{N - V}{V - 2} \qquad (2.3)$$

where:

RT = square of the residuals for the model containing all sets of data

RI = sum of the square of the residuals for the model for each curing temperature data set

N = total degrees of freedom

V = total constants being determined in the prediction models for each curing temperature

The results are given in Table 2.1. For the models to be independent of curing temperature the F value had to be less than 3. In no case this was true, however the smallest F values were obtained for a datum temperatures near -4°C. Therefore, all future work was conducted with maturities having a datum temperature of -4°C.

TABLE 2.1 - F TEST ON DATUM TEMPERATURE

MIX	F VALUES FOR DATUM TEMPERATURES						LIMITING VALUE
	-10°C	-8°C	-6°C	-4°C	-2°C	0°C	
111	62	51	41	38	49	92	3
112	118	97	76	57	48	56	3
113	138	114	89	67	58	83	3
121	24	17	13	16	32	72	3
122	21	14	8	6	14	41	3
123	37	26	17	13	19	38	3
211	13	7	5	8	24	69	3
212	11	11	13	17	24	29	3
213	14	10	7	7	10	21	3
221	22	17	14	16	27	57	3
222	23	15	9	8	20	59	3
223	26	18	12	11	19	43	3

2.3 ESTABLISHING THE PREDICTION MODEL

In a paper by Carino, [14], the following model was suggested for estimating concrete strength in terms of maturity.

$$\frac{S}{SU} = \frac{A(M - Mo)}{1 + A(M - Mo)} \qquad (2.4)$$

where:

S = concrete strength

SU = ultimate concrete strength

A = constant

M = maturity at time t

Mo = maturity at time t_o, or age when strength development is assumed to begin

The values of A and Mo could be determined by rearranging equation 2.4 into the following form:

$$\frac{S/SU}{(1 - S/SU)} = - A\ Mo + A\ M \qquad (2.5)$$

The key to this equation is the establishment of SU. The NIOSH data only contained tests from 12 to 168 hours. To establish the SU two approaches were considered.

The first approach was to consider SU to be the 28 day strength of the concrete. To establish the 28 day strength it had to be estimated from the 7 day strength. To establish the relationship between the 7 and 28 day strengths, 7 and 28 day cylinder break data was obtained from the District 10 AHTD office. This data was analyzed and it was determined that the 7 day strength was 75-79% of the 28 day strength, with a standard deviation of 7.9%. This was based upon 32 samples.

A second approach to establihs SU was to vary SU when A and Mo were determined, then pick the SU which produced the best fit curve for each curing temperature. The results of this approach is given in Table 2.2. The estimated SU was obtained by the first approach.

The F Test was performed on the models listed in Table 2.2 to determine if they were independent of the curing temperature. The results are given in Table 2.3. As observed from the table, 9 of the 12 mixes were independent of curing temperature. It was also noted that SU values were dependent upon curing conditions.

2.4 TESTING THE MODEL

To test the prediction models, the compressive strengths of the cylinders and cores cured outdoors were estimated by the models. To establish the proper SU to be used in the prediction model, the maturity at the given age was compared to the ideal maturities for 37, 55 and 73°F curing for that given age. Whichever set of maturities matched the SU for that constant curing was used. The results are listed in Table 2.4. In all cases, the estimated strength was within 10-20% of the cylinder or core strength.

TABLE 2.2 - MATURITY CONSTANTS

MIX	MO	A	SU	MIX	MO	A	SU
1111	167	.00115	5760	1211	135	.00066	7260
2111	182	.00116	4760	2211	180	.00064	7010
3111	126	.00108	6260	3211	63	.00074	6260
Estimated SU			6838	Estimated SU			6221
1112	152	.00058	5510	1212	129	.00063	5260
2112	124	.00061	6510	2212	157	.00059	4760
3112	108	.00068	6010	3212	137	.00064	4260
Estimated SU			6122	Estimated SU			4164
1113	185	.00080	3260	1213	175	.00059	3510
2113	167	.00083	3260	2213	249	.00053	4010
3113	179	.00086	4260	3213	49	.00055	3510
Estimated SU			4453	Estimated SU			3171
1121	136	.00062	6760	1221	159	.00063	6510
2121	183	.00059	6010	2221	215	.00058	6760
3121	120	.00065	6260	3221	167	.00057	6510
Estimated SU			6276	Estimated SU			6351
1122	183	.00058	5010	1222	202	.00055	5010
2122	164	.00057	5010	2222	230	.00055	4510
3122	95	.00054	5010	3222	160	.00059	4510
Estimated SU			4759	Estimated SU			4388
1123	159	.00053	4010	1223	223	.00054	3510
2123	198	.00055	3510	2223	187	.00054	3010
3123	116	.00057	3760	3223	232	.00064	3010
Estimated SU			3647	Estimated SU			3042

TABLE 2.3 - F TEST RESULTS

MIX	TOTAL OBSERVATIONS	F	LIMITING VALUE
111	24	0.479	5.77
112	24	2.979	5.77
113	24	0.141	5.77
221	24	0.162	5.77
222	23	5.515	5.78
223	23	2.295	5.78
211	23	18.574	5.78
212	24	0.653	5.77
213	24	8.102	5.77
121	24	5.921	5.77
122	23	1.058	5.78
123	24	1.976	5.77

TABLE 2.4 - ESTIMATED vs CYLINDER STRENGTH for OUTDOORS

MIX	AGE (hrs)	S/SU	EST STRENGTH (psi)	OUTDOOR CURED CYLINDER (psi)	CORE STRENGTH (psi)
111	12	.1402	800	730	
	18	.2517	1450	1400	
	24	.3479	2000	1900	
	36	.4471	2580	2390	
	48	.5427	3130	2810	2340
	72	.6395	3680	3430	2720
	120	.6448	3070	3950	3180
	168	.8039	3830	4560	3470
112	12	.0638	410	260	
	18	.1159	750	510	
	24	.1633	1060	1020	
	36	.2352	1530	1450	
	48	.3329	2170	1920	1610
	72	.4444	2890	2180	1840
	120	.5976	3740	3090	2610
	168	.6765	4230	3230	3080
113	12	.1111	470	325	
	18	.2124	900	680	
	24	.2904	1235	930	
	36	.3846	1640	1190	
	48	.4453	1900	1590	1350
	72	.5406	2030	1850	1660
	120	.6765	2540	2430	2410
	168	.7424	2790	2690	2990
121	12	.0433	260	230	
	18	.1140	700	700	
	24	.1796	1100	1230	
	36	.2763	1690	1920	
	48	.3448	2100	2240	2260
	72	.3523	2150		2800
	120	.5963	3640	3590	3320
	168	.6808	4150	4090	3690
122	12	.0856	430	330	
	18	.1563	780	790	
	24	.2155	1080	1320	
	36	.2978	1490	1630	
	48	.3695	1850	1780	1750
	72	.4619	2310	2140	2070
	120	.6062	3040	2540	2660
	168	.6656	3330	3010	2940

TABLE 2.4 - (Continued)

MIX	AGE (hrs)	S/SU	EST STRENGTH (psi)	OUTDOOR CURED CYLINDER (psi)	CORE STRENGTH (psi)
123	12	.0509	180	180	
	18	.1192	420	500	
	24	.1851	650	860	
	36	.2716	950	1160	
	48	.3681	1290	1310	1400
	72	.4592	1610	1620	1540
	120	.5449	2050		1800
	168	.5935	2330	1810	2000
211	12	0	0	110	
	18	.0176	120	280	
	24	.0539	380	570	
	36	.1273	890	1160	
	48	.2050	1440	1930	1790
	72	.3211	2250	2760	2460
	120	.5267	3690	3860	3620
	268	.6313	4430	4560	3700
212	12	.0029	20	120	
	18	.0646	310	360	
	24	.1357	650	880	
	36	.2116	1010	1450	
	48	.2704	1290	1620	1910
	72	.3866	1840	2200	2270
	120	.5254	2500	2760	2250
	168	.5777	2750	3210	2690
213	12	0	0	40	
	18	0	0	100	
	24	.0021	10	210	
	36	.0746	300	520	
	48	.1519	610	810	700
	72	.2700	1080	1250	1090
	120	.4489	1800	1930	1800
	168	.5775	2320	2410	2490
221	12	0	0	70	
	18	.0143	100	220	
	24	.0666	450	530	
	36	.1495	1010	1190	
	48	.2338	1580	1910	1870
	72	.3548	2400	2700	2480
	120	.5368	3630	3960	3610
	168	.6417	4340	5100	4200

TABLE 2.4 - (Continued)

MIX	AGE (hrs)	S/SU	EST STRENGTH (psi)	OUTDOOR CURED CYLINDER (psi)	CORE STRENGTH (psi)
222	12	0	0	70	
	18	.0426	190	240	
	24	.1004	450	540	
	36	.1844	830	1020	
	48	.2825	1270	1520	1520
	72	.4099	1850	1870	2140
	120	.5611	2530	2570	2460
	168	.6553	3000	3040	3020
223	12	.0372	110	130	
	18	.1168	350	370	
	24	.1795	540	660	
	36	.2689	810	1060	
	48	.3224	970	1200	1300
	72	.4390	1320	1540	1760
	120	.5676	1710	1910	2010
	168	.6376	1920	2120	2200

CHAPTER 3

PULLOUT

3.1 PULLOUT TEST BACKGROUND

The pullout test is a nondestructive test which could be used to determine the concrete compressive strength. The test consists of placing a pullout insert, see Appendix A, into the concrete and measuring the force required to remove the insert and cone of concrete. The pullout test procedure is described in ASTM C900-82, "Pullout Strength of Hardened Concrete". Much work has been done on the correlation of the pullout force to the concrete strength. However, little research has been done on the effect of curing temperature on the pullout method.

The test consists of placing a predetermnined shaped insert (Appendix A) into the concrete. The insert is removed from the concrete by fastening a steel plate and hydraulic ram to it and pulling it out of the sample. The plate sets the diameter of the cone of concrete to be removed by the insert. The pullout force is the force required to remove the cone of conrete.

The main advantage of this test is that it tests in-place concrete and would give a good indication of the in-situ strength.

3.2 ESTABLISHING THE MODEL

The pullout model used was established in two steps. First the concrete cylinder compressive strength was correlated with cylinder's maturity and the pullout force was correlated with the slab's maturity. Next, the maturity was eliminated from the two equations in order to obtain cylinder strength in terms of pullout force. This was done in the following manner.

$$\text{Cylinder Strength} = A + B(\ln \text{maturity}) \qquad (3.1)$$

$$\text{Pullout Force} = C + D(\ln \text{maturity}) \qquad (3.2)$$

$$\text{Cylinder Strength} = \frac{B}{D}(\text{pullout force}) + \left[A - \frac{BC}{D}\right] \qquad (3.3)$$

The values of A, B, C and D for the different concrete mixes and curing temperatures are given in Table 3.1. The values of B/D and A - (B/D)C are given in Table 3.2. This procedure was used, because the data was obtained at set times not at constant maturities.

The results in Table 3.2 shows that the model of pullout force in terms of cylinder strength is dependent upon curing temperature. For B/D values range from .4 to .95 in about 1/3 of the mixes. Further observations of Table 3.1 reveals that the 55°F model tends to have the largest intercept and smallest slope. This indicates that the 55°F model represents the lower bound of the data set. Therefore, the 55°F model was used as the prediction mode. In this case, the model would predict the minimum strength, not the estimated strength.

Attempts were made to develop a relationship between pullout force and maturity similar to the one used for cylinder strength and maturity. However, when PU was determined, (ultimate pullout force) by varying PU from 4000 to 14000 it was observed that a 500 lb change in PU could change the constants A and Mo by over 100% in some cases. This indicated that the equations were not stable, so the above procedure was used to correlate cylinder compressive strength in terms of pullout force.

3.3 ESTIMATING IN-PLACE CONCRETE STRENGTH

The pullout models in Table 3.2 were used to estimate the cylinder strength and core compressive strength of the outdoor cured specimens. The results are presented in Table 3.3. In 10 of the 12 cases, the pullout procedure predicted within 10% of the cylinder or core strength, and in the remaining 2 cases, the results were within 20% of the cylinder or core compressive strength.

TABLE 3.1 - RESULTS OF CYLINDER STRENGTH vs Ln MATURITY: AND PULLOUT FORCE vs Ln MATURITY

CYLINDER STRENGTH = A + B (Ln Maturity): PULLOUT FORCE = C + D (Ln Maturity)

MIX	TEMP	A	B	C	D
111					
	37°F	-8163	1582	-17254	3285
	55°F	-7488	1406	-10789	2180
	73°F	-8547	1655	- 6385	1737
	Outdoors	-7880	1494	- 8134	1820
112					
	37°F	-6115	1153	-13149	2481
	55°F	-7797	1476	- 8253	1683
	73°F	-7781	1463	-12172	2415
	Outdoors	-6181	1164	- 9357	1803
113					
	37°F	-4287	804	-11563	2145
	55°F	-4553	854	-10203	1950
	73°F	-5927	1108	- 6348	1407
	Outdoors	-5422	988	-11036	2099
121					
	37°F	-7283	1400	-16539	3104
	55°F	-7865	1437	-10718	2116
	73°F	-8428	1557	-10711	2161
	Outdoors	-7886	1451	-11323	2213
122					
	37°F	-5272	999	-13883	2579
	55°F	-6288	1158	-10747	2044
	73°F	-6614	1205	- 9381	1830
	Outdoors	-5710	1057	- 7623	1600
123					
	37°F	-4263	798	-9497	1772
	55°F	-4536	822	-9957	1823
	73°F	-5076	924	-8798	1677
	Outdoors	-4022	808	-7215	1431
211					
	37°F	-8780	1161	-16228	3048
	55°F	-8878	1653	-16122	3039
	73°F	-8322	1575	- 6786	1709
	Outdoors	-8718	1668	-13710	2609

TABLE 3.1 - (Continued)

CYLINDER STRENGTH = A + B (Ln Maturity): PULLOUT FORCE = C + D (Ln Maturity)

MIX	TEMP	A	B	C	D
212					
	37°F	-5116	1008	-11431	2214
	55°F	-5944	1105	-14216	2688
	73°F	-5532	1028	-11140	2143
	Outdoors	-6650	1248	-12770	2406
213					
	37°F	-3834	722	-10632	1990
	55°F	-4902	886	-16784	2003
	73°F	-4486	832	- 8730	1703
	Outdoors	-4583	865	-10207	1873
221					
	37°F	-7070	1348	-13355	2545
	55°F	-9010	1630	-15657	2911
	73°F	-8825	1598	-10068	2068
	Outdoors	-10282	1863	-15224	2863
222					
	37°F	-5676	1040	-10477	1972
	55°F	-6013	1078	-11743	2217
	73°F	-6373	1145	-10510	1998
	Outdoors	-5594	1036	-11027	2017
223					
	37°F	-3927	718	- 9356	1772
	55°F	-3849	699	- 9234	1733
	73°F	-4279	769	- 6787	1361
	Outdoors	-4306	788	- 8046	1548

TABLE 3.2 - CYLINDER STRENGTH vs PULLOUT FORCE

CYLINDER STRENGTH = (B/D) * PULLOUT FORCE + [A - (B/D)C]

MIX	TEMP	B/D	A - (B/D)C
111			
	37°F	0.482	146
	55°F	0.645	- 530
	73°F	0.953	-2463
	Outdoors	0.821	-1203
112			
	37°F	0.465	- 4
	55°F	0.877	- 559
	73°F	0.606	- 407
	Outdoors	0.640	- 140
113			
	37°F	0.375	47
	55°F	0.438	- 85
	73°F	0.787	- 928
	Outdoors	0.471	- 227
121			
	37°F	0.451	177
	55°F	0.679	- 586
	73°F	0.720	- 710
	Outdoors	0.656	- 462
122			
	37°F	0.387	106
	55°F	0.567	- 199
	73°F	0.658	- 436
	Outdoors	0.661	- 674
123			
	37°F	0.456	- 14
	55°F	0.451	- 46
	73°F	0.551	- 228
	Outdoors	0.565	52
211			
	37°F	0.381	-2599
	55°F	0.544	- 108
	73°F	0.922	-2068
	Outdoors	0.639	47
212			
	37°F	0.455	88
	55°F	0.411	- 100
	73°F	0.480	- 188
	Outdoors	0.519	- 26

TABLE 3.2 - (Continued)

CYLINDER STRENGTH = (B/D) * PULLOUT FORCE + [A - (B/D)C]

213			
	37°F	0.363	23
	55°F	0.442	2522
	73°F	0.489	- 221
	Outdoors	0.462	130
221			
	37°F	0.530	4
	55°F	0.560	- 243
	73°F	0.773	-1045
	Outdoors	0.651	- 375
222			
	37°F	0.527	- 150
	55°F	0.486	- 303
	73°F	0.573	- 350
	Outdoors	0.514	70
223			
	37°F	0.405	- 136
	55°F	0.403	- 124
	73°F	0.563	- 444
	Outdoors	0.510	- 210

TABLE 3.3 - PREDICTION OF COMPRESSIVE STRENGTH by PULLOUT FORCE
(Outdoor Cylinders and Cores)

MIX	TIME (hrs)	PREDICTED STRENGTH (psi)	OUTDOOR CURED CYLINDER (psi)	SLAB CORES (psi)
111				
	24	2010	1900	
	36	2550	2390	
	48	2500	2810	2240
	72	2940	3430	2720
	120		3950	3180
	168	4000	4558	3470
112				
	24	1140	1020	
	36	1660	1450	
	48	2200	1920	1610
	72	2690	2180	1840
	120		3090	2610
	168	4060	3230	3080
113				
	24	950	930	
	36	1200	1190	
	48	1500	1590	1350
	72	2050	1850	1660
	120		2430	2410
	168	2640	2690	2990
121				
	24	1480	1230	
	36	2470	1920	
	48	2790	2400	2260
	72	2050	2070	2800
	120		3590	3320
	168	4000	4090	3690
122				
	24	1380	1320	
	36	1770	1630	
	48	1840	1780	1750
	72	2520	2440	2070
	120		2540	2660
	168	2810	3000	2940
123				
	24	900	860	
	36	1300	1160	
	48	1340	1310	1400
	72	1440	1620	1540
	120		1810	1800
	168	1780	2080	2000

TABLE 3.3 - (Continued)

MIX	TIME (hrs)	PREDICTED STRENGTH (psi)	OUTDOOR CURED CYLINDER (psi)	SLAB CORES (psi)
211				
	24	1190	570	
	36	1560	1160	
	48	1980	1930	1790
	72	2930	2760	2460
	120		3860	3620
	168	3620	4560	3700
212				
	24	880	880	
	36	1320	1450	
	48	1540	1620	1910
	72	2000	2200	2270
	120		2760	2550
	168	2450	3210	2690
213				
	24	300	210 *	[(A-B)C]assumed to be
	36	650	520 *	zero
	48	850	810 *	700
	72	1070	1250 *	1090
	120		1930 *	1800
	168	2200	2410 *	2490
221				
	24	740	520	
	36	1690	1190	
	48	2200	1910	1870
	72	2710	2700	2480
	120		3960	3610
	168	4240	5090	4200
222				
	24	500	540	
	36	870	1020	
	48	1210	1520	1520
	72	1550	1860	2140
	120		2570	2460
	168	2520	3040	3020
223				
	24	650	660	
	36	980	1060	
	48	1140	1200	1300
	72	1460	1540	1760
	120		1910	2010
	168	1620	2120	2200

CHAPTER 4

DISCUSSION OF RESULTS

4.1 DISCUSSION OF MATURITY AND PULLOUT RESULTS

Cylinder compressive strengths in terms of maturity (cylinder-maturity) prediction models were developed for twelve concrete mixes. These mixes were subjected to the four different curing conditions. The models developed were independent of curing conditions, however, the ultimate strength - SU, was dependent upon the curing conditions. The selection of the SU for use in the model is of some concern. In the test comparisons presented, SU was selected by comparing the outdoor maturity to constant temperature maturities for a given age and selecting the SU from the maturities (constant temperature) that came closest in matching. This resulted in a good correlation between the estimated values of concrete compressive strength with the cylinder and core compressive strengths. A second approach to picking SU would be to select the SU as the design strength of the concrete. This approach would be conservative if the SU was greater than the 28 day strength and liberal if SU was less than the 28 day stength. The estimated strength was obtained by multiplying the S/SU ratio obtained from the model by SU. Therefore, the selection of SU has a major role in the results of the model.

The cylinder-maturity model was within 10% of estimating the cylinder or core compressive strength in 11 of the 12 cases studied. The outdoor cured cylinders and slabs were cured in Milwaukee, Wisconsin during April and May. The results obtained by the cylinder-maturity model revealed that this model would be a good means of estimating the inplace strength of concrete in the field. However it should be noted that a closer review of Table 2.2, Maturity Constants, would reveal that the constants used within the model are unique for each mix design. Therefore, a test should be performed which would determine if the concrete poured has the same mix properties as the mix used in developing the model. This could be done by the pullout test, which is a physical test on the in-place concrete. Therefore, it could pick up any changes in the mix designs.

The pullout method was studied and found to be a good means of estimating the in-place strength of the concrete. This was observed by the results presented in Table 3.3, where the pullout test was used to estimate the compressive strength of cylinders and cores stored outdoors. In 10 of the 12 cases studied the pullout estimated within 10% of the concrete cylinder or core compressive strength. It should be noted that it was not possible to develop a pullout model that was independent of curing temperature. The model developed was based upon samples cured at 55°F. The 55°F curing temperature was chosen because in most cases it gives the lowest estimated strength when compared to 37° or 73°F curing. The results presented in Table 3.3 reveal that the model developed does give a good estimate of the concrete compressive strength.

However, due to the design of the experiment, the results of the pullout tests presented in this report should only be used as a preliminary investigation into the method. Recent research by Brinkley [24] indicates that 7 to 10 tests should be performed at a given age. In this experiment, only 3 were performed at a given time, and in many cases the test had a wide scatter of results. Taking this into account, the pullout method appears to be a good means of estimating the in-place strength of concrete. However, due to the nature of the test, placement of the pullout plugs, the number and location of the plugs need to be planned before any field concrete is placed.

CHAPTER 5

REVIEW OF CONSTRUCTION TECHNIQUES AND SPECIFICATION

5.1 REVIEW OF THE "STANDARD SPECIFICATIONS" AND DISCUSSION OF EARLY AGE STRENGTH DETERMINATIONS

The Highway Department's Standard Specifications were reviewed. This review consisted of locating areas where the early age strength determination could be applied. The early age strength determination could be applied in two areas; in section 802.09 Handling and Placing Concrete and 802.18, Removal of Falsework, Forms and Housings. These sections require a minimum time and 3000 psi strength of concrete before the concrete could be loaded or forms removed. The early age strength determination (maturity and pullout) could be used to estimate the in-place concrete strength. In some cases, these methods would give a better estimate of the in-place concrete strength than cylinders, for the maturity and pullout techniques are subjected to actual field conditions, not laboratory simulated ones. This would give a better estimate of the in-place concrete strength. Also, estimating the concrete strength by maturity does not require test samples, therefore it could be run at any time and repeated any number of times. The cylinder-maturity model could also estimate when the minimum 3000 psi strength would be obtained in the field, and at that time the test cylinders could be tested.

5.2 FIELD VISIT

Field visits were made to two highway projects. One was to a bridge under construction and the other was to the construction of a box culvert.

The bridge construction site visit revealed that the early age strength determination technique would be useful in establishing form removal times.

Since forms are reused, the construction rate could be speeded up by reducing the form time. Similar observations were noted at the box culvert site.

The application of the maturity and pullout methods in the field appears to be no problem. The maturity could be obtained by mounting a self contained maturity meter to the formwork, out of normal walkways. The pullouts would be harder to implement in the field. They would have to be placed in the top of slabs or in the formwork. If placed in forms, the forms would have to be designed so a small section, 6" x 6", could be removed in order to perform the pullout test. One good location to place the pullouts would be in the cold joint between pours provided the second pour has to be performed after the concrete obtains a 3000 psi strength. An alternate solution would be to pour a test block in the field and perform the pullout test on the block. This way the block would be subjected to the same curing conditions and mix design.

5.3 RESIDENT ENGINEER'S COMMENTS

The project results were discussed with the Resident Engineer of District 10, Ralph J. Blackwell and his assistant Brent Watkins. The following conclusions were drawn:

1. The approach could be used as a check if there was a low cylinder break.

2. The approach could be used to check if the bridge deck was not properly cured.

3. The approach could be used to determine the bridge deck's concrete strength if it was preloaded. This could help to determine if there was any damage by the preloading.

4. If the approach was proven in predicting strengths within 10%, it could be used to reduce form times to 4 days or 3000 psi concrete strengths.

5. The approach will provide more checks on the contractors and also, it could give the contractor more freedom, such as reducing form time.

6. More research should be conducted into methods of making the pullout approach more flexible. This should consist of reducing the number of inserts and replacing the inserts with a bolt. The concrete could be drilled and a bolt inserted and glued in the concrete. Then the concrete strength could be estimated by the force required to remove the bolt and cone of concrete.

CHAPTER 6

SUMMARY AND CONCLUSION

The research conducted during this project resulted in a method of establishing the in-place strength of concrete at early ages, 24 hrs to 7 days. Two procedures were investigated; maturity and pullout. Maturity was used to develop prediction models which established concrete strength that were independent of curing temperatures. Also, an investigation into the selection of the datum temperature was conducted and an optimum datum temperature was established, (-4°C). The maturity model developed establishes the percentage of the ultimate compressive strength present for a given maturity. This percentage is multiplied by the concrete's ultimate compressive strength in order to establish the estimated concrete compressive strength. Judgement needs to be applied in the selection of ultimate strength, for its value is dependent upon the curing temperature. This could be done by comparing the given maturity to the maturity obtained by constant curing temperatures. The ultimate compressive strength, SU, that corresponds to the maturity produced by constant temperature curing should be used. A good correlation was obtained between the outdoor cured cylinder and core compressive strengths and the estimated values by the maturity model.

A pullout prediction model was developed. It was not possible to obtain a model that was independent of curing temperatures. However, the model developed is designed to predict the minimum concrete compressive strength for a given pullout force. Comparisons were made between the estimated strength by pullout force and the core and cylinder compressive strengths subjected to outdoor curing conditions. A good correlation was obtained, which shows that the model would be useful in establishing the in-place strength of field cored concrete.

Site visits were made to study the implementation of the tests in the field. It was concluded that it would be easy to implement these tests in the field at a minimal cost. It is estimated that the equations could be developed for approximately $5000. A set of equations would have to be developed for each mix produced by the different suppliers since the equations are supplier dependent. The development costs could be spread over several jobs. In the field, a maturity meter could be used to monitor the concrete and they cost approximately $500. The pullout equipment cost is approximately $750 and the inserts cost approximately $1.50 each and could be reused. From the low equipment costs and the long life of the equipment, the application of the tests in the field is low.

The principal conclusion of the research is that the maturity and pullout tests could be used to establish the in-place strength of concrete in the field. The could be used to establish form removal time and loading times. This would give the contractor more control over the project and should help to reduce construction times and costs.

The laboratory test procedure required to establish the maturity and pull-out models is given in Appendix C.

CHAPTER 7

RECOMMENDATIONS

Judging from the results of this research, it is recommended that the following studies be conducted:

First - Prediction models should be developed for the mix designs used by the highway department. The times used to develop the model should be expanded from 12-168 hrs to 1-14 days.

Second - The models should be field tested in order to establish their accuracy in the field as compared to the laboratory and ease of implementation in the field.

Third - Time studies should be done to determine the reduction in form removal times which could occur by using the models. Also, an economic analysis should be conducted to determine the reduced costs that could occur.

Fourth - A study should be conducted to determine if the ambient air temperature could be monitored in order to determine the concrete's maturity. Factors could be developed which would account for the effects of the forms, mass, and thickness of the concrete when simulating the concrete's maturity by the air's maturity

Fifth - Recent studies have been done on developing pullout methods where the plug does not need to be placed prior to the concrete pour. This approach may be more adaptable to field usage. This would result in not having to pre-plan the pullout tests, and it would permit additional pullout tests if required. Therefore, this approach should be studied in order to determine its reliability.

CHAPTER 8

IMPLEMENTATION OF PROCEDURE AND BENEFITS

8.1 IMPLEMENTATION IN THE FIELD

The cylinder compressive strength estimation by maturity and pullout tests should be performed together. The maturity would be used to estimate the minimum required strength. Once the minimum strength has been obtained the pullout test would be performed to confirm the maturity results.

To estimate the concrete strength by maturity, the temperature of the conrete has to be monitored, by a maturity meter, which records the time temperature history of the concrete. The prediction model could be used to establish the maturity associated with the required concrete strength. Once the required maturity is obtained in the field, the pullout test could be performed to verify the maturity results.

8.2 "STANDARD SPECIFICATIONS" CHANGES

The Standard Specifications in sections 802.10c and 802.18 would have to be rewritten. Wherever it states that test cylinders are used to establish the minimum compressive strength, it should read test cylinders or early age testing techniques.

8.3 BENEFITS

Several benefits would be obtained by using the maturity and pullout tests. First, these tests could reduce form stripping times, which would reduce forming costs and help to reduce construction costs. Second, the tests could give a more accurate estimate of the quality and strength of the in-place strength of the concrete. The pullout test estimates the in-place concrete compressive strength, therefore the effects of the actual curing condition is being monitored. Third, the tests are performed in the field, therefore, there is no time delay of having to obtain concrete strength results from the lab. Fourth, a more uniform estimate of the concrete strength is achieved for the pullout tests could be performed at several locations within the pour area. The cost of the tests are low, for the pullout plugs could be reused and the equipment costs are minimal. Sixth, the construction time could be reduced. This would help to reduce the departments costs associated with site inspections and quality control.

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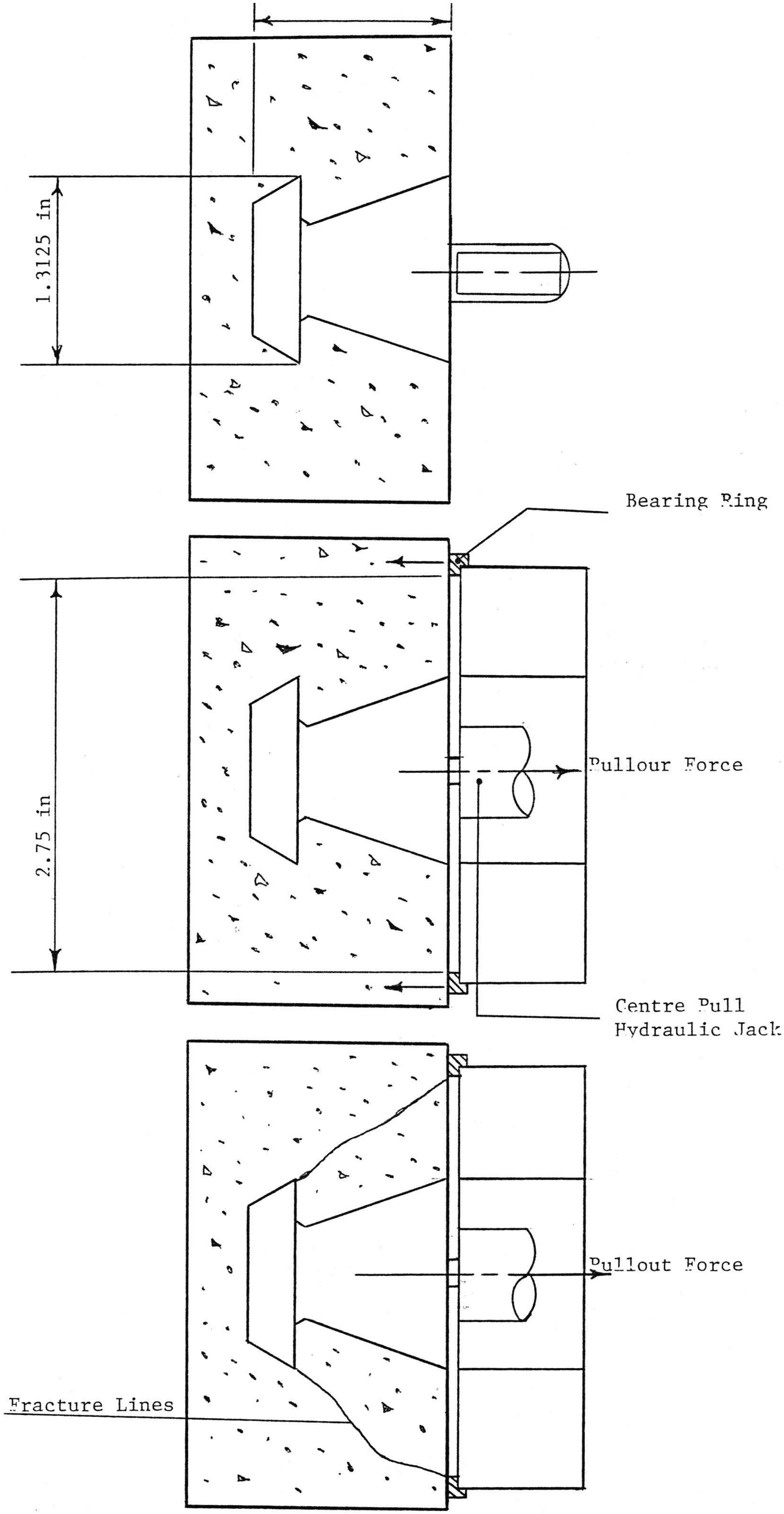
APPENDIX A

FIGURE OF PULLOUT INSERT


1.3125 in
Bearing Ring
2.75 in
Pullout Force
Centre Pull
Hydraulic Jack
Pullout Force
Fracture Lines

APPENDIX B

S/SU vs MATURITY GRAPHS

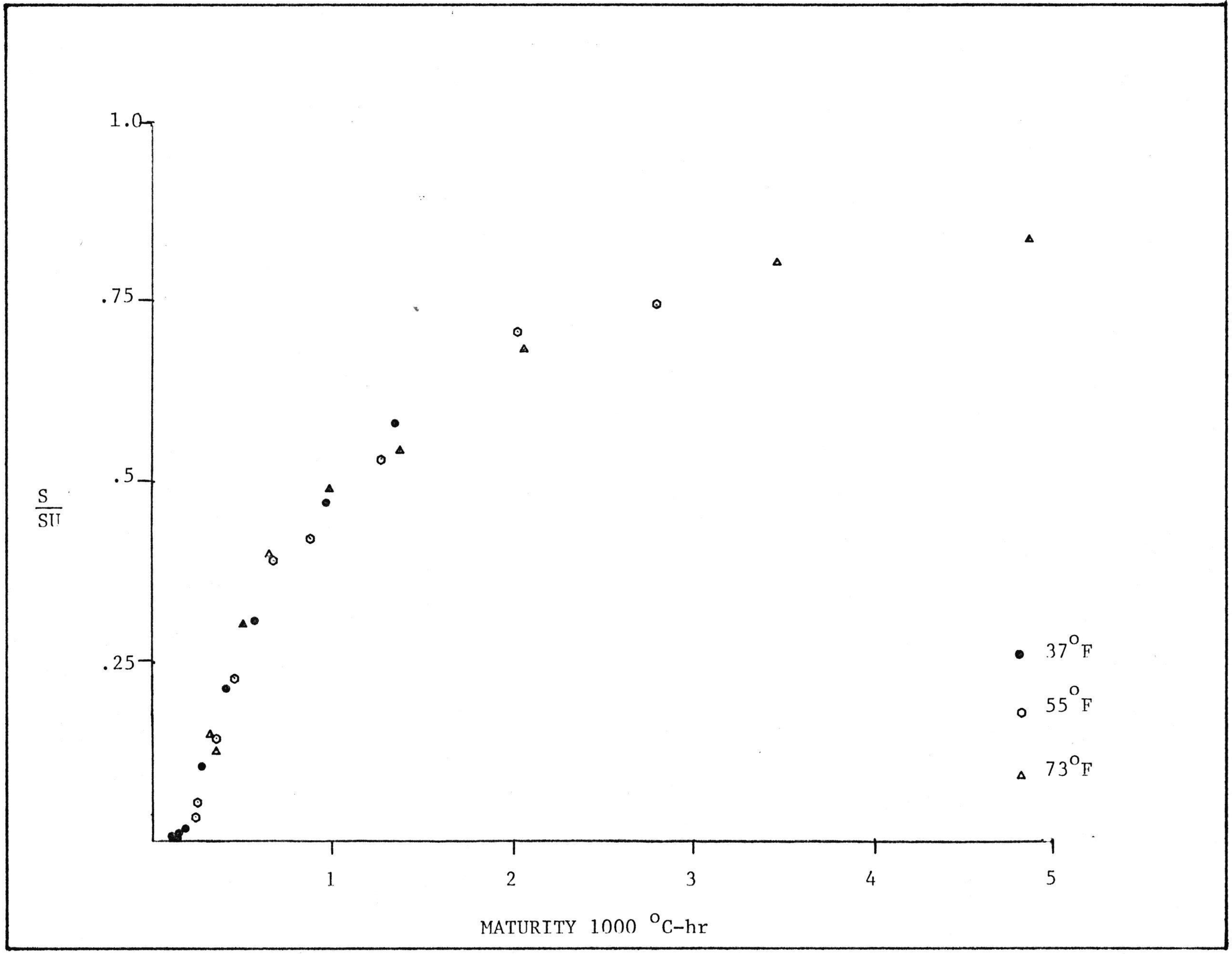


TABLE B.1 S/SU vs MATURITY FOR MIX 111

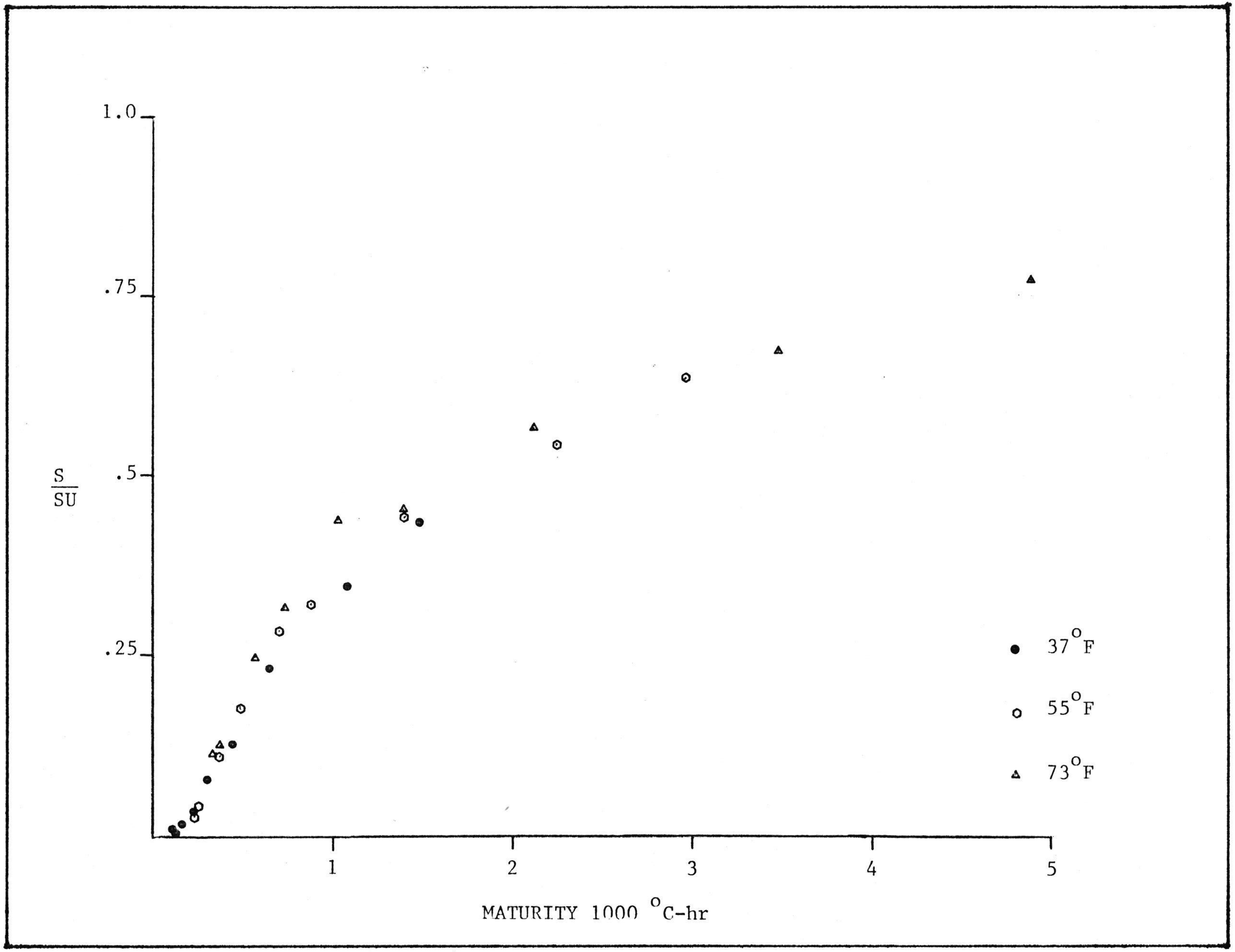


TABLE B.2 S/SU vs MATURITY FOR MIX 112

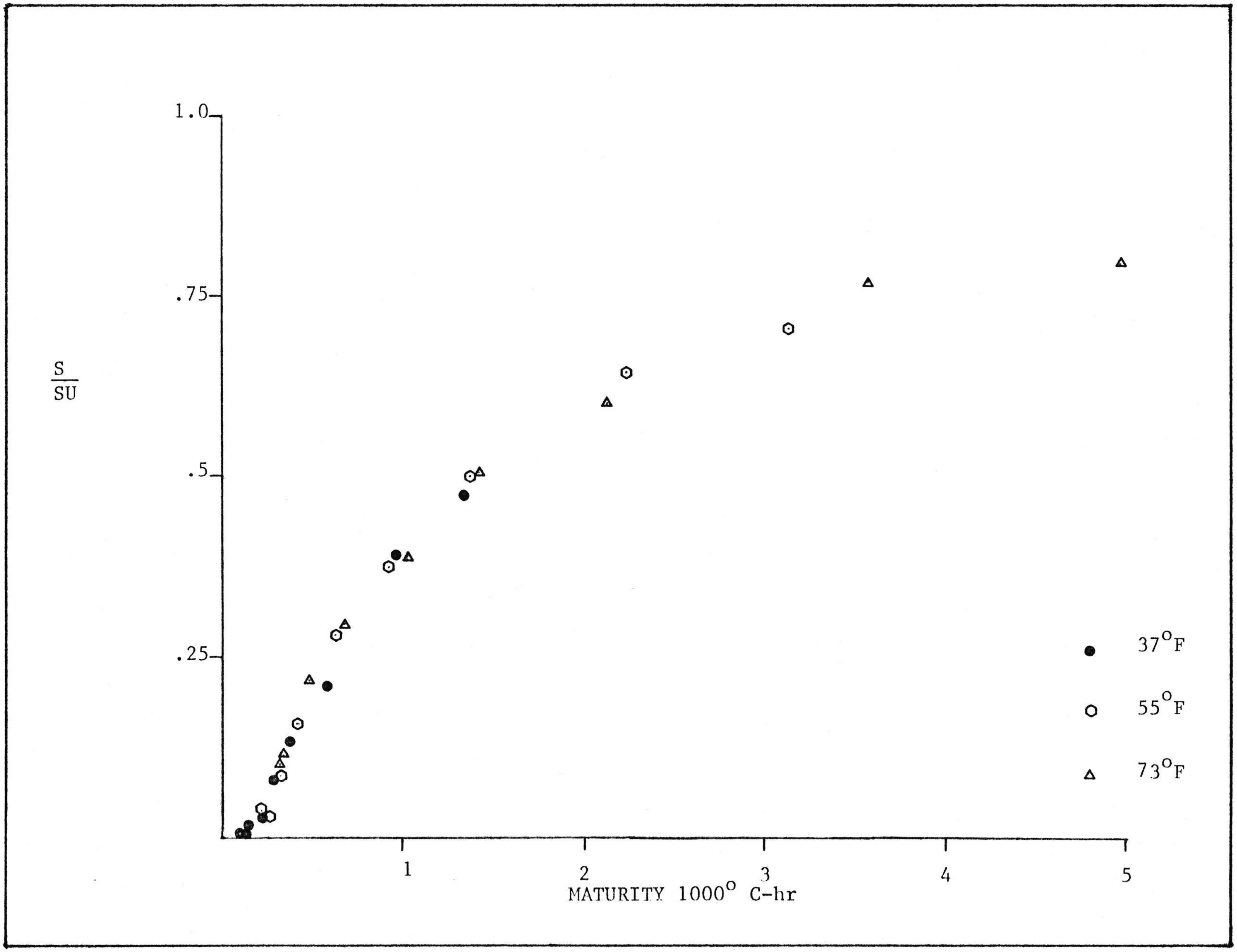


TABLE B.3 S/SU vs MATURITY FOR MIX 113

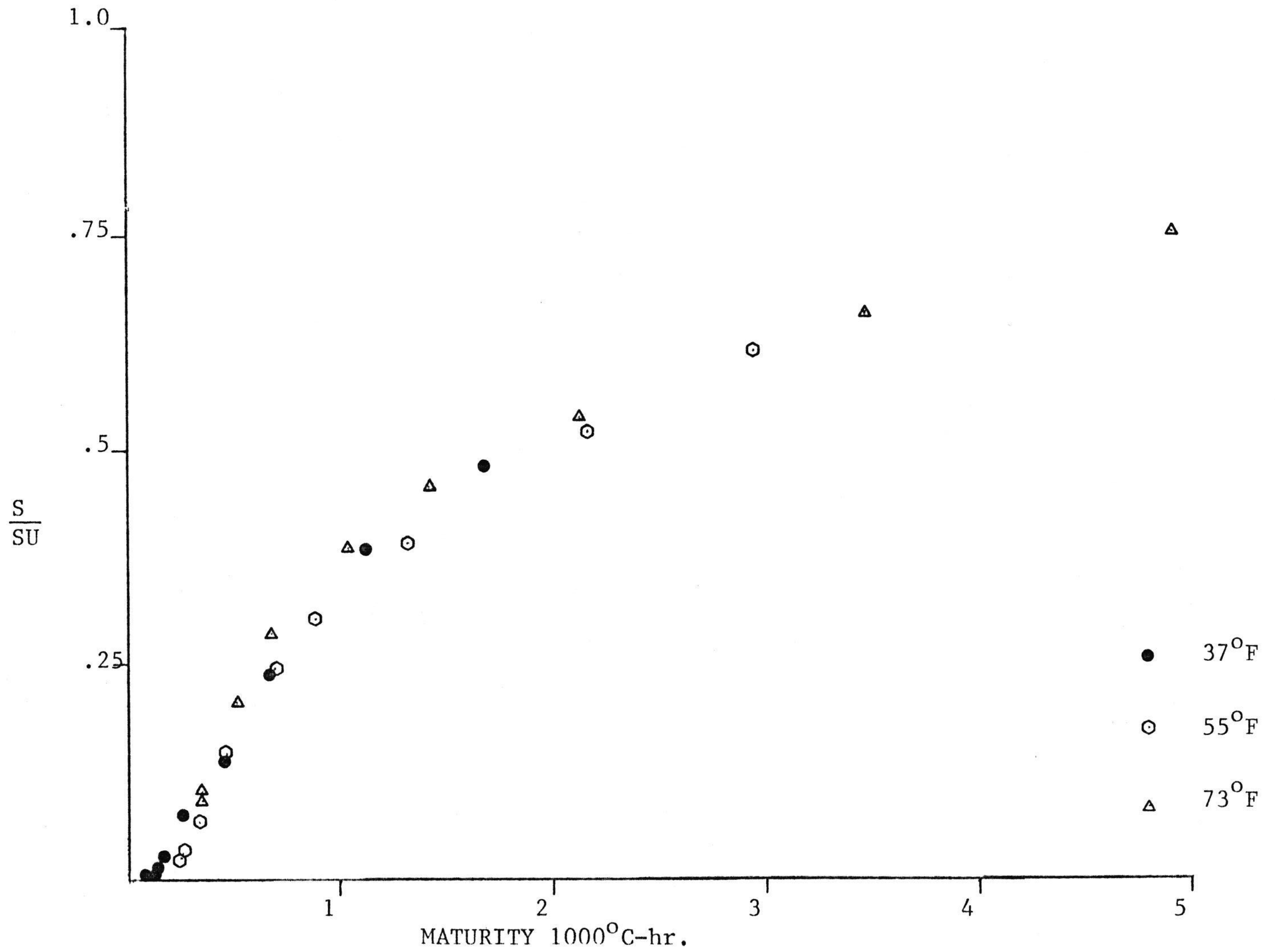


TABLE B.4 S/SU vs MATURITY FOR MIX 121

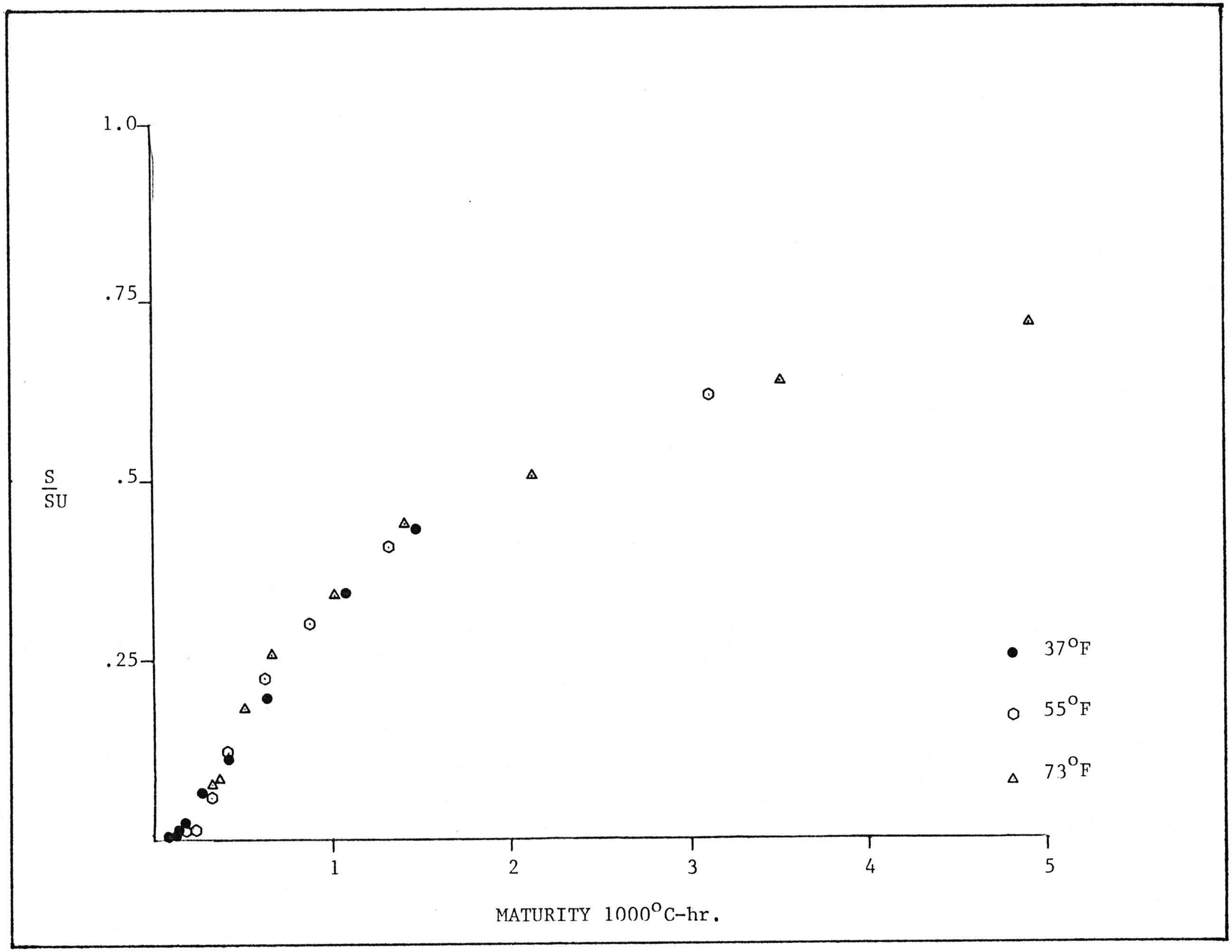


TABLE B.5- S/SU vs MATURITY FOR MIX 122

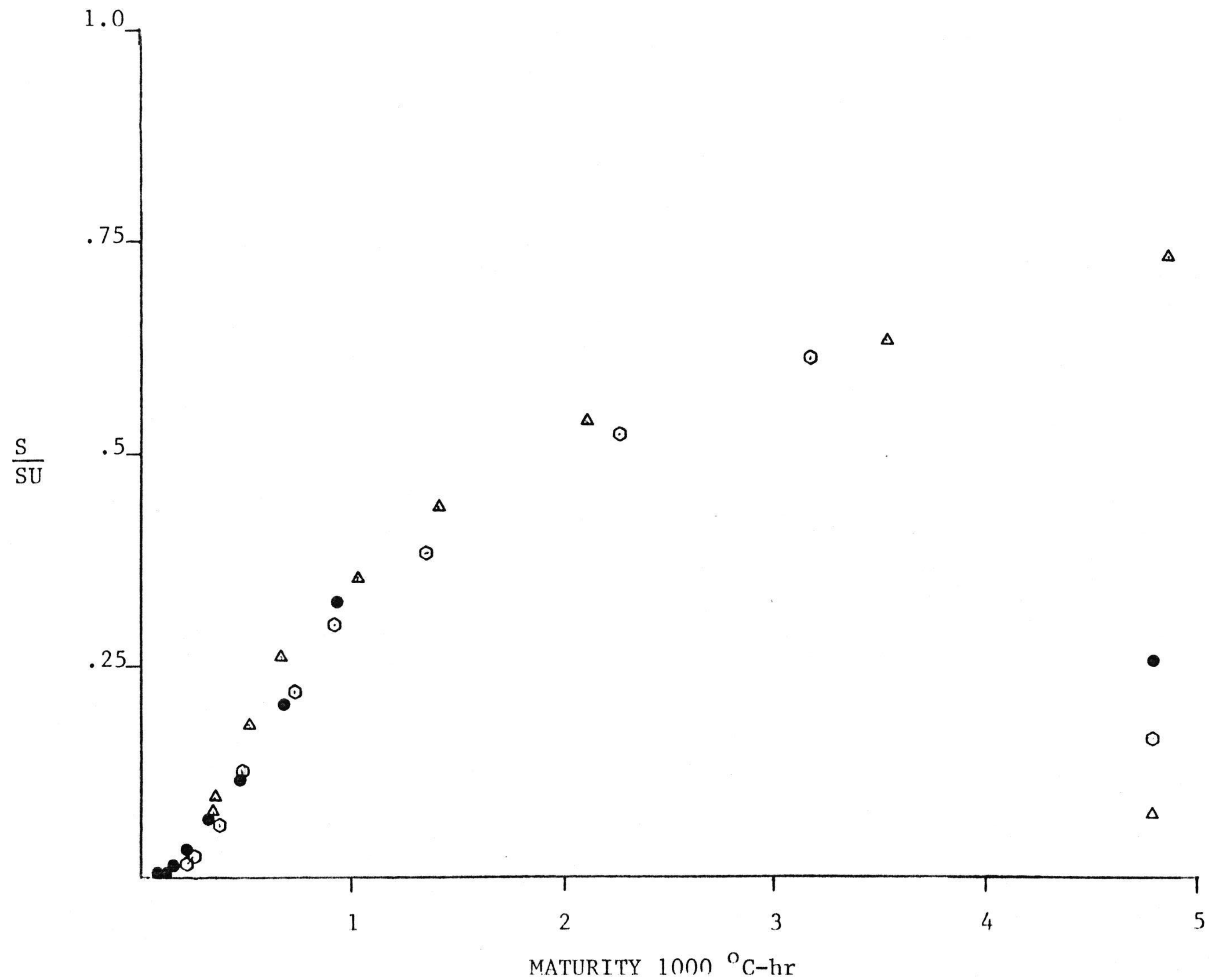


TABLE B-6 S/SU vs MATURITY FOR MIX 123

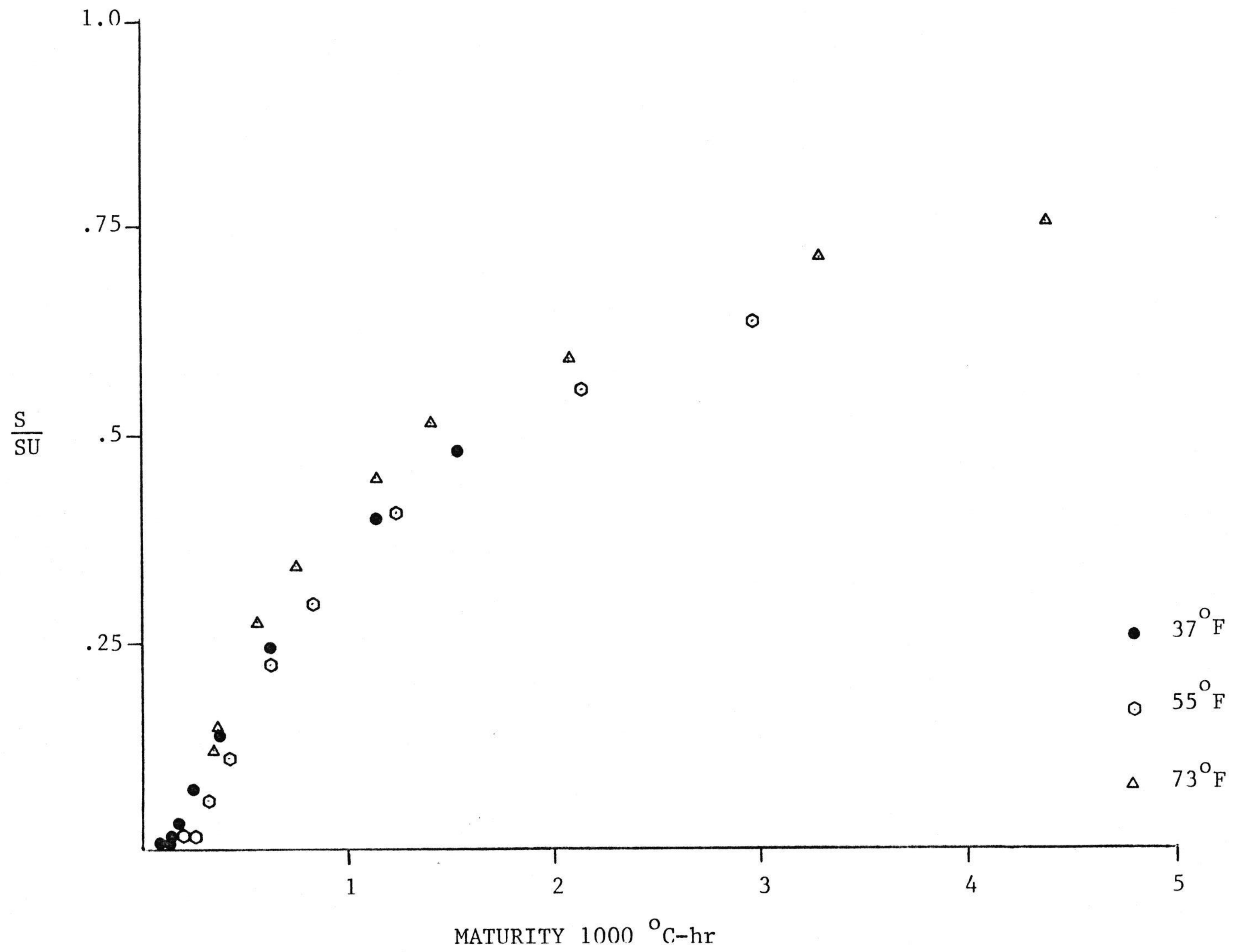


TABLE B.7 S/SU vs MATURITY FOR MIX 211

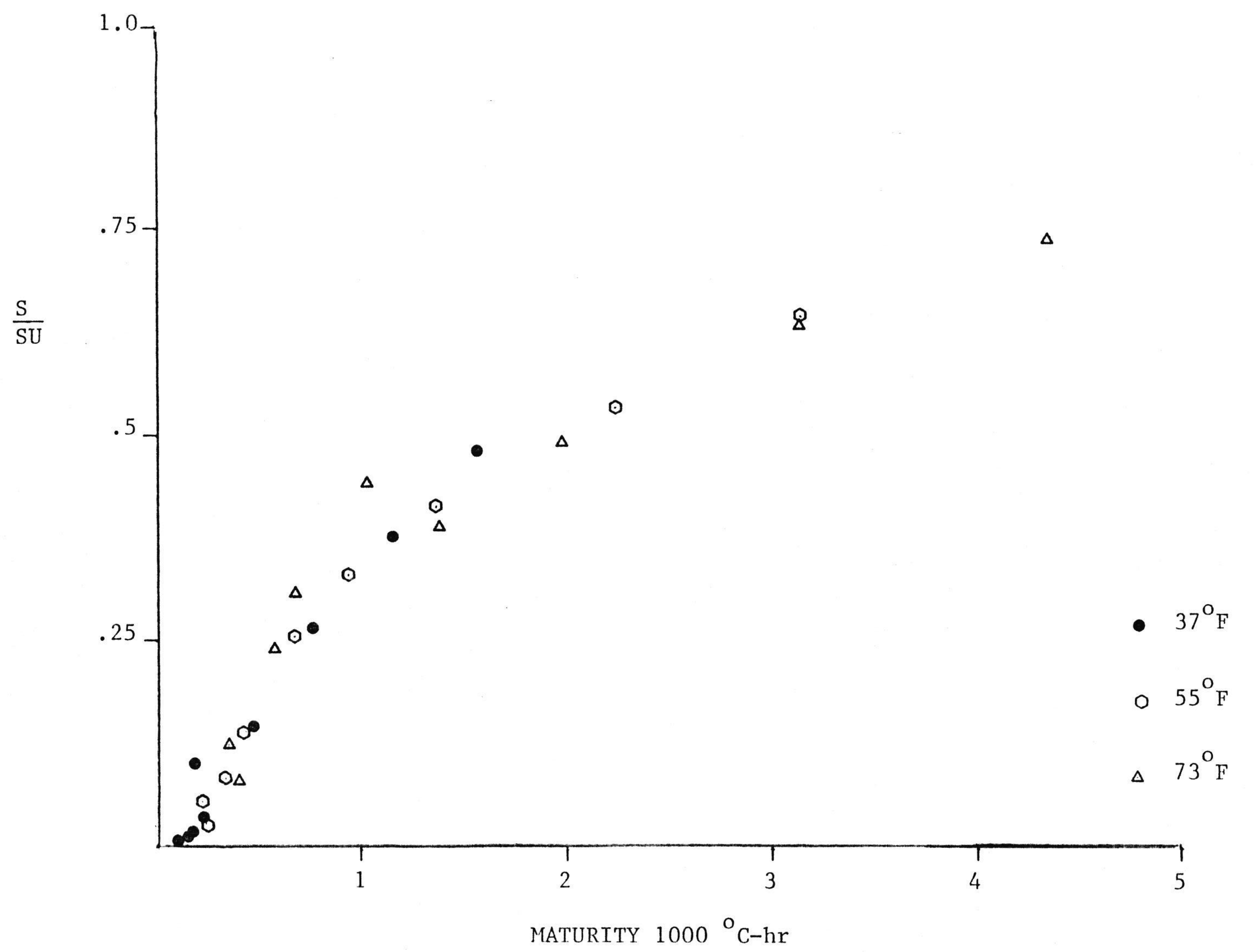


TABLE B.8 S/SU vs MATURITY FOR MIX 212

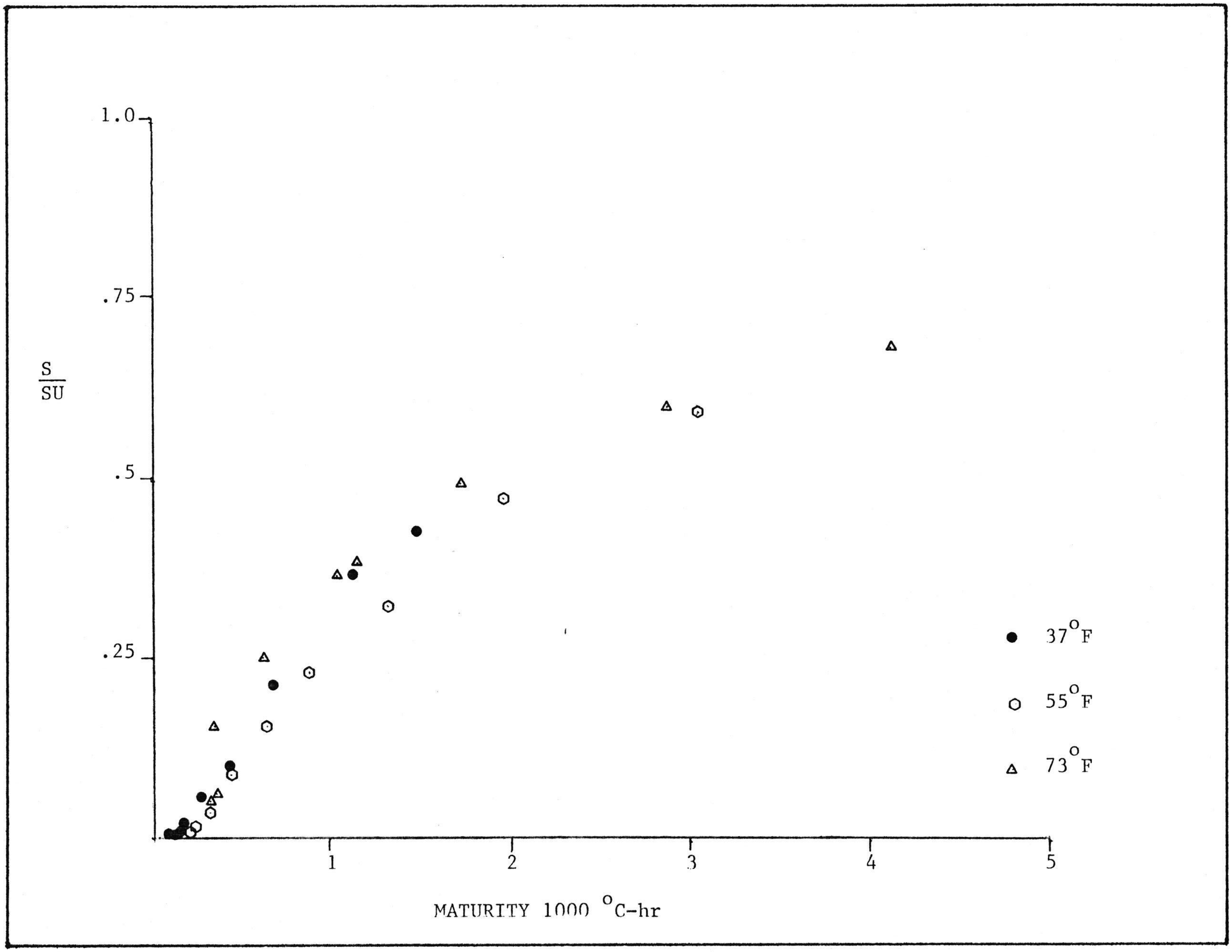


TABLE B.9 S/SU vs MATURITY FOR MIX 213

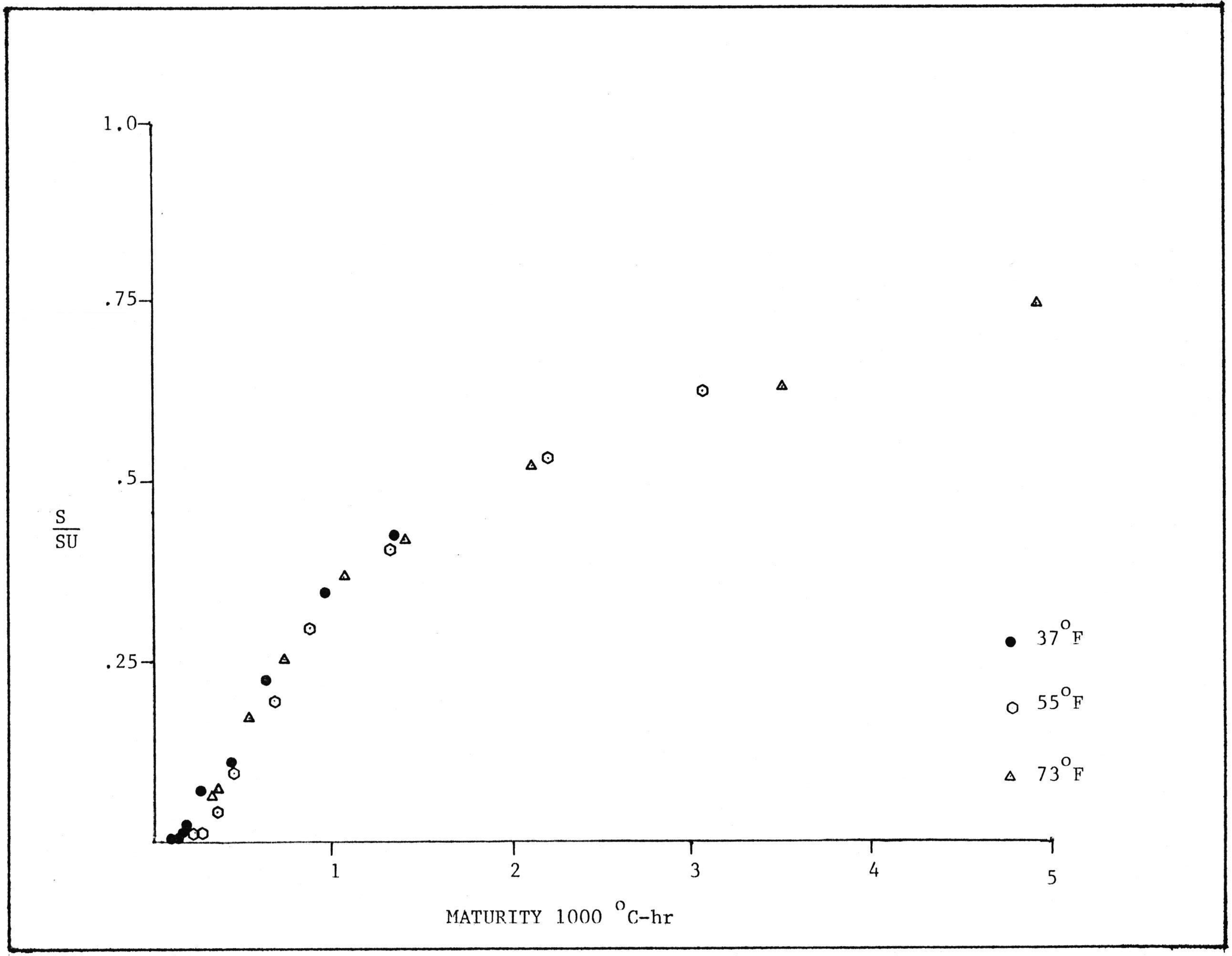


TABLE B.10 S/SU vs MATURITY FOR MIX 221

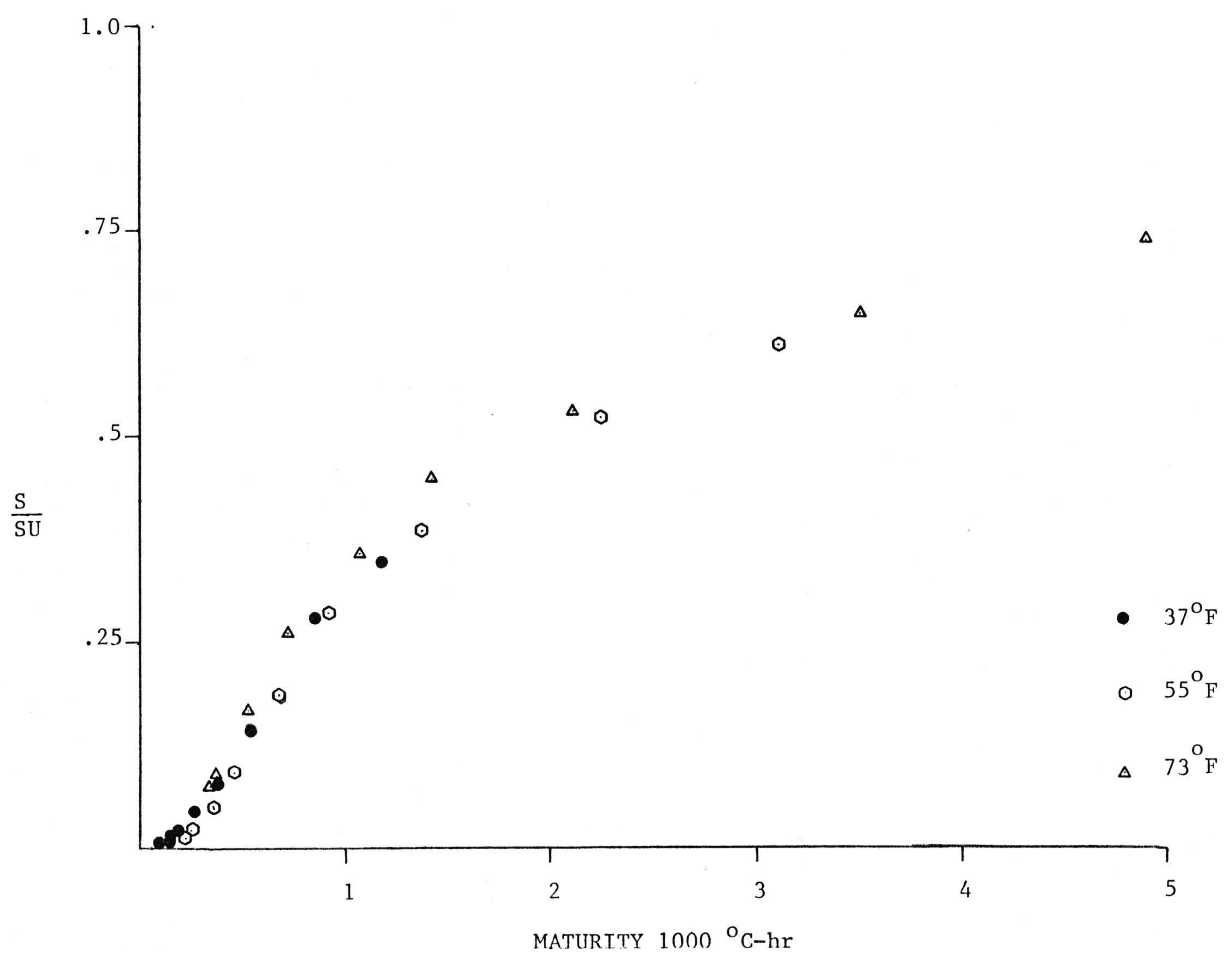


TABLE B.11 S/SU vs MATURITY FOR MIX 222

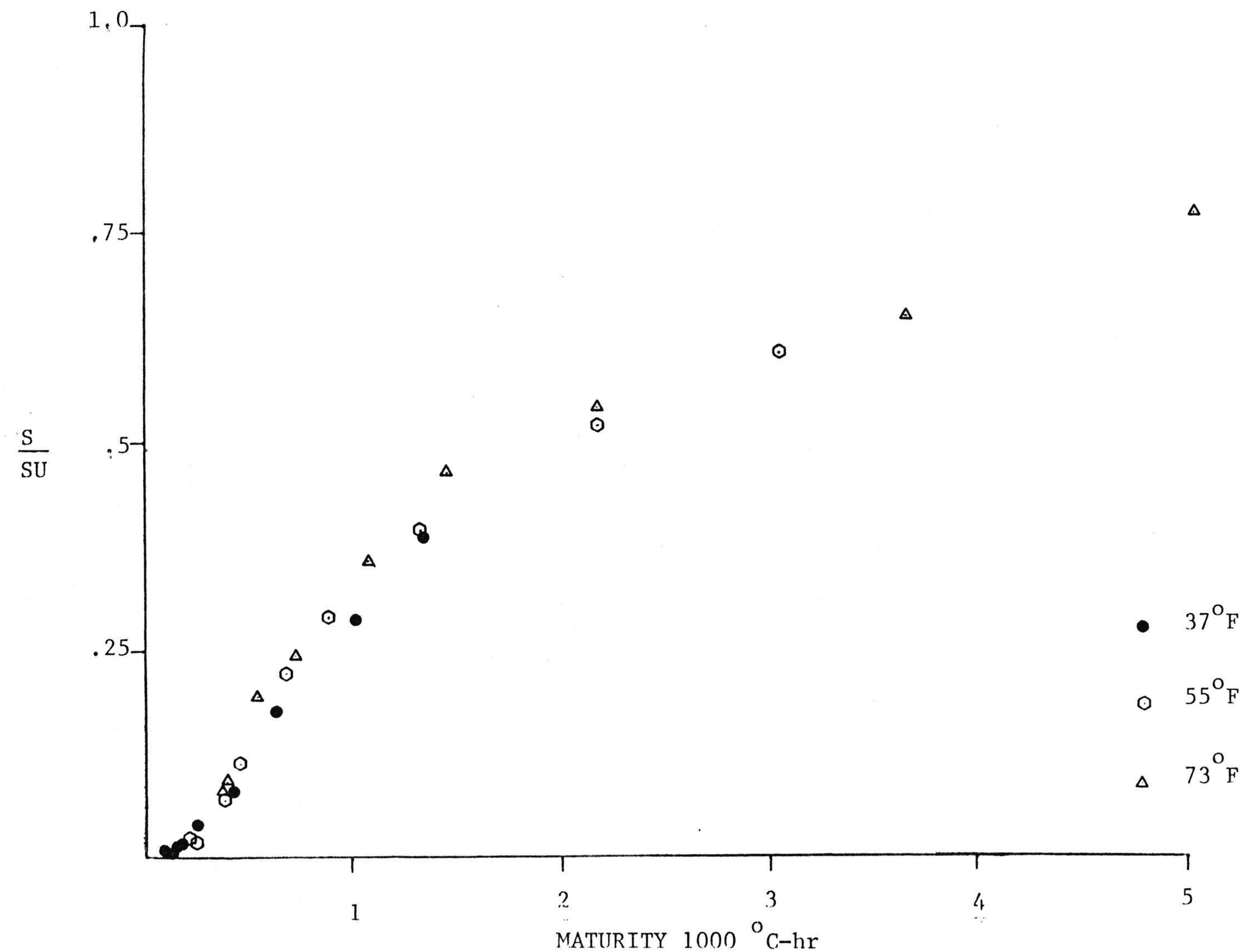


TABLE B.12 S/SU vs MATURITY FOR MIX 223

APPENDIX C

TEST PROCEDURE

APPENDIX C

TEST PROCEDURE

The following test procedure is recommended for the development and use of the prediction models.

C.1 Sample preparation

All specimens should be prepared and cured according to ASTM procedures. The following specimens need to be prepared:

a) Cylinders - 24 4"x8" should be casted. (The use of 4x8 instead of 6x12 cylinders will save materials and curing space)

b) Slabs - 4 36"x6"x8" slabs with 6 inserts per long side could be casted.

c) The maturity of two cylinders and slabs should be monitored by a maturity meter or use a temperature probe and calculate the maturity.

d) Testing Times - the following tests should be performed at the specified times.

	Number of Tests	
Time (days)	Cylinders	Pullout
1	3	6
2	3	6
3	3	6
5	3	6
7	3	6
10	3	6
14	3	6
28	3	-

e) Curing Temperature - the specimens should be cured at 55°F ± 1°F

f) Two additional sets of cylinders should be cured. One set should be cured at 37°F and a the other at 73°F. Each set should contain 18 cylinders with 3 tested at 1, 3, 5, 7, 14 and 28 days. This data would be used to develop the SU strengths which are dependent upon curing temperature.

C.2 Data Analysis

A least squares regression analysis routine should be used. The analysis routine should be based upon the following operation and provide at least a, b, and r^2 values.

$$y = a + bx$$

This routine will be used to develop the maturity and pullout models.

a) Maturity Model

The maturity model is given by Equation 2.5. In order to determine A, Mo and SU the following procedure is used on the cylinder = maturity data.

1. Let SU range in value from 4000 to 15,000 by increments of 250

2. Perform a regression analysis for each value of SU by letting

$$y = (S/SU)/(1 - S/SU)$$

$$x = \text{maturity}$$

3. Review the r^2 values and determine the best fit curve.

4. Calculate Mo and A by:

   A = b from analysis

   Mo = a/b from analysis

5. Substitute the value of A and Mo into Equation 2.4 to form the maturity model.

b) Pullout Model

To develop the pullout-model two regressions have to be performed: cylinder strength in terms of maturity and pullout force in terms of maturity.

To perform the first regression - cylinder strength in terms of maturity let

y = cylinder strength

x = Ln of the cylinder's maturity

and use the regression routine.

To perform the second regression - pullout force in terms of maturity let

y = pullout force

x = Ln of the slab's maturity

and use the regression routine.

Substitute the results into Equation 3.3 to develop the pullout model.

C.3 Use of Models

a) Maturity Model

To determine the concrete strength in the field, determine the field concrete's maturity and substitute it into the maturity model [Equation 2.4]. The SU value used in the model or Equation 2.4 could be obtained by two sources.

1. For a given time, match the field maturity to the maturity values for 37, 55 and 73°F curing, and pick the SU value obtained from the corresponding constant curing data.

2. Use the 28 day strength obtained in the model development.

The results obtained is the estimated concrete strength.

b) Pullout Model

Once the proper estimated concrete strength has been obtained, six pullout inserts should be tested in the field cured concrete, noting the pullout force. Average the forces and insert the force into the pullout model [Equation 3.3] to obtain the in-place concrete strength.

If the concrete strength obtained by the pullout model is equal to or greater than the strength obtained by maturity remove forms or load concrete. If not check the concrete strength at a later date, or wait for the cylinder tests.