CURING AND TENSILE STRENGTH CHARACTERISTICS OF AGGREGATE-LIME-POZZOLAN

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The tensile strength of aggregate-lime-pozzolan was found to be a very good indicator of the resistance of the material to freeze-thaw action. A tensile strength of approximately 68 psi (469 kPa) or greater must be attained for the material to have a reasonable chance to withstand freeze-thaw action as exhibited during the freezing season in Pennsylvania. The rate of development of tensile strength of a particular aggregate-lime-pozzolan mix is primarily a function of curing temperature. The higher the curing temperature is, the greater is the rate of gain in strength for the same amount of heat energy input. At temperatures below 50 F (10 C), no appreciable gain in tensile strength is achieved under field conditions.

•FOR the last 3 years, the Bureau of Materials, Testing and Research, Pennsylvania Department of Transportation (DOT), has been conducting extensive research on the characteristics of aggregate-lime-pozzolan material toward the following objectives:

1. To investigate the feasibility of tensile strength testing as a replacement for the standard freeze-thaw and unconfined compression tests;
2. To investigate the influence of selected variables (curing time and temperature, moisture conditions, type and amount of aggregate, amount of lime, amount of fly ash, density, and molded moisture content) on the final stabilized product; and
3. To evaluate the development of compressive and tensile strength in the field as a function of time, temperature, density, and moisture content and to correlate the results with the results obtained from laboratory tests.

When this project was initiated, it was determined impractical to study every aggregate, lime, or fly ash type. Therefore, one type of each was chosen for the initial experiment. The aggregate was a limestone with a specific gravity of 2.78 and 0.24 percent absorption. The gradation of the aggregate is shown in Figure 1. The physical properties of the fly ash and lime are as follows:

Property	Lime	Fly Ash
Percentage passing		
No. 100 sieve	96.4	97.7
No. 200 sieve	88.2	92.2
No. 325 sieve	80.2	81.6
Specific gravity		2.46
Loss on ignition	18.0	

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The chemical properties of the lime and fly ash in percentage weight are as follows:

Chemical	Lime	Fly Ash
SiO_2	Trace	45.3
Fe_2O_3	2.0	15.6
Al_2O_3		24.6
CaO	47.4	4.2
MgO	32.6	1.3
C	1.3	2.4

Even with these limitations, the scope was still much too large based on the many mix designs that were possible. Thus, several mix designs were investigated in a preliminary study. From this study, the highest strengths were achieved with 3 percent lime, 15 percent fly ash, and 82 percent limestone aggregate. For this reason and because this mix design is very typical of most designs for aggregate-lime-pozzolan in Pennsylvania, it was chosen as the master mix design to be used for this research.

TENSILE STRENGTH AS RELATED TO FREEZE-THAW CHARACTERISTICS

Road bases stabilized with lime and fly ash admixtures may not gain sufficient strength in 7 or 28 days to satisfactorily carry heavy traffic or withstand repeated freeze-thaw cycles (1). Davidson, Mateos, and Katti (1) proposed that, for adequate freeze-thaw resistance, aggregate-lime-pozzolan bases may need a strength of 300 to 500 psi (2070 to 3450 kPa) in compression, depending on material type stabilized, thickness of the bituminous surfacing, and severity of the climate. The authors believe that the failure of aggregate-lime-pozzolan material in the field due to freeze-thaw action or instability can be related to tensile strength insufficient to sustain the induced tensile strain produced by freeze-thaw action. Thus, the tensile properties should be the prime consideration in a laboratory evaluation of the material.

Figures 2 and 3 show the relationship between tensile strength and freeze-thaw cycles. Each point on the curves in Figures 2 and 3 represents the average strength of three specimens. Each curve represents a group of samples that were placed in the freeze-thaw test (AASHO T-136-70) at the same initial tensile strength.

After each specified number of freeze-thaw cycles, three samples were subjected to the double punch tensile test as described by Fang and Chen (2). The test was conducted at a strain rate of 0.2 in./min (5 mm/min). The tensile strength was calculated from the following equation:

$$\sigma_t = \frac{P}{(1.08bH - a^2)} \tag{1}$$

where

σ_t = simple tensile strength in psi (kPa),
P = applied load in lbf (N),
b = radius of specimen in in. (mm),
H = height of specimen in in. (mm), and
a = radius of piston in in. (mm).

With this procedure, the gain or loss of tensile strength was determined in relationship

Figure 1. Gradation of aggregate used in experimental mix.

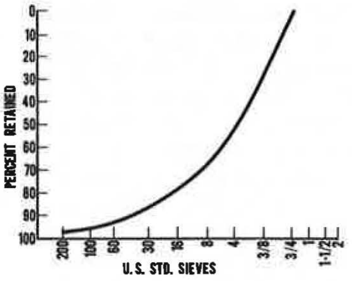


Figure 2. Relationship between tensile strength and freeze-thaw cycles for low initial tensile strength.

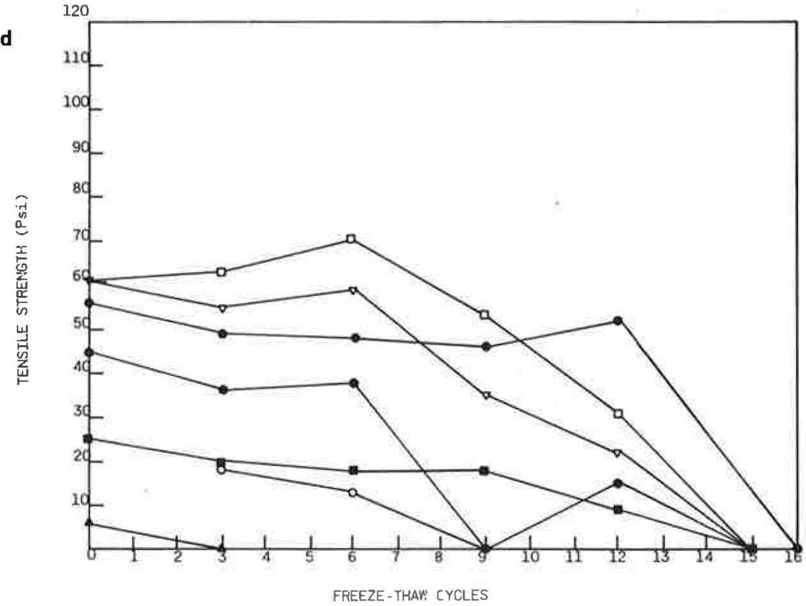
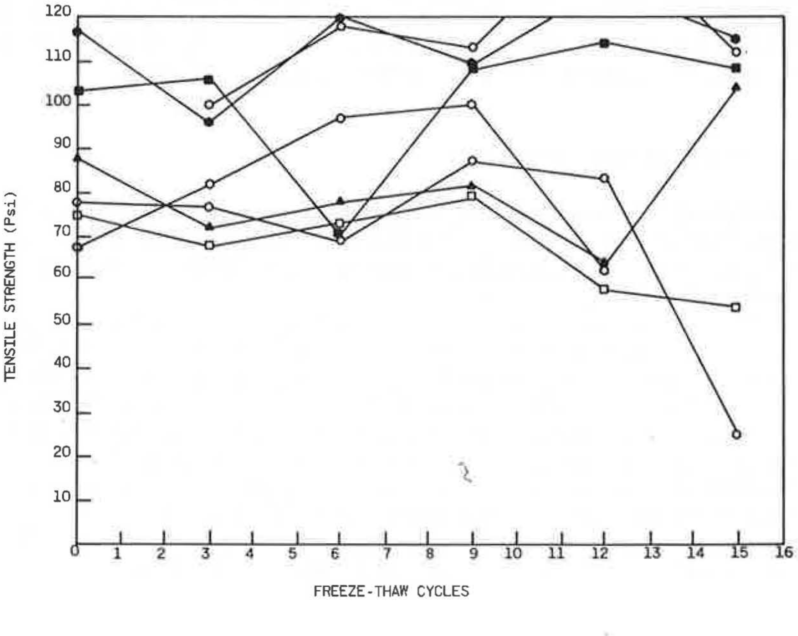


Figure 3. Relationship between tensile strength and freeze-thaw cycles for high initial tensile strength.



to the number of freeze-thaw cycles that the specimens had experienced. Table 1 gives the number of freeze-thaw test cycles that several samples withstood after they had achieved the initial tensile strength indicated (AASHO T-136-70).

Similar results were achieved from field samples cored from the shoulder of township Route 141 in Lancaster County. This material was placed between May 17 and May 27, 1971. Table 2 gives the dates when samples were cored, tensile strengths of the material when cored (average of three specimens), and number of freeze-thaw cycles (average of three specimens) that the cores withstood.

Table 3 gives the percentage loss by weight after 12 cycles of freeze-thaw when samples were placed in freeze-thaw at the initial tensile strength indicated. The type of aggregate used in developing this table was gravel instead of limestone as used in most of the research project.

Data shown in Figure 2 indicate a definite decrease in tensile strength with increasing freeze-thaw cycles. Also, note that the initial tensile strength of all the samples is below 61 psi (421 kPa) before freeze-thaw action. On the other hand, Figure 3 shows more stable tensile strengths and in some cases even an increase in tensile strength development with increasing freeze-thaw cycles. In Figure 3, the initial tensile strength of all samples is above 68 psi (469 kPa) before freeze-thaw cycling. Figures 2 and 3 show that, if a sample can withstand 15 to 18 freeze-thaw cycles, it will probably be able to withstand any reasonable number of cycles. The Pennsylvania DOT has only a few data to substantiate this conclusion. From an analysis of pavement temperatures during the last 4 years at 14 field test sites located throughout Pennsylvania, as many as 50 freeze-thaw cycles can be expected to occur at the top of the base. As many as 24 cycles can be expected in the base. A higher number of cycles occur in less severe winters. Thus, from the relatively high number and variability of freeze-thaw cycles that the base undergoes, it appears that the 12-cycle freeze-thaw test (AASHO T-136-70) is not a good indicator of actual field conditions. A possible relationship appears to be if a sample can withstand 12 freeze-thaw cycles it stands a reasonable chance of resisting a much larger number of cycles without detrimental effects.

From the data presented, failure of aggregate-lime-pozzolan material can be attributed to loss in tensile strength due to freeze-thaw action when an insufficient strength level has been achieved before freeze-thaw action begins. It appears that a tensile strength of 68 psi (469 kPa) or greater must be attained for the material to have a reasonable chance to withstand freeze-thaw action as exhibited during the freezing season in Pennsylvania. To consider a lower value of tensile strength requires that many more data be accumulated in the 50 to 70-psi (345 to 480-kPa) tensile strength range. This conclusion is valid only if there is a reliable relationship between the laboratory freeze-thaw test and what actually happens in the field. To date the literature to substantiate this relationship is rather sparse.

CURING CHARACTERISTICS

To establish a tensile strength criterion as a possible replacement for the standard freeze-thaw test and also establish a construction cutoff date for late season placement of aggregate-lime-pozzolan, a thorough knowledge of the curing characteristics of the material must be acquired.

The rate of strength gain of aggregate-lime-pozzolan is considerably influenced by the temperature at which it is cured (3, 4). The importance of this variable may be readily recognized through Figure 4. (Data for the development of Figure 4 are given in Table 4.) A higher tensile strength is achieved when the same amount of heat energy is supplied at a higher temperature. Therefore, the tensile strength is dependent not only on the amount of heat energy supplied but also on the temperature at which it is furnished. Furthermore, heat energy supplied at temperatures below 50 F (10 C) makes an insignificant contribution toward tensile strength development in the field as can be seen when the 50 F curing curve is compared with the 60 F (16 C) curve in Figure 4 and is, therefore, neglected in field application.

Table 1. Laboratory comparison of freeze-thaw cycles with tensile strength.

Initial Tensile Strength (psi)	Freeze-Thaw Cycles for 14 Percent Loss by Weight	Freeze-Thaw Cycles to Complete Failure[a]
6	3	3
25	6	15
45	9	9
56	16	16
61	15	15
61	12	15
68	12	>12
75	>12	>15
78	15	>15
88	>15	>15
103	>15	>15
117	>15	>15

Note: 1 psi = 6.9 kPa.

[a] Complete failure is defined as complete loss of samples or zero strength.

Table 2. Comparison of freeze-thaw cycles with tensile strength of cores from township Route 141.

Date Cored	Tensile Strength (psi)	Freeze-Thaw Cycles to Failure
8/14/71	44	7
9/14/71	82	12
10/10/71	88	15
2/15/72	47	5

Note: 1 psi = 6.9 kPa.

Table 3. Tensile strength and freeze-thaw characteristics of gravel.

Curing Time at 100 F (days)	Tensile Strength (psi)	Percentage Loss After 12 Cycles
3	20	100
4	20	100
6	44	51
3	29	100
4	46	42
6	51	12
3	31	75
4	61	11
6	74	10
3	27	100
4	51	47
6	72	11
3	27	100
4	43	20
6	89	9
3	27	100
4	42	100
6	92	9

Note: 1 F = 1.8 C + 32; 1 psi = 6.9 kPa.

Figure 4. Relationship between curing temperature and tensile strength.

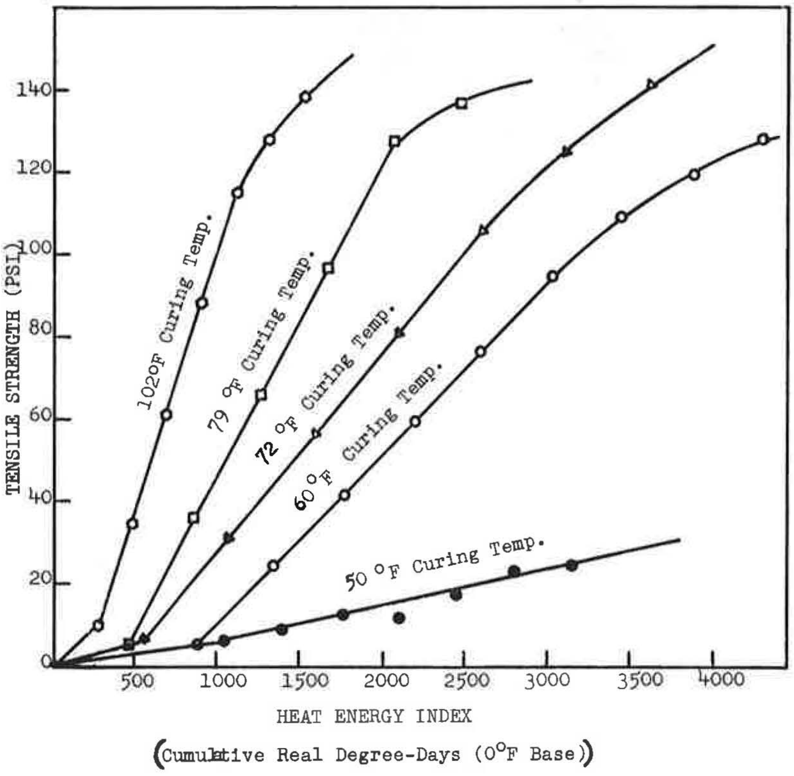
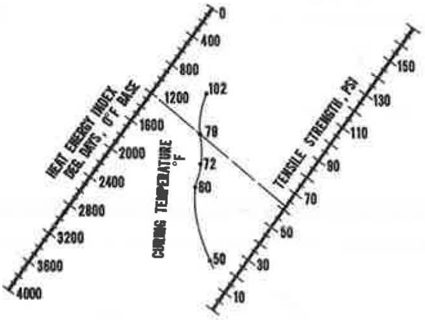


Table 4. Relationship between curing time and tensile strength for base temperature of 0 F (-18 C).

Curing Temperature (F)	Days Cured	Degree Days	Real Degree Days	σ_t (psi)
50	21	1,050	1,122	6
	28	1,400	1,472	9
	35	1,750	1,822	13
	42	2,100	2,172	12
	49	2,450	2,522	17
	56	2,800	2,872	23
	63	3,150	3,222	25
60	7	420	492	2
	14	840	912	7
	21	1,260	1,332	25
	28	1,680	1,752	42
	35	2,100	2,172	60
	42	2,520	2,592	77
	49	2,940	3,012	95
	56	3,360	3,432	110
	63	3,780	3,852	120
	70	4,200	4,272	129
	84	5,040	5,112	141
72	7	504	576	8
	14	1,008	1,080	32
72	21	1,512	1,584	57
	28	2,016	2,088	81
	35	2,520	2,592	106
	42	3,024	3,096	129
	49	3,528	3,600	142
79	5	395	467	5
	10	790	862	36
	15	1,185	1,257	66
	20	1,580	1,652	97
	25	1,975	2,047	128
	30	2,370	2,442	137
102	2	204	276	10
	4	408	480	35
	6	612	684	61
	8	816	888	88
	10	1,020	1,092	115
	12	1,224	1,296	128
	14	1,428	1,500	139

Note: Degree days = number of days x curing temperature with base temperature of 0 F. Real degree days include 1-day soak period at 72 F.
1 F = 1.8 C + 32; 1 psi = 6.9 kPa.

Figure 5. Nomogram for determining predicted tensile strength of aggregate-lime-pozzolan material.



Compaction is another variable that greatly affects the rate of strength gain in the field. The rate is significantly reduced when the material is placed below maximum density and optimum moisture content. This problem can be eliminated by strict construction control (5, 6).

Although compaction can be controlled in the field, little can be done to control the temperature. Thus, a knowledge of the curing characteristics of aggregate-lime-pozzolan is necessary for late season construction.

The authors have developed an equation and a nomogram (based on 114 samples) for predicting the tensile strength of aggregate-lime-pozzolan from curing time and temperature data. In the development of the equation for predicting tensile strength in the field, the following assumptions are made:

1. The material is compacted to maximum density and at optimum moisture content;
2. The materials and mix design are the same or similar to the ones used in this research project;
3. The 79 F (26 C) curing curve in Figure 4 approximates the curing of the material throughout the average daily temperature range greater than 75 F (24 C);
4. The 72 F (22 C) curing curve in Figure 4 approximates the curing of the material throughout the average daily temperature range of 68 to 75 F (20 to 24 C);
5. The 60 F (16 C) curing curve in Figure 4 approximates the curing of the material throughout the average daily temperature range of 55 to 67 F (13 to 19 C); and
6. The 50 F (10 C) curing curve in Figure 4 approximates the curing of the material throughout the average daily temperature range below 55 F (13 C) and will be neglected in the development of the equation.

The relationship developed by determining the equation of the curve for each curing temperature in Figure 4 is

$$\sigma_t = 8.0 + 0.041(X) + 0.049(Y) + 0.078(Z) \tag{2}$$

where

X = cumulative real degree days for the 55 to 67 F (13 to 19 C) range,
Y = cumulative real degree days for the 68 to 75 F (20 to 24 C) range, and
Z = cumulative real degree days for greater than 75 F (24 C).

It was also determined that, under field conditions, approximately 8 days were required before the curing rate reached the straight-line portion of the curves in Figure 4. In the initial 8 days of cure, an average tensile strength of 8 psi (55 kPa) was developed. Thus, in our use of equation 2, tensile strength at any time is equal to the tensile strength after 8 days of initial placement of the material (8 psi) plus the cumulative real degree days during the investigated time period and for each temperature range mentioned above multiplied by the slope of the curve in Figure 4 for that particular curing temperature range.

A nomogram was also developed (Figure 5) and is used in the following manner. Determine the heat energy index, cumulative degree days concept with 0 F base temperature (0 F was used because this gives the greater fan effect or separation of the curves in Figure 4 and it also simplifies the calculations in the conversion to cumulative degree days).

1. Determine the average daily temperature for each day during the period being investigated.
2. Sum the temperatures in the range of 55 to 67 F (13 to 19 C). Temperatures below 55 F have insignificant contributions toward tensile strength development in the field and are, therefore, neglected.
3. Sum the temperatures in the range of 68 to 75 F (20 to 24 C).

4. Sum the temperatures greater than 75 F (24 C).

Use the curing temperature scale and

5. Project a straight line from the heat energy index scale (sum of the temperatures determined in step 2 above) through 60 F (16 C) on the curing temperature scale and read the partial tensile strength,
6. Project a straight line from the heat energy index scale (sum of the temperatures determined in step 3 above) through 72 F (22 C) on the curing temperature scale and read the partial tensile strength value, and
7. Project a straight line from the heat energy index scale (sum of the temperatures determined in step 4 above) through 79 F (26 C) on the curing temperature scale and read the partial tensile strength value.

For predicting the total tensile strength development for the time period in question, add the partial tensile strength values determined in steps 5, 6, and 7.

The nomogram and equation 2 are valid only for the materials and mix design investigated in this research. Currently, industry is working on additives and different types of lime that would increase the curing rate of aggregate-lime-pozzolan to facilitate late season construction. With increased curing rates, revisions to the nomogram and equation 2 will have to be developed.

CONCLUSIONS

Based on the research work completed, the following conclusions have been drawn.

1. One of the major causes of failure in aggregate-lime-pozzolan material is the loss in tensile strength caused by freeze-thaw action.
2. A tensile strength of approximately 68 psi (469 kPa) or greater should be attained in order for the material to have a reasonable chance to withstand freeze-thaw action as exhibited during the freezing season in Pennsylvania. This tensile strength must be achieved before the first freeze of the season. This conclusion also leads to the recommendation that a construction cutoff date be established based on the probability of failure at a given tensile strength and a statistical analysis of Pennsylvania weather conditions with respect to the curing characteristics of aggregate-lime-pozzolan. For construction after the cutoff date, additives or a different type of lime in the mix would have to be used to increase the rate of gain in tensile strength development.
3. The rate of gain in tensile strength of a particular mix is primarily a function of curing temperature. The higher the curing temperature is, the greater is the gain in strength for the same amount of heat energy input.
4. At temperatures below 50 F (10 C), no appreciable gain in tensile strength is achieved under field conditions.
5. For the materials and mix design investigated in this research, equation 2 may be used to predict the tensile strength development of aggregate-lime-pozzolan in the field.
6. The feasibility of replacing the standard freeze-thaw test with a tensile strength test is excellent.

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DISCUSSION

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The authors have shown very useful data by using the double punch tensile strength related to the freeze-thaw action of aggregate-lime-pozzolan material. Figure 4 developed by the authors has a significant value for further material classifications based on the tensile strength. Because the double punch test was developed at Lehigh in early 1970 (2), the writer wishes to update research results and make additional comments regarding the double punch tensile test that relate to the basic procedure on stabilized soil.

The parameter (1.08) shown in equation 1 is not a constant. It depends on the specimen size and material types. For practical purposes, the following values have been recommended (9, 11):

Mold	Soil	Stabilized Materials
Proctor, 4 × 4.6 in.	1.0	1.2
CBR, 6 × 7 in.	0.8	1.0

The effect of the loading rate on the tensile strength has been studied (9, 13). These results show that there is no definite trend in tensile strength variation or deformation at failure when the loading rate varies from 0.03 to 2.0 in./min (0.7 to 51 mm/min). It was, therefore, recommended that the ASTM loading rate for the unconfined compression test be used for the double punch test. The effect of punch size is essential, and, based on experimental results, the ratios of the diameter of the specimen to the diameter of the disk (punch) of 0.2 to 0.3 are suitable for the test (2, 14). However, both theoretical (7) and laboratory studies show that the shape of the specimen does not affect the double punch tensile results. Because the double punch test is a type of penetration test on unconfined soil mass, the cracks always travel in the shortest distance from the center of the punch. The test has been extended to test bricks, masonry block, compacted and stabilized waste disposal material, and polymer-concrete block. Furthermore, the tensile test together with the unconfined compression test can be used for estimating other strength parameters, cohesion, and ϕ—the internal friction angle based on the method proposed by Fang and Hirst (10).

As previously pointed out, the conventional split tensile test measures the value of tensile strength across a predetermined failure plane, whereas the double punch test always causes failure on the weakest plane (random failure plane), resulting in a measurement of the true tensile strength of the soil (11, 12, 13). Tests have shown that, for rocks (8) and stabilized materials with high nonhomogeneous properties, results from the double punch test are lower than those obtained from the split tensile test. Because of a random failure plane, the double punch test is a very useful and sensitive method for studying the consistency characteristics and classification of soil, stabilized soils, and other construction materials.

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