Improving Thermoplastic Stripe Adhesion on Concrete Pavements

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Thermoplastic striping material can be used as a pavement-marking system and has several advantages over other systems; however, it also has the disadvantage that, in some cases, the entire system is lost prematurely. These failures have been attributed to faulty application procedures. This paper examines four important possible application criteria—the temperature of the molten thermoplastic material, the air temperature, the pavement temperature, and the moisture condition of the pavement—for inclusion in a specification. A minimum bond strength necessary to ensure an acceptable service life of the material of 862 kPa (125 lbf/in^2) is suggested. It was concluded that (a) the temperature of the thermoplastic material at application is important, and a small range should be specified based on test results; (b) the air temperature does not affect the bond strength and should not be included in a specification; (c) the temperature of the pavement is an important criterion, and no thermoplastic material should be applied to pavements colder than 12.8°C (55°F); and (d) the moisture in the pavement has relatively little effect on the adhesion, and thermoplastic may be applied to any surface-dry pavement.

In the past 10 years, the highway departments of this nation have taken many steps toward achieving safety for the motorist. There is a continual search for new safety devices that will save lives. Some of the major accomplishments include improvements in the geometric design of highways, better and more-standardized signing, and better highway alignments. All of these improvements have added to the safety of the driver, but they have also allowed for faster speeds. At these higher speeds, a driver must assign priorities to that which he or she will see and react to. These priorities are first, positional information; second, situational information; and third, navigational information (1). If the first priority, alignment in the traffic lane, requires all of the driver's time, then the other significant information will be ignored. For this reason, it is most important that the roadway be well defined under all conditions. Traffic engineers have realized the importance of lane lines; consequently, there is a continual maintenance program in most states to replace worn stripes. At present, in most states, lane lines on heavily traveled roadways are replaced as often as 3 times/year, and Iowa reports that the line is "frequently absent during a considerable portion of the winter period" (2). The failure of the stripe can be due to many factors, but the life of the stripe can be shortened drastically by bad application procedures. The cost and, more importantly, the personpower of reapplication becomes burdensome to the departments.

The delineation systems in use today around the country are many in number. Most of these striping systems have shortcomings that may range from poor wet-night visibility to high losses because of unprojected failures. With the limited budgets of most agencies today, these premature losses cannot be afforded. The thermoplastic stripe system is one such system. Excessive losses of thermoplastic stripe systems are particularly common in areas in which snowplows are frequently used and, in many cases, for unexplainable reasons. Thermoplastic striping, on the other hand, is a very durable material and has a service life projected to be up to 5 years. The system is also far better than most in a wet-night situation.

The price of thermoplastic striping as projected in 1972 for a 5-year effective-life cost analysis was \$2.00/m (\$0.61/ft) on concrete and \$1.08/m (\$0.33/ft) on bituminous surfaces (3). The high cost on concrete reflected its limited service life. The lower cost on bituminous surfaces, although high compared with that of an equivalent paint stripe, is competitive with other systems. The advantages of thermoplastic striping outweigh its expense as compared with conventional paint. The question then becomes, can the losses on concrete pavements be reduced and such a system be made economically competitive?

In the research reported in this paper, the failure mechanisms were investigated of the losses of thermoplastic striping in winter. Second, because a comprehensive specification for thermoplastic stripe applications is needed, requirements are suggested that should be included in a draft specification to ensure the adhesion necessary to avoid losses.

THE PROBLEM

Generally, striping, whether it be paint or thermoplastic, does well on most bituminous pavements but experiences extensive failures on concrete surfaces (and new concrete surfaces are the worst). A letter requesting information pertaining to this peculiarity was sent to highway departments in five states in an attempt to identify the source of the problem. The responses indicated that the prevalent mode of failure on bituminous pavements subjected to snowplow activity is due to shaving of the thermoplastic rather than to adhesive failure. The opposite is true on concrete pavements; lack of adhesion between the thermoplastic and the pavement is the prevalent failure mechanism. A further indication of the lack of performance of thermoplastics on concrete pavements is found in a report (4) in which this statement was made: "It has been well documented that most paints perform better on bituminous surfaces than on portland cement concrete". The problem on concrete pavements is one of adhesion and is generally not encountered on bituminous pavements. Many conjectures have been made as to why this is true, but a definitive answer has never been offered. This paper does not attempt to explain completely the phenomenon; however, it does quantify several factors that are necessary for obtaining good adhesion. Because of the general acceptance of the performance of thermoplastic striping on bituminous pavements, the typical value of the adhesion of thermoplastic to bituminous pavements was used as a quantitative standard for comparison with adhesion on concrete pavements.

THEORY OF FAILURES

Four aspects of application procedures were studied to determine their effects on the adhesion properties of thermoplastics:

1. The temperature of the molten thermoplastic material,
2. The air temperature,
3. The pavement temperature, and

Table 1. Summary of specifications.

Specification	Plastic Temperature (°C)	Air Temperature (°C)	Pavement Temperature (°C)	Moisture Condition
California	204-218			
Illinois	177-246	10		
Oklahoma	177-260 (as per manufacturer's recommendation)		4	Dry pavement
Texas			10	Dry pavement
British Standards	Manufacturer's recommendation		5	Can dry by heating
AASHTO	211 ± 7			
ITE	191-246			

Note: $t°C = (t°F - 32)/1.8$.

4. The pavement moisture content.

A literature search was conducted of the current specifications of four states [California (5), Illinois (6), Oklahoma (7), and Texas (8)] and the specifications published by the Institute of Transportation Engineers (ITE) (9), the American Association of State Highway and Transportation Officials (AASHTO) (10), and the British Standards Institution (11). The consistency of these specifications pertaining to the four aspects is summarized in Table 1. The first aspect, temperature of the molten thermoplastic material, has been ignored in most specifications, the belief being that these materials will not function properly if not heated to the right temperature. The specifications reviewed showed a maximum range from 177°C to 260°C (350°F to 500°F), i.e., that practiced in Oklahoma. A stipulation sometimes was added that the temperature should be based on the manufacturer's recommendations. The wide range might be deemed necessary by the fact that there are numerous generically different formulations in use today. Thus, the effects were explored of small temperature variations on the adhesion of the thermoplastic to determine whether an application-temperature limitation is necessary and, if so, what ranges should be used. Because of the possibility of individual temperature ranges for different materials, in these tests all parameters (including the type of material) except temperature were maintained constant.

The second application specification in use today is that of a minimum air temperature that must exist before application can begin. Many failures have been linked to applications made on cold days or early in the morning, suggesting a temperature at application that is too low. The specification search showed that only one state organization specifies minimum air temperatures [Illinois, which specifies a minimum air temperature of 10°C (50°F)]. The research in this area was initiated by the conjecture that the air temperature is not as critical to good adhesion as is the pavement temperature. A room-temperature pavement [22.8°C (73°F)] was used to simulate striping on warm pavements at times when the air may already be cool (as in the early evening). A range of air temperatures was used to determine the effects, if any, that cold air temperatures have on the adhesion of the thermoplastic material to the pavement and whether a specification of air temperature is necessary. In these tests all parameters except air temperature were kept constant.

The third step was to determine the effects of pavement temperatures on the adhesion of thermoplastic. The theory behind this type of failure is similar to that discussed above; that is, a high percentage of failures is related to cold pavements. The problem again is intensified on concrete pavements. The literature search showed that three organizations specify pavement temperatures [Oklahoma, which stipulates 4.4°C (40°F) and rising; the British Standards Institution, which specifies 5°C (41°F); and Texas, which specifies 10°C (50°F)]. The research was devised to demonstrate quantitatively a temperature at which thermoplastic should not be applied. Alleviation of unnecessary failures, whether by air-temperature or pavement-temperature specification, is of utmost importance in the conservation of monies and personpower.

The fourth aspect studied involved the effects of pavement moisture on the adhesion of thermoplastic to pavement. Much research has been conducted related to the time span necessary between the conclusion of a rainstorm and the application of paint stripes. Many agencies require a drying period of at least 48 h before paint application. On the contrary, there has been almost no research on the effects of moisture on the adhesion of thermoplastic. Early morning moisture also has been blamed as a cause of failure. The specification search showed that no agency specifies a drying period. The British specification does suggest that the pavement can be dried by flame if it is wet. If moisture has an effect on adhesion, most organizations are in need of a quantitative specification. The major difficulty lies in a method of measurement of the pavement moisture content.

TEST PROCEDURES

Because there were no practical tests available, the first step was to devise a bond-strength test to measure specifically the direct tensile strength of the adhesion of the thermoplastic to a substrate. The test was arranged so that the different adverse conditions could be measured quantitatively. This bond-strength test was the basic test of the research and was conducted on a test material and a test primer at both room temperature (22.8°C) and a freezing temperature [-17.8°C (0°F)]. The test material and the primer consisted of a commercial material and a primer extensively used in the field chosen to represent an average system common to most products in use today.

A brief description of the testing apparatus used is in order. The equipment was devised at the Texas Transportation Institute, originally to measure the tensile bond strength of concrete pavements (12). Later it was revised to accommodate the testing of the thermoplastic adhesion. The test uses the following components:

1. Portland cement concrete blocks, 8.9×19.1×39.4 cm (3.5×7.5×15.5 in), that have been sandblasted and conditioned for at least 24 h in a 22.8°C environment (Figure 1);
2. A thermoplastic patty form (Figure 2);
3. Six 5.1-cm (2-in) diameter cylinders (Figure 3);
4. The direct tensile tester (Figure 4), and
5. Epoxy cement glue or its equivalent.

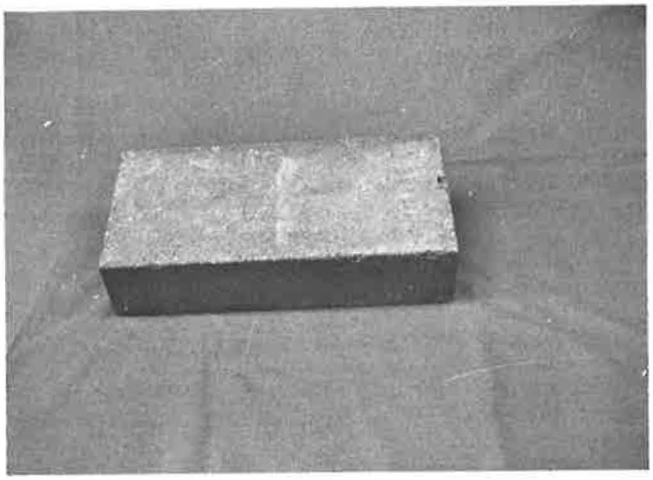


Figure 1. Test concrete blocks.

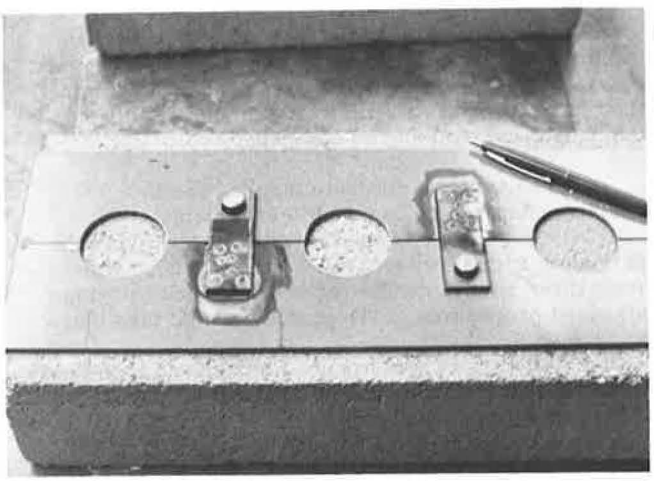


Figure 2. Thermoplastic patty form.

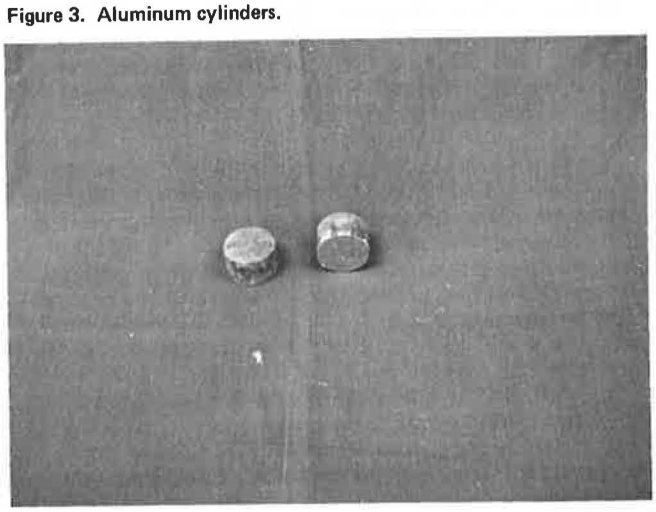


Figure 3. Aluminum cylinders.

The test procedure is as follows:

1. Heat the thermoplastic material to 204°C (400°F).
2. Apply the test primer at an approximate thickness of 0.005 cm (2 mils) and allow a 10-min curing time.

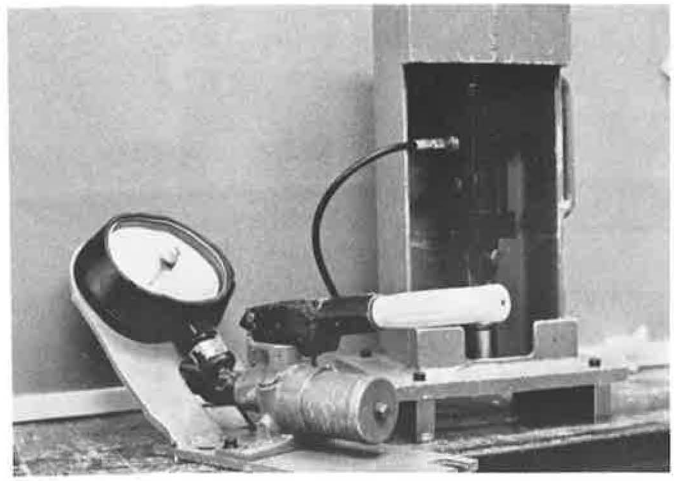


Figure 4. Bond-strength test apparatus.

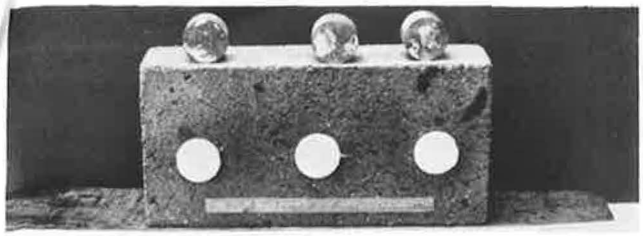
3. Remove the can of heated thermoplastic material and stir well.
4. Pour six 5.1-cm-diameter patties of the thermoplastic material into the patty form on the concrete blocks (three each on two separate blocks) and remove any excess material above the top of the form.
5. Allow to cure for 24 h.
6. Glue one of the 5.1-cm-diameter cylinders to each thermoplastic patty, taking care not to allow any epoxy to flow over the thermoplastic or removing any that does, and allow a proper curing time for the epoxy (24 h).
7. Cool one block in a -17.8°C environment for 24 h.
8. After the cooling period, test the bond strength of each patty—screw the coupler of the tensile tester into the metal cylinder and connect the coupler to the hydraulic cylinder; then apply a tensile stress to the thermoplastic at a loading rate of 890 N/min (200 lbf/min), which is equivalent to 518 kPa/min (75 lbf/in^2/min); and carefully note the pressure required to pull the material from the concrete.
9. Use the thermoplastic samples that have been subjected to normal (22.8°C) temperatures and repeat step 8.

In reporting the results, the tensile strength of the material was obtained by multiplying 0.375 (the effective area of the hydraulic cylinder) by the gauge reading obtained when the bond was broken and dividing the product by the square of the radius of the metal cylinder. The type of failure was noted as either epoxy, thermoplastic, bond, or concrete or any combination of them (see Figure 5). An epoxy failure was a failure of the epoxy to join the aluminum cylinder to the thermoplastic patty. A thermoplastic failure was a cohesive failure in the thermoplastic itself. A bond failure was an adhesive failure in the primer between the thermoplastic and the substrate. Finally, a concrete failure was the removal of a large piece of concrete.

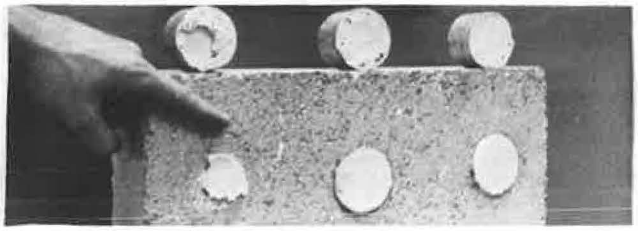
The test produced quantitative results that were for the most part reproducible. Many factors appeared to contribute to the inconsistency of the results, and the different types of failures made the analysis difficult. The concrete and thermoplastic failure showed adhesion in excess of the recorded value, and the use of this value as is would be conservative. The epoxy failures were felt to be laboratory-procedure errors. Fortunately, no real epoxy failures were encountered in the research.

After completion of the experimentation, it appeared that the time between application of the primer to the substrate and application of the thermoplastic was a

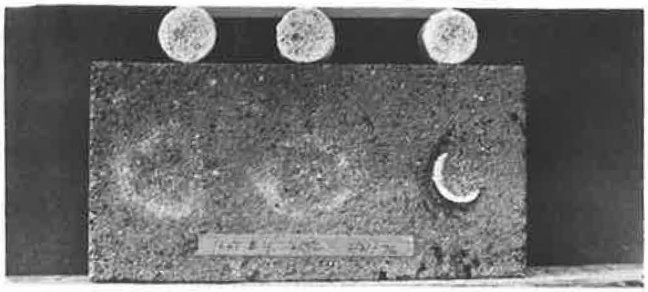
Figure 5. Types of failures.



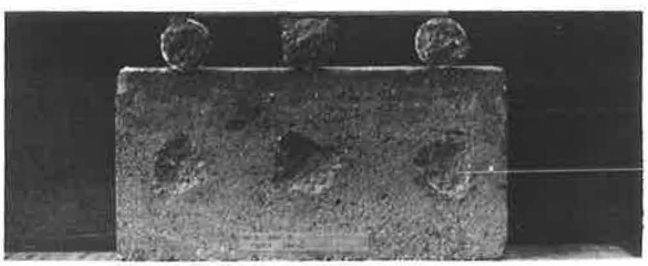
a. Epoxy Failure



b. Thermoplastic Failure



c. Bond Failure



d. Concrete Failure

critical factor. Time did not permit exploration of this factor. For the test results reported, a constant time of 10 min was used; however, any variations most likely contributed to the inconsistency of the results.

The following tests are all modifications of the bond-strength test designed to investigate the various specification criteria considered. The first test determined the effect of application temperature of the thermoplastic. It was important to decide the necessity of a thermoplastic application-temperature specification. The test procedure was as follows:

1. Prepare three concrete blocks in a 22.8°C environment for a minimum of 24 h.
2. Heat sufficient thermoplastic for nine bond-strength patties to a temperature of 162.8°C (325°F) and pour three patties using the test primer and recommended curing times.
3. Heat the remaining thermoplastic to 190.6°C (375°F) and pour three more patties.
4. Heat the remaining thermoplastic to 218.3°C (425°F) and pour the remaining three patties.
5. Allow the blocks to cure 24 h and epoxy the bond-test cylinders to the patties.
6. Wait an additional 24-h period and pull each patty, recording the bond strength, mode of failure, and temperature at which the patty was poured.

The second test was designed to determine whether the air temperature has any effect on the adhesion of the material and whether this factor should be included in a specification. The test procedure was as follows:

1. Condition three blocks in a 22.8°C environment for a minimum of 2 d.
2. Heat the test material to 204°C and apply the test primer to each block.
3. Remove the three blocks and place one in a -17.8°C environment and two in a 0°C (32°F) environment. Pour bond-strength patties immediately on each block.
4. Allow 1-h curing time and remove all blocks to a 22.8°C environment.
5. Test all patties for bond strength after a minimum curing period of 24 h.

A substitute for the air-temperature specification would be to specify a minimum pavement temperature. The following procedure was developed to determine the effects of pavement temperature on the adhesion of thermoplastic material to concrete.

1. Condition two concrete blocks, one in a 0°C environment and one in a 12.8°C environment.
2. Heat the thermoplastic material and apply the primer to each block and allow the set curing time. Pour three bond-strength patties per block following standard procedures. The pouring should take place in each environment.
3. Allow the blocks to cure for 24 h and then epoxy the bond-test cylinders to the patties.
4. Allow the epoxy to cure and then test each patty for bond strength (include the values of bond strength at 22.8°C found in the first test for reporting purposes).

Finally, a test was devised to determine whether a high moisture content of the concrete at the time of thermoplastic placement has an adverse effect on the bond of the thermoplastic to the concrete. The test procedure was as follows:

1. Place two concrete blocks in each of three different relative humidity (RH) environments (0, 58, and 95 percent RH). Record the block number and the RH of the environment in which it is placed. Stack the blocks with small wooden separator strips to permit full air circulation around them. Leave in the environment a minimum of 5 d.
2. Heat sufficient thermoplastic to 204°C for 18 bond-strength test patties.
3. Remove the concrete blocks from the RH environment. Wipe each lightly with a paper towel.
4. Wait 10 min, and then apply the primer and thermoplastic in accordance with the bond-strength test instructions.
5. After the thermoplastic has set (a minimum of 2 h), epoxy an aluminum test cylinder to each thermoplastic patty.
6. Place each block in the RH environment from which it came for an additional 24 h (to allow the epoxy to fully cure).
7. Remove one concrete block from each environment and place it in a -17.8°C environment.

8. After a minimum of 24 h, test and record the bond strength of each patty.

These procedures were the basis of the results reported below. It is realized that the tests have fallacies, but it is believed that the results reflect the general trends. From the results, quantitative solutions were obtained that can be used as specifications to ensure good thermoplastic adhesion to concrete pavements.

TEST FINDINGS

The initial objective of this research was to determine an

Figure 6. Effect of thermoplastic application temperature on adhesion.

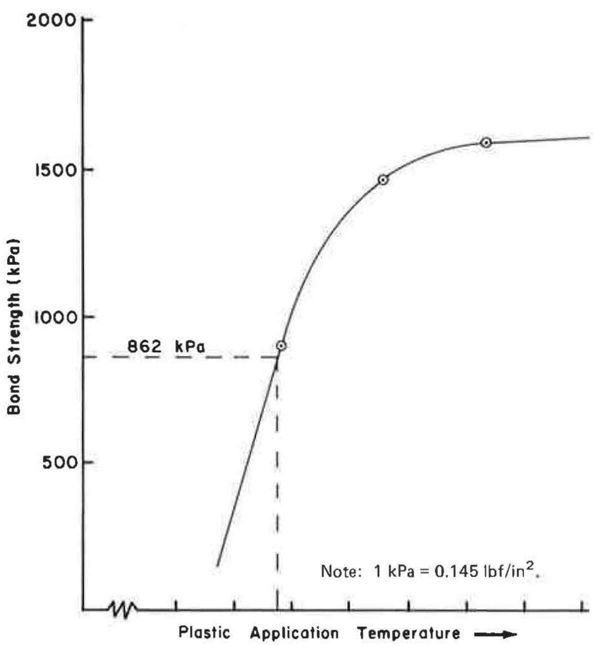
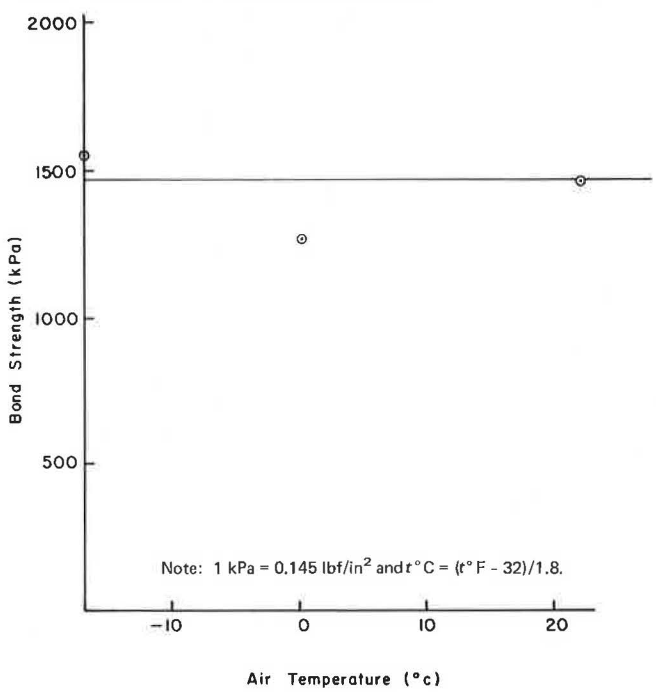


Figure 7. Effect of air temperature on adhesion.



acceptable value for the bond strength. The AASHTO and the California specifications recommend a minimum value of 1.24 MPa (180 lbf/in^2) whereas the ITE specification uses a minimum value of 1.03 MPa (150 lbf/in^2). As discussed above, many agencies report that the adhesion to bituminous pavements is sufficient but that adhesive losses are prevalent on concrete pavements. The first test procedure described above (bond strength) was conducted on the test thermoplastic and primer on both a concrete pavement and a bituminous pavement. The average bond strength for the samples tested at 22.8°C on the concrete pavement was 1.54 MPa (222 lbf/in^2) (see below) (1 MPa = 145 lbf/in^2).

Condition	Bond Strength (MPa)	Type of Failure
23°C (73°F)	1.52	Bond and concrete
	1.60	Bond and concrete
	1.50	Bond and concrete
-18°C (0°F)	1.42	Concrete
	1.66	Concrete
	1.19	Concrete
After five freeze-thaw cycles	0.283	Bond
	0.283	Bond
	0.103	Epoxy and bond

The bond strengths of the patties bonded to the bituminous surfaces reflected the strength of the substrate; all failures were failures of the pavements. A modification of the bond-strength test, called the freeze-thaw test, was conducted on the patties bonded to both concrete and bituminous pavements. A freeze-thaw cycle consisted of 8 h in a -23.3°C (-10°F) environment and 18 h in a 77.8°C (100°F) environment. The samples were subjected to five cycles of freeze-thaw. On completion of the cycles, the bond strengths were measured. The bond strength of the samples on the concrete pavement after the subjection to freeze-thaw cycles was only 221 kPa (32 lbf/in^2); the failures were mostly of the bond. Therefore, subjection to freeze-thaw cycles was identified as a critical factor in adhesive failures. The fact that, in most cases, thermoplastic placed on bituminous pavements performed well resulted in the testing of the bituminous substrate. After 5 cycles of freeze-thaw, the results were relatively consistent with previous bond-strength tests (see below).

Condition	Bond Strength (MPa)	Type of Failure
After five freeze-thaw cycles	0.931	Bituminous
	0.800	Bituminous
	0.772	Bituminous

An average bond strength of 834 kPa (121 lbf/in^2) was found; these failures were failures of the substrate. This reflected the fact that freeze-thaw cycles do not cause deterioration of the adhesion on bituminous pavements. Therefore, under the most critical condition, an adhesion greater than 834 kPa should be sufficient for good field service. Consequently, it is recommended that a value of 862 kPa (125 lbf/in^2) be used as a minimum specification criteria. This value was used to determine the minimum requirements reported here.

The second test was performed to determine the effect of the thermoplastic application temperature on the bond strengths. As can be seen from Figure 6, the curve shows a sharp increase in bond strength with only slight temperature changes. The minimum value for 862 kPa is approximately 189°C (373°F). The curve shows no upper limit. The top limiting factors would be the temperature at which the thermoplastic could still be extruded or sprayed and the temperature at which the components would not break down. The curve does show a leveling off between 216°C and 232°C (420°F and 450°F). The test demonstrates that adhesion can be enhanced greatly by proper application temperatures. Furthermore, a designated range should be included in a specification according to the desired adhesion. A set range for all materials is not feasible. Therefore, a range should be set by using the test procedure described, and field compliance should be insisted upon.

The third test determined the effect of air temperatures on the adhesion of the thermoplastic. Figure 7 shows that, although there is slight inconsistency, air temperatures have almost no effect on the adhesion.

Figure 8. Effect of pavement temperature on adhesion.

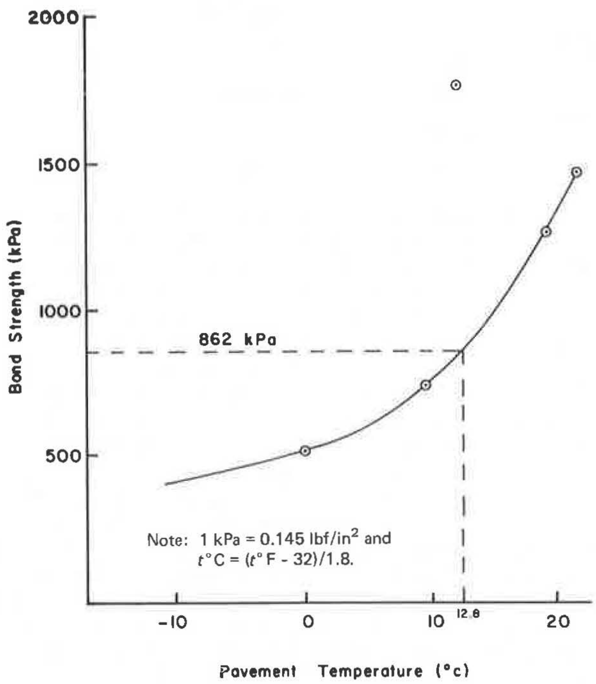
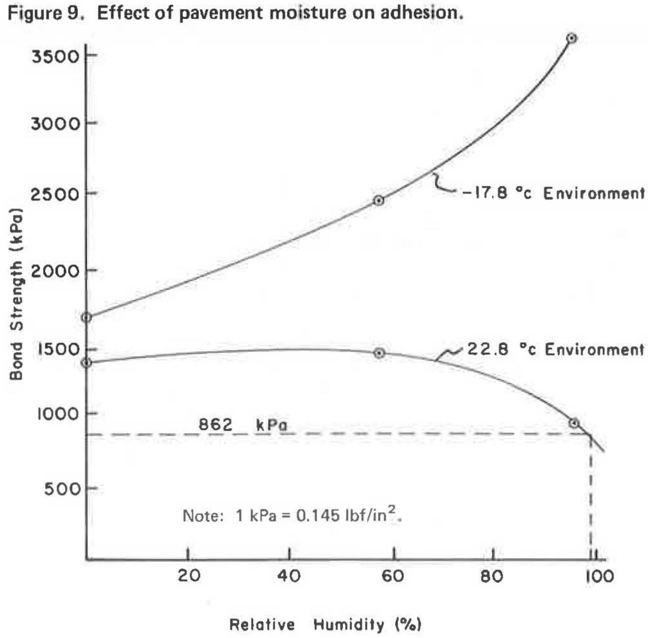


Figure 9. Effect of pavement moisture on adhesion.



The minimum value of 862 kPa is well below even the lowest value found. Consequently, it is believed that an air-temperature specification is unwarranted and could even be detrimental to the adhesion if relied on. The air temperature can be above the minimum when the pavement temperature is still very low (early morning), which would result in poor adhesion.

The fourth test demonstrated the necessity for a pavement-temperature specification to replace the air-temperature specification. Figure 8 shows a definite increase in the bond strengths of thermoplastics applied at pavement temperatures greater than 7.2°C (45°F). Values obtained at temperatures of 12.8°C (55°F) were consistently greater than 1379 kPa (200 lbf/in²), but values at temperatures greater than 15.6°C (60°F) were lower. This phenomenon was unexplainable. Consequently, the curve was drawn through the minimum points to obtain a conservative estimate of the minimum temperature effects. For a minimum bond strength of 862 kPa, a value of 12.8°C (55°F) was obtained. Thermoplastic should not be applied to pavements at temperatures less than 12.8°C and, as can be seen, the warmer the pavement, the greater the adhesion. When possible, warmer pavements should be sought; however, for specification purposes, a minimum value of 12.8°C is recommended.

Finally, the effects of pavement moisture on adhesion were tested. The test was run in both a 22.8°C environment and a -17.8°C environment. As seen below and in Figure 9, the minimum bond strength for the cold environment is 1662 kPa (241 lbf/in²), which is well above the 862 kPa minimum.

Condition	Relative Humidity (%)	Bond Strength (MPa)	Type of Failure
23°C (73°F)	0	1.32	Thermoplastic
		1.34	Concrete and bond
		1.37	Concrete and thermoplastic
	58	1.46	Bond
		1.14	Bond
		1.71	Bond
	95	0.883	Bond
		0.772	Bond
		1.01	Bond
-18°C (0°F)	0	1.63	Concrete
		1.45	Concrete
		1.92	Concrete and bond
	58	2.22	Thermoplastic
		2.77	Concrete
		2.43	Thermoplastic
	95	3.62	Thermoplastic
		3.44	Thermoplastic
		3.62	Thermoplastic

The moisture in the block tended to increase the bond strength under freezing conditions but, on thawing, the bond strength is reduced. The second curve demonstrates that there is a reduction in adhesion with an increase in the relative humidity at 22.8°C. The lowest value, 889 kPa (129 lbf/in²), occurs at a relative humidity of 95 percent and is thus still above the acceptable minimum of 862 kPa. It is recommended that thermoplastic not be applied to a wet surface.

CONCLUSIONS

This research has investigated the effects of four important specification criteria on the adhesion of thermoplastic materials to concrete pavements. The graphs generated from the data illustrate the various temperatures and conditions necessary to obtain maximum adhesion. Also, minimum criteria are set that should be included in a specification for application of thermoplastic materials.

When conducted on a bituminous surface after five freeze-thaw cycles (the critical situation that is succeeding in the field), the basic bond-strength test resulted in a substrate strength of 834 kPa. From this, a value of 862 kPa was determined as the minimum bond strength that will ensure an effective life.

Secondly, a thermoplastic application temperature range was deemed important and it was determined that the range should be small. For the test material and primer, the minimum temperature was determined to be 189°C and the desirable range for maximum adhesion to be 216°C to 232°C. It is recommended that a range be included in a specification and that the range should be determined by the test method described above for the material being used. The test is simple and requires very little time. As the curves show, if the material is applied at too low a temperature, the adhesion is very poor. Therefore, a range should be set and complied with in the field.

The air temperature was determined to be irrelevant to adhesion of the thermoplastic to the pavement. For this reason, a specification should not include an air-temperature criterion but should substitute a pavement-temperature criterion.

The pavement temperature was probably the most important aspect studied. It was found that pavement temperatures are quite critical to good adhesion. At the minimum bond strength, a pavement temperature of 12.8°C was reported. This value is recommended as a minimum pavement-temperature specification. When possible, thermoplastic material should be applied to warmer pavements because this enhances the adhesion.

Finally, it was found that only under wet conditions does pavement moisture affect the adhesion. Only at 98 percent RH does the bond strength drop below the minimum acceptable value. Therefore, it is suggested that a specification should state that the pavement should be dry to the satisfaction of the inspecting engineer.

The use of thermoplastic striping "has practically doubled since 1965" (3). The system has many advantages relating to the safety of the driver and, if the early failures can be avoided, it will become a more important tool for the transportation engineer. It is believed that these specification recommendations are a step forward in reducing the losses of thermoplastic striping systems on concrete pavements. The curves presented here are a basis for determining the adhesion that can be expected under various conditions, and the test procedures provide an excellent means of obtaining quantitative data.

ACKNOWLEDGMENT

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Acceptance Sampling of Structural Paints

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An investigation of acceptance sampling procedures for structural paints is described. The general paint manufacturing process was briefly reviewed, and historical data on frequency of rejections under specifications formerly in use in New York State were analyzed, resulting in some