Early Strength of Concrete Patching Materials at Low Temperatures

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Winter repair and maintenance operations of concrete bridge decks and pavement require high early strength patching materials suitable for application at subfreezing temperatures. An extensive experimental program at Rutgers University has identified four generic materials as potentially suitable to fulfil this role. Early strength tests included compressive cylinder strength of patching material and slant shear bond strength to existing concrete at 1 day and 7 days, and static and fatigue flexure strength of patched specimens at 7 days. All patch materials were cast and cured at temperatures of 15°F to 20°F. The four generically distinct materials identified were: *(a)* a methyl methacrylate-based material, *(b)* two types of magnesium phosphate-based materials, and *(c)* a polyurethane binder. Early strengths ranged from 1,700 psi to more than 8,000 psi. Slant shear bond strengths ranged from 2,000 psi to more than 5,000 psi. Flexural strengths, both in static and fatigue loading, are also suitable, with most materials displaying performance comparable to that of the control (unpatched) specimens. Flexure test results, however, are highly variable. The causes of this variability and ways of reducing it need further investigation.

With national resources being increasingly devoted to repair and maintenance of deteriorating infrastructure, considerable saving could be achieved through continuous, year-round operations. Such year-round operations require the availability of fast-setting, high early strength patching materials, suitable for application under largely varying weather conditions, including subfreezing winter temperatures.

Substantial advances have been made in recent years in the development of fast-setting, high-performance patching materials *(1)*. Research and experience with these materials has, however, been largely limited to mild temperatures. Reported results of low temperature application, scarce as they are, have been largely disappointing *(2, 3)*. The investigation reported in this paper forms part of a project sponsored by the New Jersey Department of Transportation and FHWA aimed at identifying and evaluating concrete patching materials suitable for cold-weather application. The literature survey portion of the project indicated that a large number of commercially available materials may be suitable for such application *(1)*. In the absence of adequate information on low temperature application, it was found necessary to split the investigation into a number of stages. The study presented in this paper is concerned primarily with strength aspects of the first two stages. In the first stage, 17 candidate materials were screened for early strength development at low temperatures. Four generic materials performed well in the screening stage and were selected for the second stage, at which they were tested for a number of performance criteria at the small-scale specimen level. The two stages are presented sequentially in the sections that follow.

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SCREENING TESTS

Materials

As mentioned earlier, a large number of materials emerged from the literature survey as potentially suitable for cold-weather application. These materials can be grouped under three categories: portland cement-based, polymer-based, and non-portland cement-based materials.

Portland Cement-Based Materials

Portland cement concretes are modified in some way to adapt them to low temperature applications. The modification may be of the cement itself or of the fresh concrete through the addition of admixtures, or a combination of the two methods. In addition to cold-weather application, concrete for pavement patching involves set acceleration. Set acceleration is often an exothermic process and may help prevent premature freezing. Some accelerating admixtures (e.g., calcium chloride) may also have an antifreezing effect.

Modified portland cements include high early strength cement (Type III), regulated set cement, and shrinkage-compensating cement *(3–5)*. The relevance of the latter in patching concrete may be for improving bond to existing concrete.

Admixtures may include, in addition to air-entraining and water-reducing agents, accelerating-antifreezing and other early strength promoting materials (e.g., silica fume). Of the accelerating-antifreezing agents, the most commonly used is calcium chloride ($CaCl_2$). The effect of this agent on corrosion is still controversial. In the United States its content is generally limited to 2 percent or less *(6)*. For calcium chloride to be effective on its own, without heating, substantially higher contents are required. Most of the experience with high calcium chloride contents comes from the Soviet Union *(7)* with supporting evidence from the U.S. *(8)*. Other antifreezing agents were used by the Soviet group *(7, 9)*, particularly sodium nitrite ($NaNO_2$). The latter, however, does not have an accelerating effect.

Various proprietary admixtures are available for cold-weather application that contain various active ingredients *(10)*, but actual experience and test data at subfreezing temperatures are very scarce.

Some polymer modifiers are accompanied by exothermic reactions, which could have a freeze-retarding as well as a water-reducing effect *(11)*. Polymerization, however, is usually retarded at low temperatures.

Polymer Concrete

The binding agent for the aggregate in polymer concrete is a polymer rather than portland cement. Polymer concretes, because they do not contain water, are not subject to frost damage. Low temperatures can, however, affect their setting rate and other physical properties.

The most widely used and tested polymer concrete is methyl methacrylate (MMA) based *(12)*, but only one source reports a sub-freezing application, which was unsuccessful *(13)*. Other polymers for use as binders in polymer concrete include polyester, epoxies, and polyurethane *(14)*. Some tests at low temperatures were carried out on these polymers *(14)*, with encouraging results reported for polyester and polyurethane, but epoxies do not set well at sub-freezing temperatures.

Non-Portland Cements

Most prominent among non-portland cements is magnesium-phosphate cement *(3, 15)*. Other materials are based on calcium aluminate (high alumina cements), gypsum, and various commercial products of undisclosed composition *(1)*.

Test Procedure and Results

Seventeen materials were obtained from manufacturers and tested under the screening tests program. The materials are listed generically (with results and comments) in Table 1 under their respective groups. Some fast-setting materials, particularly water based, may require short-term heating to accelerate setting and prevent premature freezing. A heating method was developed to accommodate such options, employing 0.75 percent to 1 percent steel fiber reinforcement and a low voltage power source *(16)*. The fibers act as a conductor/resistor for the electric current, which can be adjusted to provide the required amount of heating. Heating was employed only for compressive strength test specimens. As heating did not produce significantly better results, it was not used for specimens cast subsequently (see Table 1).

All specimens were 4- × 8-in. cylinders cast and maintained at ambient temperatures of 15°F to 20°F. The cylinders were tested for compressive strength at 24 hr after casting. Ordinary portland cement mixes were based on a standard mix (see the Specimen Tests section of this paper for details). Commercial products were prepared in accordance with manufacturers' instructions.

Results of the screening tests are presented in Table 1 for both heated and non-heated specimens. It can be observed that none of the portland cement-based mixes produced adequate strength at 24 hr. Of the polymer concretes, methyl methacrylate- and polyurethane-based materials performed well. The polyester-based material, although possessing adequate strength, performed poorly by other criteria, having poor workability, high shrinkage, and a strong odor. This material was, therefore, omitted from the second phase. In the non-portland cement materials group, the magnesium phosphate-based products performed well.

SPECIMEN TESTS

Materials

Based on results of the preliminary screening tests, five products, representing four generically distinct materials, were se-

TABLE 1 SCREENING TEST RESULTS

	24 hr Compressive Strength (psi)		Comments
	Non-Heated	Heated	
Portland Cement Admixtures			
1. $CaCl_2$ (1–4%)	Did not set	NA	
2. Proprietary	Did not set	Did not set	
3. Proprietary	Did not set	Did not set	
4. Proprietary	Did not set	Did not set	
5. Proprietary	Did not set	Did not set	
6. Regulated Set	Did not set	450	
Polymer Concrete			
7. Polyester	2,000	NA	Strong odor, low workability
8. MMA	3,900	NA	Strong odor, good workability
9. MMA	3,600	NA	Strong odor, good workability
10. Polyurethane	1,760	NA	Very fast set, low elastic modulus, disposable utensils required
Non-Portland Cements			
11. Magnesium phosphate (water-based)	3,000	NA	Good workability
12. Magnesium phosphate (non-water-based)	1,600	3,800	Mild odor, good workability
13. Calcium aluminate	760	1,000	
14. Proprietary	Did not set	Did not set	
15. Proprietary	Did not set	Did not set	
16. Proprietary	Did not set	Did not set	
17. Proprietary	Did not set	517	High shrinkage

NOTE: NA = not applied.

lected for further investigation at the specimen level. These materials are designated as follows:

- M_1, M_2 Methyl methacrylate-based polymer concrete (Nos. 8 and 9, respectively, in Table 1). M_1 and M_2 are nominally equivalent products produced by two different manufacturers.
- P_1 Water-based magnesium phosphate (No. 11 in Table 1).
- P_2 Non-water-based magnesium phosphate (No. 12 in Table 1).
- U Polyurethane polymer concrete (No. 10 in Table 1).

The specimens themselves, representing existing or parent concrete, were cast of a standard mix using ordinary portland cement, ASTM Type III. Weight proportions of cement to sand to coarse aggregate were 1:2.45:1.63. The water-cement ratio was 0.45 and the coarse aggregate was 3/8 in. crushed basalt. An air-entraining agent was used with the air content, as measured by the pressure method (ASTM C231-82), ranging from 5.5 to 7 percent by volume. Slump ranged from 1 to 4 in.

Testing Program

Strength of patching materials involves two distinct types of strength: *(a)* the strength of the patching material itself, and *(b)* the strength of the bond of the patching to the parent material. In the context of bridge and pavement materials, strengths under two types of loads are of interest, namely, static (or slow) loading, and cyclic or fatigue load. Finally, the loading mode affects the measured response. Two loading modes are of particular interest—direct compression and flexure. The experiment was designed to include all these aspects of strength measurement as a basis for comparison of the five materials selected.

Two distinct specimen geometries were adopted to accommodate the various strength tests indicated above. Direct compression tests were performed on cylindrical specimens whereas flexure tests employed prisms. In all, four experiments were carried out as follows:

Cylinder Tests

- Compression on neat patch material
- Slant shear of patched specimens

Flexure Tests

- Static loading of patched specimens
- Cyclic (fatigue) loading of patched prisms

In order to assess the effect of patch geometry on the flexural strength of patched specimens, three patch depths were included in the investigation (Figure 1): a shallow depth (approximately 0.10 of the specimen's depth), half depth and full depth. The effect, if any, was expected to be particularly relevant to bond strength. Some age effect was included in the cylinder tests, which were performed at 24 hr and at 7 days after casting/patching. Flexure tests were all performed at the patch age of 7 days. By way of summary, cylinder tests (Experiments 1 and 2) can be considered as factorial experiments of two factors—material and age—at five (this was later augmented to seven) and two levels, respectively. The flexure tests are also factorial experiments of two factors—material and patch depth—at five and three levels, respectively.

Procedure

Specimen Preparation

Specimens were cast of the standard mix over a period of 6 months. Specimens consisted of 4 × 8 in. cylinders and 3- × 3- × 14-in. prisms, with the patch of 7-in. long by the appropriate depth blocked out. Some full prisms were cast as controls. Prism specimens were reinforced with two No. 3 bars (Figure 1). Specimens were cured for 7 days under plastic cover and then stored in air in the laboratory for a minimum of 3 months before patching and testing operations took place. This procedure ensured mature concrete with time and maturity effects expected to be negligible [Figure 2 shows the test setup of the prisms]. Cylinders were taken from some batches for 28 days of moist curing and testing of compressive strength.

Cylinder Tests

Cylinder specimens for slant shear tests were diamond cut at 45 degrees to their axis (Figure 3), each cylinder producing two half cylinders for parent material. In all, twelve 4- × 8-in.

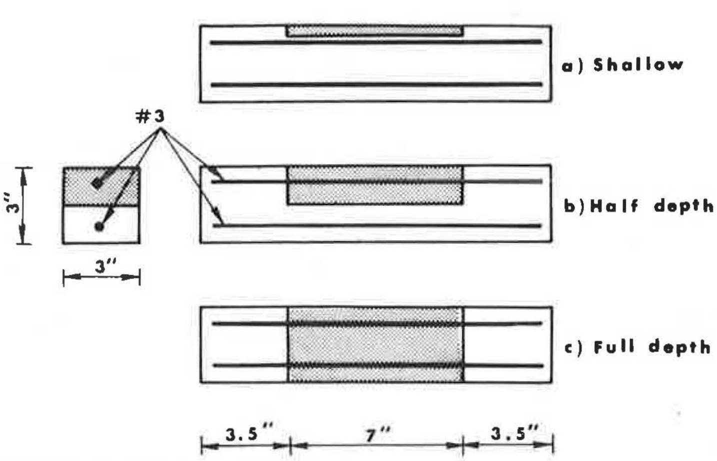

FIGURE 1 Flexure specimens.

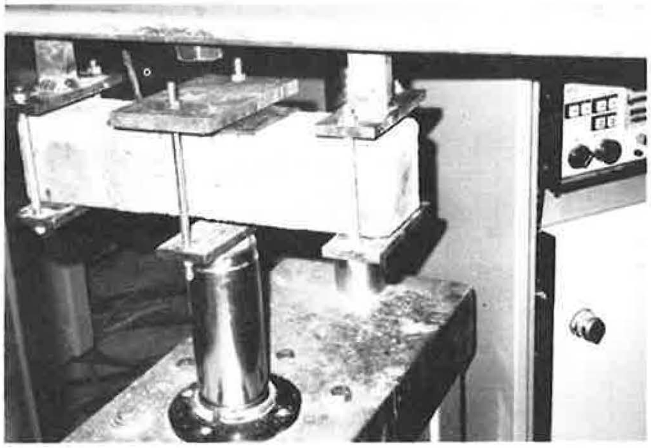

FIGURE 2 Flexure test setup.

cylinders were cast of each patching material, six full and six half cylinders cast over the diamond-cut surface of the parent concrete.

All cylinders were cast in a temperature-controlled room at temperatures of 15°F to 20°F. Patch mixes were prepared in accordance with manufacturers' instructions, where applicable. Magnesium phosphate materials were prepackaged and cast as received. Methyl methacrylate may be cast with or without coarse pea gravel added to the sand containing prepackaged material, depending on patch depth. Accordingly, two sets of cylinders were cast of each of the two MMA-based materials—one with and one without $^3/_8$-in. pea gravel, thus augmenting the number of materials tested by two. The gravel-containing mixes are denoted M1(G) and M2(G) to distinguish them from the non-gravel-containing mixes of M1 and M2, respectively. The polyurethane binder is a low-viscosity liquid that is poured over the preplaced aggregate ($^3/_8$-in. pea gravel).

Three cylinders of each specimen type were tested in compression at 24 hr and at 7 days after casting and curing in the cold room for the full period. Specimens were allowed to thaw for 1 to 2 hr before testing in order to maintain uniform conditions during the test.

Control cylinders of the parent concrete were tested at 28 days moist cured. Other cylinders were cured with the specimens and tested simultaneously with flexure tests to assess the actual strength of the parent concrete at the time of the tests.

Flexure Tests

Casting procedure for flexure specimens was similar to that of cylinders. Patches were cast in the cold room and stored there for 7 days. Shallow patches of MMA materials contained only sand. Half- and full-depth patches also contained $^3/_8$-in. pea gravel. Shallow, polyurethane patches contained no aggregate whereas half- and full-depth patches contained $^3/_8$-in. pea gravel.

Static tests consisted of loading the specimen at a constant rate of deflection (stroke controlled) to failure. The full load-displacement curve and the failure mode were recorded (see Figure 2). Fatigue tests were carried out in the same test frame. Load was cycled between 250 and 1,750 lb (approximately 0.06 to 0.5 of the ultimate load) at 10 cycles/sec. Ultrasonic pulse velocity readings were taken before testing and after

(a)

(b)

(c)

FIGURE 3 Typical slant shear failure modes: (a) bond failure, (b) materials failure, and (c) combined failure.

30,000 cycles to assess the extent of cracking (see Figure 4). Cycling was then continued to failure or to 1 million cycles, whichever occurred first. Because of the time-consuming nature of this experiment, flexure tests were not replicated—one specimen only was tested of each material or patch configuration.

Test Results

Cylinder Tests

Table 2 presents results of compressive strengths and slant shear bond strengths for the seven patching materials. Failure modes of slant shear tests are also indicated. The three failure modes—bond failure, material failure (parent or patching) and the combined mode—are illustrated in Figure 3. The results are presented graphically in Figures 5 and 6. The error bars shown are the standard deviation and indicate the variability of the results.

It can be observed that all materials possess adequate strength. Slant-shear strengths are generally lower than com-

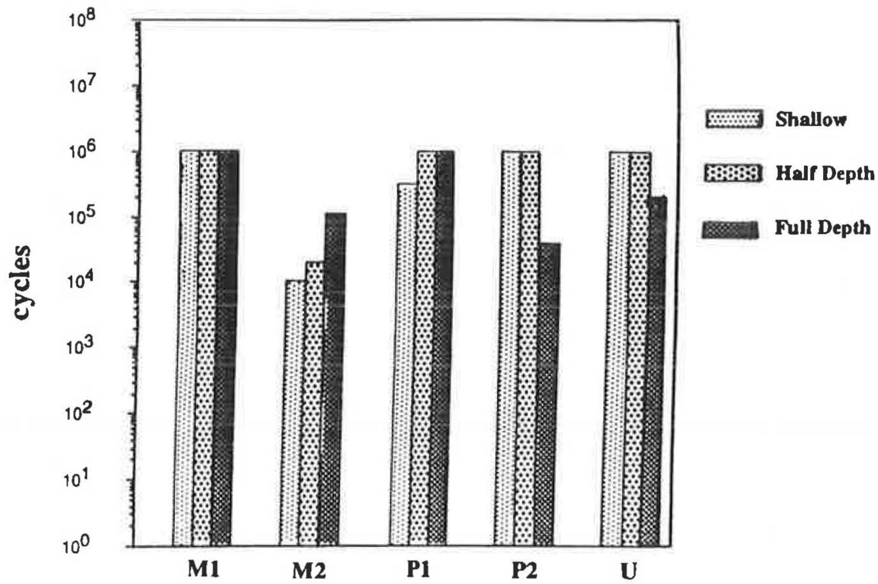

FIGURE 4 Fatigue test results.

TABLE 2 CYLINDER TEST RESULTS

Material	Compressive Strength (psi) Material 1 day	Compressive Strength (psi) Material 7 days	Compressive Strength (psi) Parent (28 days)[b]	Slant Shear Strength (psi) and Failure Mode (F.M.)[a] 1 day	F.M.	7 days	F.M.
M1	9788	7918	3541	4138	PC	3661	PC
	9828	8475	±261	4019	PC	3820	PC
	9828	8037		4536	PC	3700	PC
M1(G)	6605	7003	4806	4456	PC+B	5252	PC
	6486	8117	±981	5411	PC	5133	PC
		7878		4456	PC+B	5889	PC+B
M2	6923	6287	3385	4218	PC	3700	B
	6525	6326	±224	5650	B	3899	B
	7043	6366		3581	B	3661	B
M2(G)	4775	5610	4070	4297	PC	5133	PC
	4934	5531	±524	4536	PC+PM	5411	PC+PM
	4775	5570		4456	PC	5093	PC
P1	6923	7639	3578	2984	B	4934	B
	6724	7242	±250	2149	B	5262	B
	6366	7162				4257	PC
P2	4615	4775	3501	3820	PC+B	4576	PC
	4536	5769	±236	2467	PC+B	3979	PC+PM
	4775	5411		3342	PC+B	3479	PC+B
U	1671	2984	4505	2109	B	2546	PC+PM
	1870	2865	±648	2149	B	2905	B
	1751	2865		2069	B	2825	B

[a]PM = patch material, PC = patent concrete, B = bond.

[b]Mean ± standard deviation of siz sets of 3 cylinders taken from parent concrete batches used in slant shear tests.

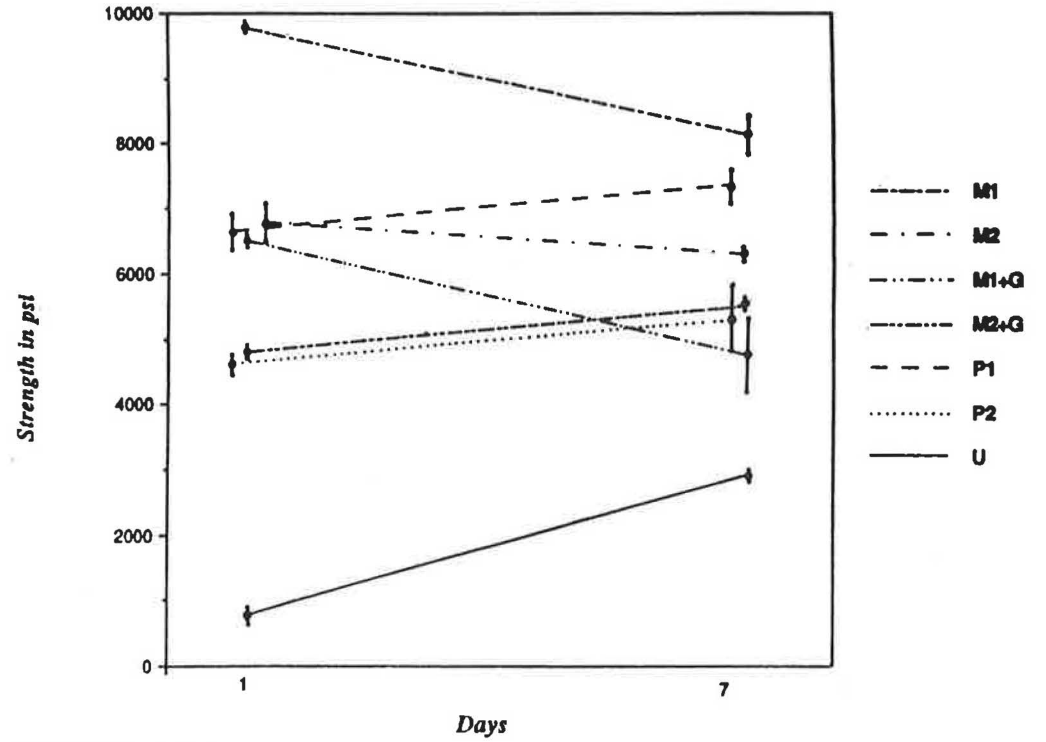

FIGURE 5 Cylinder test results: compressive strength.

pressive strengths, with gravel-containing MMA-based material having somewhat higher strength than the magnesium phosphates. The behavior of MMA-based materials is noteworthy.

- Gravel-containing mixes have higher slant-shear strength but lower compressive strength than the plain mixes.
- While there is generally an increase in strength with age, plain MMA mixes appear to shed strength with age.
- There is considerable difference between the two MMA compounds, with M1 being clearly superior to M2.

These aspects will be further examined in the discussion that follows.

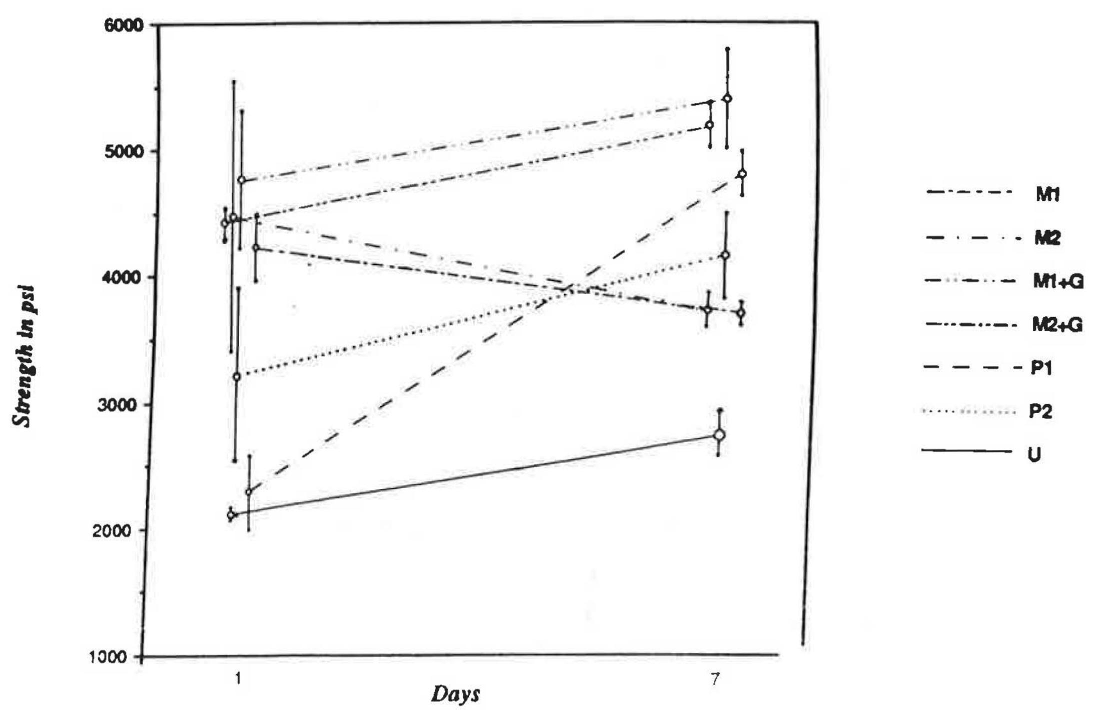

FIGURE 6 Cylinder test results: slant shear.

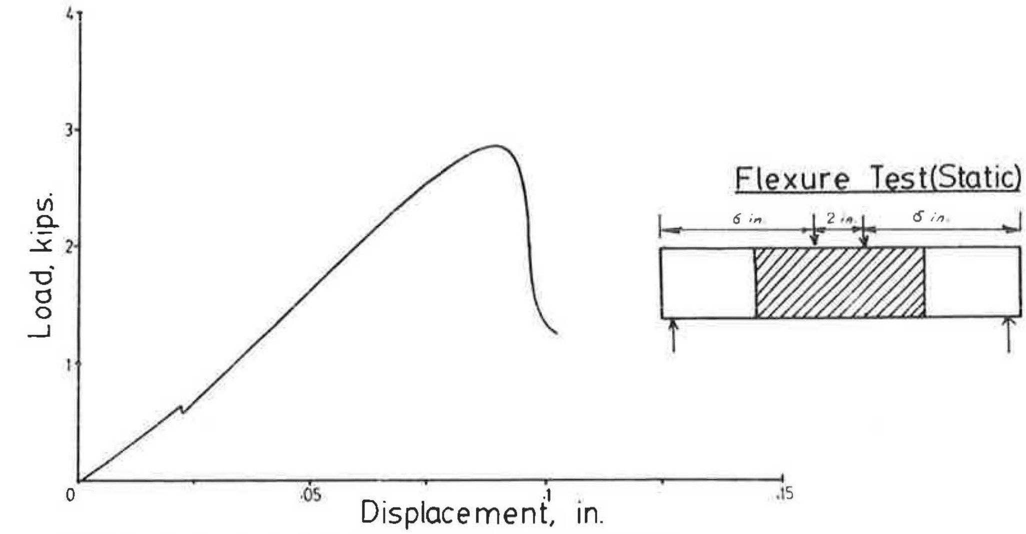

FIGURE 7 Typical flexure load-displacement curves: static load.

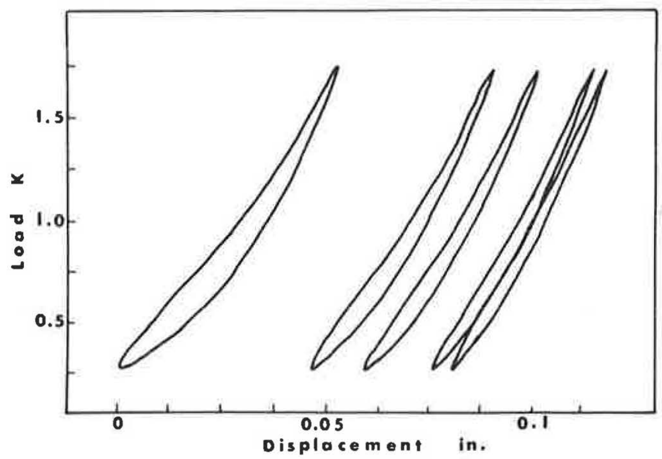

FIGURE 8 Typical flexure load-displacement curves: cyclic load.

Flexure Tests

Figure 7 displays typical load deflection curves of statically loaded and Figure 8 those of cyclic-loaded specimens. Failure was often initiated by tensile bond failure at the patch-parent boundary, followed by a shear failure. No delamination of patches (particularly shallow patches) was observed.

Results of the static tests are presented in Table 3 and in Figure 9. The cyclic tests are presented in Table 4 and in Figures 4 and 10. Figure 5 presents the results in terms of number of cycles to failure. Figure 10 presents the results in terms of the change in dynamic modulus, as measured by ultrasonic pulse velocity after 30,000 cycles as compared to the value before testing. The maximum change in dynamic modulus, which is proportional to the square of the pulse velocity, is given in Table 4 and in Figure 10. The maximum change in

TABLE 3 STATIC FLEXURE TEST RESULTS

Material	Depth[a]	Pu(kips)[b]	f'c(psi)[c]	Failure Mode[d]
M1	S	2.6	6,700	B+S
	H	4.4	5,900	B+S
	F	4.2	6,450(+)	B
M2	S	3.3	5,700	F+S
	H	3.1	5,700	B+S
	F	3.9	6,800	B+S
P1	S	3.6	5,500	S
	H	4.1	5,900	F+S
	F	3.9	6,960	B+S
P2	S	3.45	5,900	F+S
	H	2.7	5,500	B+S
	F	2.7	6,300	B
U	S	3.4	5,650	B+S
	H	3.5	5,700	B+F
	F	2.7	5,050	B
Control		4.0	5,100(+)	F+S
		4.3	6,100	F+S
		3.9	7,200(+)	F+S

NOTE: (+) 28 days moist cured cylinder.
[a]Patch depth: S = shallow, H = half depth, F = full depth.
[b]1 kip = 1,000 lb.
[c]Cylinder compressive strength of parent concrete cured with specimen.
[d]B = tensile bond, F = flexure, S = diagonal shear. The latters in combined modes appear in sequence of occurrence.

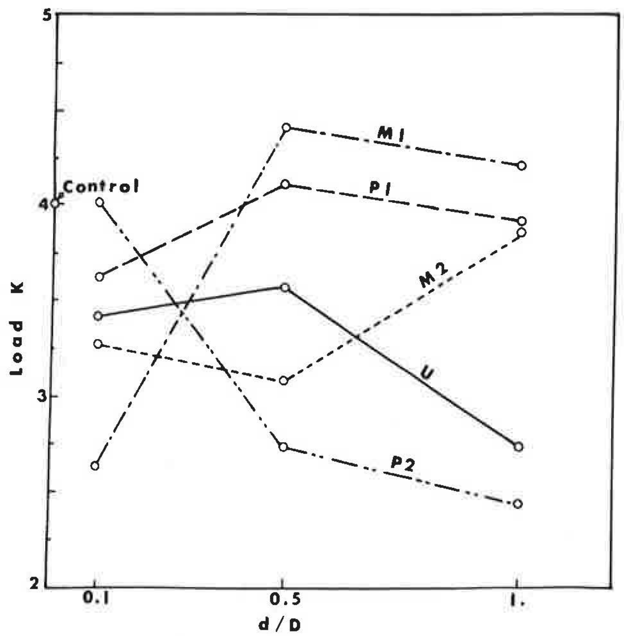

FIGURE 9 Static flexure test results.

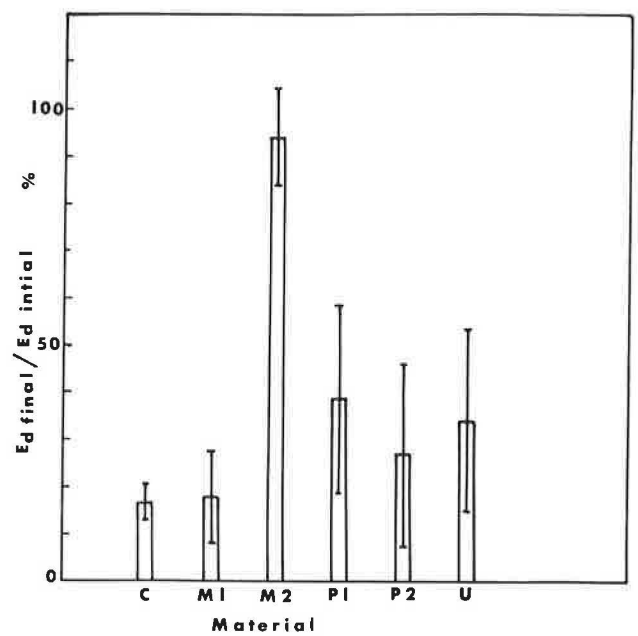

FIGURE 10 Reduction of dynamic modulus of fatigue specimens after 30,000 cycles.

velocity is the best indication of a major crack, but it should be noted that the presence of reinforcing bars makes the detection of cracks difficult. In Figure 10, results for the three patch geometries of each material were combined, since patch geometry would not affect patch-parent cracking significantly and no such effect was observed in the results. This allows for error estimate as shown by the error bars in Figure 10.

It can be observed that the results, particularly of the cyclic tests, are highly variable. The effect of patch geometry, if any, is not apparent. The general pattern, however, is clear and in general agreement with the cylinder tests. Again, M1 appears to be superior to other materials, followed closely by P1. The difference between the two methacrylates is even more pronounced than in the cylinder tests. M2 performed particularly poorly in the fatigue tests as compared to the other materials.

Analysis and Interpretation of Test Results

Cylinder Tests

The results of cylinder tests are presented in Tables 5, 6, 7 and 8 for the compressive strength and slant shear tests, respectively. Tables 5 and 7 present the means and standard devia-

TABLE 4 CYCLIC FLEXURE TEST RESULTS

Material	Depth[a]	$(\Delta E_d/E_d)_{max}$ 30,000 Cycles[b]	Maximum No. of Cycles	Comments
M1	S	15	10^6	Bond, flexure cracks
	H	9	10^6	No cracks
	F	28	10^6	No cracks
M2	S	100	11.4×10^3	Bond-shear failure
	H	100	20.5×10^3	Bond-shear failure
	F	81.5	108.5×10^3	Bond failure
P1	S	37	330.0×10^3	Bond-shear failure
	H	18.5	10^6	No cracks
	F	24	10^6	No cracks
P2	S	10	10^6	Bond, flexure cracks
	H	45	10^6	No cracks
	F	24	42.8×10^3	Bond failure
U	S	52	10^6	Flexure cracks
	H	33.2	10^6	No cracks
	F	13.8	204.6×10^3	Bond failure
Control		17.5	10^6	Flexure cracks
		13.9	10^6	Flexure cracks
		23.9	10^6	Flexure crack

[a]S = shallow, H = half depth, F = full depth.
[b]Maximum change in dynamic modulus: $(\Delta E_d/E_d)_{max} = \max[(upv_{initial})^2 - (upv_{final})^2]/(upv_{initial})^2$.
upv = ultrasonic pulse velocity.

TABLE 5 COMPRESSIVE STRENGTH ANALYSIS OF RESULTS

Material	Age: 1 Day	Age: 7 Days	Row Mean
M1	9,815 ± 23	8,143 ± 293	8,979
M1 (G)	6,545 ± 84	7,666 ± 586	7,106
M2	6,830 ± 271	6,326 ± 40	6,578
M2 (G)	4,828 ± 92	5,570 ± 40	5,199
P1	6,671 ± 282	7,348 ± 255	7,014
P2	4,642 ± 122	5,318 ± 503	4,980
U	1,764 ± 100	2,905 ± 689	2,334
Column mean	5,871	6,138	
		Overall mean	6,027

tions of the observations of Table 2, in the form of two-way tables. The row and column means indicate the effect of material and age, respectively. Tables 6 and 8 present the analysis of variance of the results. The F test of significance yields very high significance (at less than 1 percent level) for both age and material effect and for their interaction in both experiments. The strong interaction means that the effect of one factor (e.g., material) depends strongly on the level of the other (e.g., age). This strong interaction is due largely to the anomalous behavior of M1 and M2 without gravel, namely, the reduction in strength with age. The interaction is apparent in Figure 5 by the out-of-parallel of curves for different materials. If the two plain methacrylates are ignored, the interaction becomes small and the row means of Tables 5 and 6 provide a good comparison of material performance. Ignoring the M1 and M2 behavior is justified on the grounds that the methacrylates are not used without gravel except in very shallow patches, where the material behavior is not well represented by a cylindrical specimen. Since all materials possess adequate strength, the slant-shear tests are the more interesting of the two experiments for comparison of performance. Table 6 yields the following grading of performance in descending order: M1(G); M2(G); and P2-P1, U. This grading is, roughly, in agreement with failure modes observed in Table 2 (ascending number of bond failures).

Flexure Tests

Static Loading The results for the ultimate static load of patched specimens (Figure 9) show very high variability in behavior, expressed as strong interactions between material and patch depth. The low result for shallow patch of M1 is particularly surprising because shallow patches are not expected to have much effect on the static load behavior as they are entirely

TABLE 6 ANALYSIS OF VARIANCE FOR TABLE 5

Source of Variation	Sum of Square ($\times 10^6$)	Degrees of Freedom	Mean Square ($\times 10^6$)	Significance F	Significance $F(0.01)$
Material	159.4	6	28.47	421	3.56
Age	1.029	1	2.923	43.2	7.68
Interaction	9.598	6	3.493	51.6	3.56
Residual	1.894	27	0.06764		
Total	171.921	40			

TABLE 7 SLANT SHEAR ANALYSIS OF RESULTS

Material	1 Day	7 Days	Row Mean
M1	4,231 ± 271	3,727 ± 83	3,979
M1 (G)	4,774 ± 551	5,425 ± 407	5,100
M2	4,438 ± 1,060	3,753 ± 128	4,118
M2 (G)	4,430 ± 122	5,212 ± 173	4,821
P1	2,567 ± 590	4,814 ± 185	3,691
P2	3,209 ± 686	4,178 ± 345	3,694
U	2,109 ± 40	2,759 ± 188	2,419
Column mean	3,686	4,263	3,974
		Overall mean	

TABLE 8 ANALYSIS OF VARIANCE FOR TABLE 7

Source of Variation	Sum of Square ($\times 10^6$)	Degrees of Freedom	Mean Square ($\times 10^6$)	Significance F	Significance $F(0.01)$
Material	27.490	6	10.558	49.5	3.56
Age	3.488	1	9.464	44.3	7.68
Interaction	8.802	6	7.443	34.9	3.56
Residual	5.976	27	0.234		
Total	45.756	40			

TABLE 9 ANALYSIS OF VARIANCE OF STATIC FLEXURE TESTS

Source of Variation	Sum of Square ($\times 10^6$)	Degrees of Freedom	Mean Square ($\times 10^6$)	Significance	
				F	F(0.05)
Material	3.264	4	0.816	5.64	3.52
Depth	0.016	1	0.016		
Interaction	0.706	4	0.177		
Total	3.986	9			

in the cracked zone under flexure. Replication will show whether this result is spurious or real. The strong interactions and absence of replication preclude full statistical analysis. If, however, results for shallow patches are ignored and the experiment is analyzed as two-factorial experiments with five materials and two depths (half and full), the variance of the interaction and of the effect of depth are relatively small. If these two effects are combined to provide an estimate of the experimental error with five degrees of freedom, the F test yields significance of the material effect at the 5 percent significance level. The analysis of variance is presented in Table 9. Replication would provide a clearer picture of the significance of patch depth and patch depth-material interaction.

Fatigue Tests The results of fatigue tests are erratic, as apparent from Table 4 and Figures 4 and 10. This is the reason that these two figures were drawn as block rather than as line diagrams; the high variability meant statistical analysis was of no real value.

A general trend, however, emerges. As in static tests, and perhaps even more so here, patch depth does not appear to have a significant effect. With the exception of material M2, all materials performed well, most specimens sustaining in excess of 1 million cycles and extent of cracking at 30,000 cycles comparable to that of the control. The reason for the apparent inferiority of M2 is not clear. It could indicate high variability in the performance of MMA in general, high sensitivity to small variations in composition and, hence, variability of sources, or it may be due simply to a faulty batch of material received. This point requires further investigation.

SUMMARY AND CONCLUSIONS

An experimental investigation has identified four high early strength materials as suitable for cold weather patching of concrete pavement and bridge structures. The materials are: *(a)* methyl methacrylate-based polymer concrete, *(b)* magnesium phosphate-based materials, either water or non-water activated, and polyurethane polymer concrete. The MMA and magnesium phosphate-based materials are superior to the polyurethane in most performance criteria but an apparent high variability in performance of MMA under fatigue loading requires further investigation. Twenty-four hours' compressive strengths ranging from 1,700 psi to over 9,000 psi have been obtained. Slant-shear bond strength on saw-cut surfaces ranged from 2,000 psi to over 4,000 psi at 24 hours. Flexure strengths comparable to those of mature control specimens were obtained for MMA and water-based magnesium phosphate materials aged 7 days under both static and fatigue loading.

It can be concluded that, from the strength point of view, several materials are available today that are suitable for subfreezing concrete patching. Durability and field performance testing are, however, required to confirm this conclusion before undertaking large-scale field applications.

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Early Age Properties of Magnesium Phosphate-Based Cements Under Various Temperature Conditions

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Presented in this paper are the effects of temperature on the early age properties of two rapid-hardening magnesium phosphate-based cements and their combinations, as follows: *(a)* magnesium phosphate cement for cold and regular weather use; *(b)* magnesium phosphate cement for hot weather use; *(c)* a 50-50 blend of magnesium phosphate cement and magnesium phosphate cement for hot weather use; and *(d)* magnesium phosphate cement with the addition of borax. A combination of both mechanical (setting and compressive strength) and physicochemical (X-ray diffraction; optical microscopy and infrared spectroscopy) tests was performed. Overall, 35 mixes were made, cured under various temperature conditions, and tested. The strengths were determined at the ages of 1, 3, and 24 hr. Freeze-thaw experiment was left for future work. The tests revealed that all the above cements develop almost 2,000 psi (14 MPa) compressive strength within an hour regardless of various curing conditions; the 28 days' strengths are more than 4,500 psi (31 MPa); and the 90 days' strengths are more than 6,500 psi (45 MPa) under normal curing conditions. Thus, their applicability for rapid road repair and other concrete repair works seems promising. Further, the MPH cement appears to have the best mechanical properties among them all under the majority of weather conditions.

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Rapid hardening cements have an important application in the repair of concrete structures. Especially, their high early strengths could solve many emergency repair works such as pot holes, concrete pavements, airport runways, wall patching, bridge decks, and other concrete structures. The investigation focused on

1. Conducting laboratory experiments to determine the strength effects of various curing conditions on these cements; and
2. Using physicochemical methods such as X-ray diffraction, optical microscopy, and infrared spectroscopy to obtain the basic nature of rapid-hardening magnesium phosphate base cements.

This paper is the continuation of an earlier publication on rapid-hardening cements for repair of concrete *(1)*. The investigation on later age properties will be presented in the next paper.

SUMMARY OF AN EARLIER INVESTIGATION

The main goal of earlier research with the same materials was to identify or modify an existing inorganic cementing material that would be suitable for emergency repair of damaged airport