ESL-TR-87-33

EVALUATION OF BARRIER CABLE IMPACT PAD MATERIALS

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MARCH 1988

FINAL REPORT

SEPTEMBER 1983-SEPTEMBER 1984

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release;
distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ESL Technical Report 87-33

6a. NAME OF PERFORMING ORGANIZATION
USAEWES
Structures Laboratory

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
PO Box 631
Vicksburg, MS 39180-0631

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION Air Force Engineering and Services Center

8b. OFFICE SYMBOL *(If applicable)*
RDCP

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*
Tyndall Air Force Base, FL 32403

10. SOURCE OF FUNDING NUMBERS See reverse

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
63723F	2104	1A01	

11. TITLE *(Include Security Classification)*
Evaluation of Barrier Cable Impact Pad Materials

12. PERSONAL AUTHOR(S)
Husbands, Tony B., and Bean, Dennis L.

13a. TYPE OF REPORT
Final report

13b. TIME COVERED
FROM 09/83 TO 09/84

14. DATE OF REPORT *(Year, Month, Day)*
March 1988

15. PAGE COUNT
92

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
See reverse.

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

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(Continued)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE *(Include Area Code)*

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

10. SOURCE OF FUNDING NUMBERS (Continued).

MIPR Number N-90-29, dated 6 May 1980, and MIPR Number F-83-73, dated 27 September 1983.

18. SUBJECT TERMS (Continued).

Aircraft arresting systems, Epoxy resin, Impact-abrasion testing, Impact pad materials, Polymers, Polyurethane, Silica fume concrete

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PREFACE

The investigation described in this report was conducted by personnel of the Concrete Technology Division (CTD) of the Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES). The program was sponsored by the Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida. The work was authorized by Military Intradepartmental Purchase Request Numbers N-80-29, dated 6 May 1980, and F-83-73, dated 27 September 1983. Mr. Hank Marien, Major John Centrone, and Mr. Charles Bailey were the AFESC/RDCP project officers.

The investigation was performed under the general supervision of Mr. Bryant Mather, Chief, SL; and Mr. John M. Scanlon, CTD; and under the direct supervision of Mr. Richard L Stowe, Chief, Materials and Concrete Analysis Group, CTD. Mr. Charles L. White, CTD, assisted in the evaluation of the materials tested. Mr. Dale Glass, CTD, assisted in the design and installation of the cable abrasion testing apparatus, and Messrs. Dan E. Wilson, Tommy G. Ray, Jr., and R. Cliff Gill, CTD, performed many of the tests. The report was prepared by Messrs. Tony B. Husbands and Dennis L. Bean, CTD.

Mr. Bill Peacock, Chief, Operations and Maintenance, and Mr. Cliff Sanders, Pavement Engineer, Headquarters TAC, Langley Air Force Base, Virginia, arranged the field tests. Civil engineering personnel at Homestead (Florida), Tyndall (Florida), and Seymour-Johnson (North Carolina) Air Force Bases performed the field applications of the various barrier pad materials. Col Dwayne G. Lee, CE, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and approved for publication.

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20060223341

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ESL Technical Report 87-33
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7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS *(City, State, and ZIP Code)* PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS *(City, State, and ZIP Code)*
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8c. ADDRESS *(City, State, and ZIP Code)* Tyndall Air Force Base, FL 32403	10. SOURCE OF FUNDING NUMBERS See reverse

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(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)* / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
foot-pounds (force)	1.355818	metre-newtons or joules
gallons (US liquid)	3.785412	litres
inches	25.4	millimetres
pints (US liquid)	0.4731765	litres
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
quarts (US liquid)	0.9463529	litres

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

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SECTION I
INTRODUCTION

To provide emergency stopping capability for aircraft, aircraft arresting systems have been developed and installed on many Air Force runways. These arresting systems use a braking mechanism attached to a cable, 1 or 1 1/4 inches* in diameter, stretched across the runway. During emergencies the aircraft extends a hook which drags along the runway and catches the cable. The barrier cable remains stretched across the runway at all times and is supported by 6-inch-outside-diameter rubber donuts which keep the cable 2 inches above the surface of the runway. During normal operations, aircraft tires repeatedly roll over the cable and damage the pavement beneath the cable. When the cable-to-runway-surface distance becomes less than 2 inches on runways, the area underneath the barrier cable must be replaced.

The Air Force has used several different kinds of materials to inlay the area underneath the barrier cable. These efforts began about 16 years ago and have met with varying degrees of success. Materials used by the Air Force include a polyurethane, an epoxy-rubber compound, steel plates, and a cementitious material containing iron shavings. The most widely used has been the epoxy-rubber compound and the polyurethane materials as inlays. The basic problems with the epoxy-rubber compound have been higher wear rates than desired, poor handling characteristics and poor installation, and the lack of adequate practices for repairing the material. The polyurethane materials are moisture-sensitive, and bond failures with the pavement have occurred.

The Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base (AFB) requested that the US Army Engineer Waterways Experiment Station (WES) survey materials that could be used as barrier cable impact pads and evaluate four to six of the more promising materials in the laboratory. Two of the better materials were field-tested. This study is referred to as the Phase I study.

After this study was completed, the AFESC requested that WES conduct an additional survey in 1983 to locate other materials which would be suitable

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page ix.

as barrier cable impact pads. AFESC requested that emphasis be placed on elastomeric materials which would reduce cable damage. This second study is referred to as the Phase II study. A survey was made, and a number of materials were tested. Two of the more promising materials were installed at Seymour-Johnson AFB, North Carolina, for field evaluation.

SECTION II
PHASE I STUDY

A. SURVEY OF MATERIALS

1. Desirable Properties

The AFESC furnished WES with the following desirable characteristics for barrier cable pad materials:

a. The material must be durable. It must be able to withstand the effects of 250,000 cycles of aircraft traffic before eroding to a depth of more than 1 inch.

b. It must cause minimal damage to the barrier cable. The cable must not have distorted, bent, or braided wires within it after usage on the barrier cable pad material.

c. The material should induce no bounce to the cable and should adsorb the energy imparted by the cable so that cable bounce does not damage the aircraft.

d. The material should be capable of being installed by Air Force technicians at temperatures varying from 40° to 100° F in asphalt or concrete pavements.

e. The material should be moisture tolerant with no inherent shrinkage and expansion.

f. The material should be easily repaired by Air Force labor, using available materials and no special techniques.

g. The material should be inexpensive. Life-cycle cost should be less than the cost of replacing asphalt or concretes.

2. Manufacturers Contacted

Materials on the market that could meet the requirements necessary for a barrier cable impact pad were sought by contacting suppliers of pavement materials, epoxy resins, and other polymers. One hundred and two suppliers of materials were contacted. Forty-one of the suppliers submitted 56 samples for evaluation, along with available information on properties and material application. A list of the suppliers contacted and the materials submitted for evaluation is presented in Table 1.

TABLE 1. MANUFACTURERS CONTACTED AND MATERIALS

Supplier of Material	Trade Name	Chemical Classification
Abatron		
Acme Chemicals	Acme 4045	Epoxy
Adhesive Engineering	Concressive 1064	Epoxy
	Concressive 1170	Epoxy
	Concressive Polymer Concrete	Methyl methacrylate
Adhesive Products Corp.		
Adhesive Products Inc.		
Akemi Plastics	AP-2316	Epoxy
Alloco		
Allied Chemical (Castall)		
Allied Resin Corp.	Arcon EU-950	Polyurethane
Alma Plastics		
American Cyanamid	Cyanaprene A-7	Polyurethane
		Cyanaprene A-9
American Resin and Chemical		
Amicon Corp.	XT-5111	Epoxy
Amoco		
Anderson Development		
Arco Chemical		
Armstrong Products Co.	Armstrong C-4	Epoxy
Ashland Chemical		
Atlas Mineral and Chemical	RezKlad Epoxy Asphalt	Epoxy
	RezKlad Machinery Grout	Epoxy
Axel		
Bacon		
BASF		
Beacon Chemical	Magna-Tac 2167-20	Epoxy
Borden Chemical		
Borg-Warner		
Bostik		

TABLE 1. MANUFACTURERS CONTACTED AND MATERIALS (CONTINUED)

Supplier of Material	Trade Name	Chemical Classification
Cadillac Plastics		
Cal Polymers Inc.	Calthane NF-1300	Polyurethane
Carlson Thermoplastics		
Chemical Coating		
Chemical and Engineering Association		
City Services Corp.		
Claremont		
Claremont Polychemical		
Coating Products		
Coating Systems, Inc.		
Conap	Conathane EN-2523	Polyurethane
	Conathane TU-700	Polyurethane
	Conathane TU-900	Polyurethane
	Conathane EN-2	Polyurethane
Concrete Chemie		
Conoco		
Davbert Chemical		
Deer Polymer Corp.		
Delta Plastics	LV-23-9025	Epoxy
Dennis Chemicals		
Devcon		
Diamond Shamrock		
Dow Chemical	Sharan Cement Additive	Polymer additive for PPCC
Dupont	Cryclon	Methyl methacrylate polymer concrete
Dura Bond		
Dural International	Dural 306	Epoxy
	Flexocrete Type III	Epoxy
Edoco	2114	Epoxy
Emeson and Cumming	Stycast 2741	Epoxy
Engineering Plastics		

TABLE 1. MANUFACTURERS CONTACTED AND MATERIALS (CONTINUED)

Supplier of Material	Trade Name	Chemical Classification
Epic Resins	Epic S70005	Epoxy
Epoxy Surfaces of Nevada	Resimer LA-15	Epoxy rubber compound
Ethyl Corp.		
Fenwall	Pavement Sealer 599	Epoxy
	80-017-01	Epoxy
Firestone Chemical		
Freeman		
Fuller		
G.A.F.		
Garon	Hy-Speed 5000	
Hardman		
Hastings Plastic	Halflex 1950-1A	Polyurethane
Haycock Asphalt	Haycock Elastomeric Impact Compound	Polyurethane
Hughson Chemical	Tycel 7501	Polyurethane
Isochem Resins	Isochembond 811B	Polyurethane
Kristal Kraft	Uniepoxy	Epoxy
Leepoxy	X-28-202	Epoxy
	X-28-199	Polyurethane
Magnolia Plastics	Magnolia 1032	Epoxy
M and R Plastics	Mistaflex	Polyurethane
Masterbond	EP-21	Epoxy
Master Builders	Anvil Top RHE cementitious grout	Iron-filled
Anvil Top 200	Iron-filled cementitious grout	
Anvil Top 100	Iron-filled cementitious grout	
Metachem Resins	Meta Cast 427	Epoxy
Miller Stephenson Chem.	Epon 828 V-40	Epoxy
Mitchell Rand		
Mobay		

TABLE 1. MANUFACTURERS CONTACTED AND MATERIALS (CONCLUDED)

Supplier of Material	Trade Name	Chemical Classification
Palmer		
Plastcon Products		
Poly Products		
Poly Resins		
Polymer Systems Corp.	Purelast	Polyurethane
PPG		
Prochem		
Products Research Corp.	PR-480	Polyurethane
	RC-1595	Polyurethane
Quion	Q-Thane QC-4003	Polyurethane
Radiation Technology Inc.	Radgrout-H	Polyester concrete
Reichold Chem.		
Ren Plastics	RP-6413	Polyurethane
	RP-6414	Polyurethane
	RP-6422	Polyurethane
Ruco		
Sika Chemical		
Stanchem		
Sterling		
Structural Concrete Bonding	MC-64	Epoxy rubber compound
Techform	TC 459	Epoxy
Technical Labs and Engineers		
Tra-Con Inc.		
Uniroyal	Vibrathane	Polyurethane
United Paint Mfg. Co.		
US Gypsum Co.		
US Polymeric		
Upjohn		

Most of the materials submitted by the suppliers for evaluation were epoxy resins and polyurethanes--27 epoxy-resin systems and 22 polyurethane systems. Other materials included two methyl methacrylate polymer concretes, three iron-filled cementitious grouts, a polyester concrete, and a polymer additive for fresh concrete. The epoxy-resin systems varied from very flexible to rigid systems, and two were epoxy-rubber compounds (small pieces of hardened rubber added to the two components of the epoxy resin as a filler). Three of the polyurethane systems were preformed polyurethanes. Fabricators of the three preformed polyurethanes stated that these materials could be made in sheets 2 inches thick, up to 48 inches wide, and up to 12 feet long.

B. PRELIMINARY TESTING AND EVALUATION

Most of the materials received from the suppliers were given a preliminary test to determine what materials would be chosen for the detailed testing. Necessary properties, such as resilience, gel time, adhesion to concrete and asphalt, hardness, rate of cure, and abrasion resistance, could not always be obtained from the suppliers.

1. Test Methods

a. Resilience

The polymer materials received were first tested for impact resilience in accordance with American Society for Testing and Materials (ASTM) D 2632-68 (Reference 1).* Two test specimens were prepared by pouring the mixed material into an aluminum weighing dish which had a diameter of 2 1/2 inch and which was 5/8 inch deep. A light coating of grease was applied to the inside of the dish before casting the specimen. The test specimens were removed from the dish when the material had hardened sufficiently and were allowed to cure for 7 days at 73.4° ± 1.8° F before being tested; specimens tested for hardness were similarly cured.

b. Hardness

All of the elastomeric materials that did not have excessive rebound and the flexible epoxy resins were tested for hardness in accordance with ASTM D 2240-68. A Shore A and a Shore D durometer were used.

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* ASTM specifications referenced in this report are contained in Reference 1, <u>Annual Book of ASTM Standards</u>. For simplicity, further reference to ASTM specifications will be by ASTM Designation Number only.

c. Adherence to Concrete

The epoxy resins, polyesters, and methyl methacrylates were tested for bond strength in accordance with ASTM C 882-78. Three test specimens were cured for 7 days at 73.4° ± 1.8° F before testing. The test specimens prepared from polymer systems containing aggregate (the aggregates passed a 3.35 mm (Number 6) sieve) were prepared as specified in Sections 10.3 and 10.4 of the test method. Test specimens prepared from polymer systems containing aggregate retained on a 3.35 mm (Number 6) sieve were prepared in accordance with applicable portions of Section 10.6 of the test method.

A tension test developed at the WES was used to determine the bond strength of elastomeric materials to concrete. Portland cement mortar briquets were prepared and cured as specified in ASTM C 190-82. A Type II portland cement was used in making the mortar for the briquets. The briquets were moist-cured for 28 days before preparing the specimens for testing.

The briquets were cut at their midheight, forming two equal halves. The half sections were then air-dried for 48 hours in the laboratory. The two sections were then placed on a strip of tape approximately 1 inch wide by 3 inches long with the two cut surfaces facing each other and spaced 1/4 inch apart. The tape was then stuck to the sides, forming a retainer for the material to be placed between the halves. When a primer was to be used, the two cut surfaces were primed before placing the halves on the tape. The test material was then mixed and poured into the space between the briquet halves. The test specimens were cured for 7 days at 73.4° ± 1.8° F before being tested. Test specimens were tested in accordance with section 6.4.2 of ASTM C 190-82. The bond strength was determined by dividing the load carried by the specimen at failure by the cross-sectional area of the specimen. A test specimen is shown in Figure 1.

d. Adherence to Asphalt

A literature search was made to find test procedures for determining the bond strength between materials and asphalt. The authors did not find a test method; therefore one was developed. Asphaltic concrete beams (3 by 3 by 15 inches) were fabricated and tested. The mixture used in this study was developed for testing high-pressure tires (100-250 psi) in accordance with Technical Manual 5-822-8 (Reference 2). The asphaltic concrete mixture was

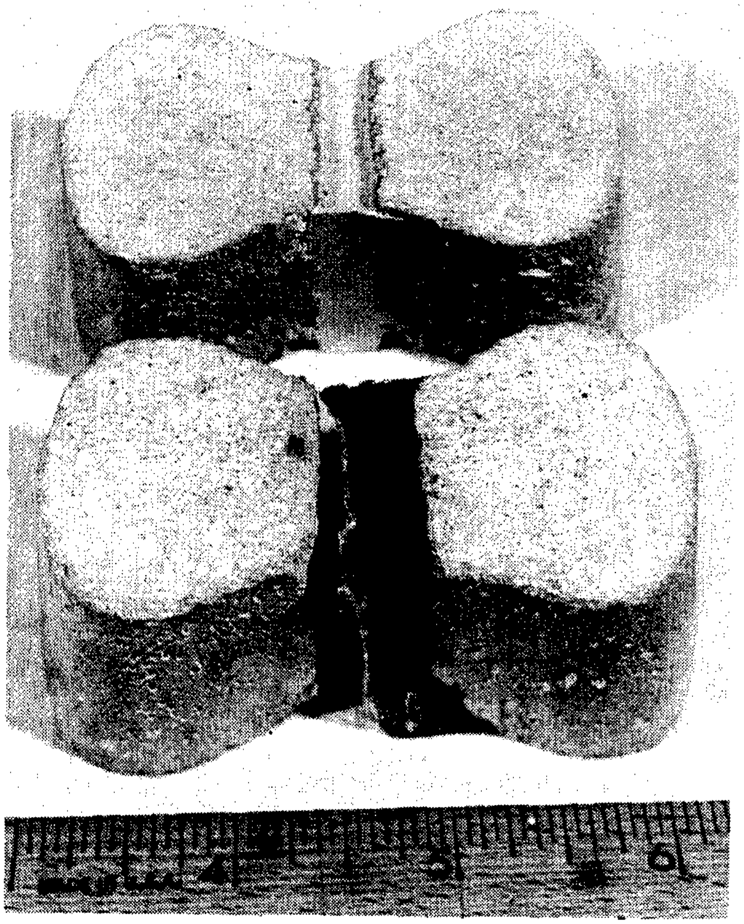
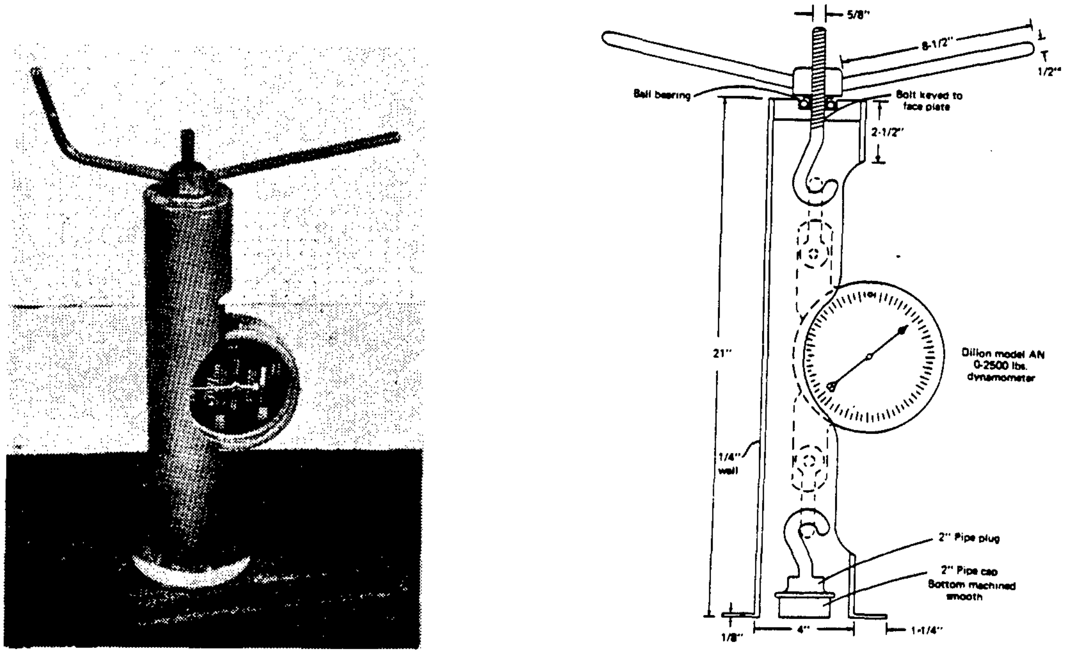


Figure 1. Adhesion to Concrete Test Specimens

placed into 15- by 3- by 3-inch steel molds and compacted to obtain 98 percent of laboratory density.

The test method developed is a modified version of the test in Appendix A of American Concrete Institute (ACI) 503-R-80 (Reference 3). A functional sketch of the testing device is shown in Figure 2. Three 2- by 4-inch cylindrical molds (made from commercially available 2-inch polyvinyl chloride (PVC) water pipe) were placed on a smooth, clean surface of the beam and sealed with wax to prevent leakage. The material being evaluated was uniformly mixed and poured into the mold to a depth of about 2 inches. The mold was removed after the material cured for the manufacturer's recommended time. A standard 1 1/2-inch pipe cap or a 2-inch steel cylinder with a smooth surface for bonding was bonded to the material previously placed on the asphaltic concrete beam. A commercial rapid-curing epoxy was used to adhere the cap to the material being evaluated. After a 2-hour curing time the test device was connected to the steel cylinder on the cap and a force applied to the



a. Mechanical Testing Device for Pulling Bonded Cap in Tension.

b. Functional Sketch of Mechanical Testing Device.

c. Typical Failure in Concrete; Dark Spots on Cap and in Aggregate Indicate Split Aggregate.

Figure 2. Adhesive Testing (Reference 2).

test specimen. The device indicated the force required to break the or material. The total force was divided by the surface area to give the bond strength in pounds per square inch.

e. Abrasion Resistance

The abrasion resistance of the materials was determined using a Tabor abraser testing machine. Two test specimens 4 inches square and 1/8 inch thick were prepared by pouring freshly mixed materials into silicone rubber molds. The polymers were allowed to cure for 7 days in the laboratory before being tested. The test specimens were weighed on an analytical balance before and after testing. The Tabor abraser was equipped with H-18 wheels and a 1 kg load was applied to the wheel. Each specimen was tested for 1,000 cycles. The amount of abrasion was reported as the weight loss.

f. Gel Time

The gel time of the polymers was determined as described in Section 11.2 of ASTM C 881-78 (1983).

2. Test Results

Most of the materials obtained (except those that had excessive expansion, gel times less than 15 minutes, and other undesirable properties) were tested for impact resilience by vertical rebound. Those materials that exceeded 25 percent rebound and that could not be modified by the addition of fillers were omitted as candidate materials. Those materials that did not exceed the rebound requirement, and a few that did but showed promise, were tested for adherence to concrete and asphalt, abrasion resistance, and hardness. These test results are shown in Tables 2-4.

a. Polyurethanes

Two of the polyurethanes, W-PU-5 and W-PU-8, exceeded the rebound requirement, but were tested for the other properties because W-PU-5 had been used as overlays for portland cement concrete pavements. W-PU-8 was a modified version of W-PU-5 formulated specifically for this project. Only three of the polyurethanes (W-PU-5, W-PU-8, and W-PU-7) had bonding strengths to concrete greater than 100 psi. A primer for concrete was supplied by the manufacturer of W-PU-5 and W-PU-8. This primer and one other were used in the testing of W-PU-3 and W-PU-1. Neither primer was found satisfactory for

TABLE 2. TEST RESULTS FOR POLYURETHANE

Material	Impact Resilience, Percent Rebound	Bond Strength, Concrete, psi	Bond Strength, Asphalt, psi	Tabor Abraser Weight Loss g	Hardness Shore Durometer A and D Scales
W-PU-1	6	53 (Adhesive)[a]	64 (Adhesive)	0.130	A62
W-PU-2	18	63 (Adhesive)	b	1.623	A56
W-PU-3	2	52 (Adhesive)	64 (Adhesive)	0.071	A57
W-PU-4	7	96 (Adhesive)	51 (Adhesive)	0.084	A40
W-PU-5	40	285 (Adhesive)	<10 (Adhesive)	0.041	A76
W-PU-6	5	37 (Adhesive)	67 (Adhesive)	0.034	A50
W-PU-7	24	486 (Mortar)	88 (Asphalt)	0.420	D50
W-PU-8	30	150 (Material)	<10 (Adhesive)	0.205	A45
W-PU-9	8				A65

[a] Failure occurred in.
[b] Manufacturer reported material was not compatible with asphalt.

TABLE 3. TEST RESULTS FOR EPOXY RESINS

Material	Impact Resilience, Percent Rebound	Bond Strength, Concrete, psi	Bond Strength, Asphalt, psi	Tabor Abraser Weight Loss g	Hardness Shore Durometer A and D Scales
W-EP-1	10	630 (Adhesive)[a]	60[b]	0.523	A65
W-EP-2	17	230 (Adhesive)	96	0.036	A38
W-EP-3	5	>2,950 (Mortar)	71	1.207	D92
W-EP-4[c]	20	1,850 (Adhesive)	112	0.355	D45
W-EP-5[c]	16	>2,740 (Mortar)	102	1.005	D83
W-EP-6[c]	8	>2,450 (Mortar)	83	0.773	D85
W-EP-7[c]	16	>2,490 (Mortar)	99	0.916	D63
W-EP-8	25	610 (Cohesive)	82	0.619	D44
W-EP-9	20	400 (Adhesive)	81	0.095	A70
W-EP-10	22	410 (Cohesive)	111	1.482	D49

[a] Failure occurred in.
[b] All failures occurred in the asphalt.
[c] Sand was added to these epoxy resins to make epoxy mortars.

TABLE 4. TEST RESULTS FOR OTHER POLYMER MATERIALS

Material	Impact Resilience, Percent Rebound	Bond Strength, Concrete, psi	Bond Strength, Asphalt, psi[b]
W-M-1	6	2,580 (Mortar)[a]	<5
W-M-2	5	3,100 (Mortar)	<5
W-M-5	19	450 (Adhesive)	<5

[a] Type of failure.
[b] All of these materials were incompatible with asphalt.

obtaining acceptable bonding strengths. Only one polyurethane, W-PU-7, was found to have acceptable bonding strengths to asphalt. Tabor abrasion test results indicated that all the polyurethanes, except for W-PU-2, had low weight losses. The two polyurethanes, W-PU-4 and W-PU-8, were considered to be too soft based on the hardness readings of A40 and A45, respectively. The test results are shown in Table 2.

b. Epoxy Resins

Two of the epoxy resins, W-EP-2 and W-EP-9, had low bond strengths to concrete. The two rubberized epoxy systems, W-EP-8 and W-EP-10, had cohesive failures during testing (a failure which occurs within the adhesive itself). All other epoxy resins were found to have satisfactory bonding strengths to concrete. All of the epoxy resins bonded satisfactorily to the asphalt. The softer epoxy resins were found to have a lower abrasion rate than the harder epoxy resins, when tested with the Tabor abraser testing machine. The weight loss for W-EP-3 was misleading since a small aggregate furnished by the manufacturer was added to the epoxy which increased the specific gravity nearly twofold. Only one epoxy resin, W-EP-2, was considered too soft for application. Test results are shown in Table 3.

c. Other Polymer Systems

The two methyl methacrylate polymer concretes, W-M-1 and W-M-2, were found to have acceptable bonding strengths to concrete. However, a low bonding strength to concrete was obtained for W-M-5. All three materials appeared to be incompatible with asphalt since they dissolved the asphalt surface on contact. Test results are shown in Table 4.

3. Selection of Materials for Detailed Testing

Based on the test results obtained at WES, the ease of application, cost, and other properties and information supplied by the manufacturers, the following materials were chosen for detailed testing:

Type of Material	Designation
Epoxy resin	W-EP-4
Epoxy resin	W-EP-7
Epoxy resin	W-EP-10
Epoxy resin	W-EP-3
Polyurethane	W-PU-7

All of the materials chosen for detailed testing were epoxy-resin systems except for W-PU-7, which was a polyurethane. The polyurethane material, W-PU-3, was considered for detailed testing because it shows a lot of promise except for the poor adhesion to concrete. A search for a satisfactory primer for this material was unsuccessful. The preformed polyurethane, W-PU-3, also showed promise but special application techniques for placing the preformed sheets would have to be developed. A number of companies contacted in the survey stated that they could fabricate this material into 2-inch-thick sheets. W-EP-10 was chosen because the material was presently being used by the Air Force for barrier cable pads.

C. DETAILED TESTING

1. Test Methods

The five materials selected for detailed testing were tested to determine whether any would meet the desirable properties described earlier. The materials were tested for thermal compatibility with portland cement concrete and asphaltic concrete, gel time and peak exotherms, effect of temperature on cure rate, effect of proportioning error, adhesion to damp surfaces, adhesion of the freshly mixed material to the hardened material, effect of exposure to fluorescent sun lamps and heat, and durability to cable abrasion. Sand was added to the epoxy resins, W-EP-4 and W-EP-7, to make epoxy mortars for testing. Three parts graded Ottawa C-109 sand to one part epoxy resin, by volume was the mixture proportion. The sand was added to reduce the cost and heat generated by the epoxy systems. Sand was also added to the polyurethane material, W-PU-7, to reduce the rebound. Two parts graded Ottawa C-109 sand to one part of the polyurethane by weight was the mixture proportion. Sand was not added to the polymers when determining the effect of exposure to fluorescent sun lamps and heat.

2. Development of Test Method for Cable Abrasion

There were no existing test methods available for evaluating the resistance of barrier cable pad materials to the abrasion and impact of the arresting cable. A test was needed to simulate aircraft tires rolling over the cable, forcing the cable into the material below and causing the material to abrade or crack.

a. Tests Developed by Otto-Graf-Institute

The AFESC supplied WES with a test report from the Otto-Graf-Institute, Germany, describing a test method used to test synthetic resin coats for barrier cable pad materials.

The test consisted of pouring the mixed material into a steel tub 19.6 by 15.1 by 2 inches. The material was allowed to cure for 7 days before being tested. The tub was then rigidly installed in a servo-controlled, electrohydraulic test machine above a piece of the steel cable 11.8 inches long attached to a piston bar. The coating surface was pointed to the bottom and formed an angle of 24 degrees with the horizontal line, the angle computed when aircraft tires roll over the cable and force the cable into the inlay. The piston bar was used to push the cable into the material. For the tests, the steel cable was first pushed into the material to a depth of 3/8 inches and the load recorded at that penetration depth. The cable was then pushed into a depth of 3/4 inches and the load was recorded at that penetration depth. The steel cable was then cycled between the two penetration depths and the number of cycles recorded. The materials were tested until a failure of the material occurred. It was determined that this test method is only satisfactory for testing elastomeric materials.

b. Electric Hydraulic Loading System

A test method similar to the one used at the Otto-Graf-Institute was developed at WES. The testing apparatus consisted of a hydraulic loading system, a holder for the test specimen, and a piece of the steel cable. A test specimen was prepared by overlaying a 12- by 6- by 4-inch concrete beam with a 2-inch layer of the test material. The test specimen was placed into a steel holder mounted to a platform below the hydraulic ram. The holder was designed so that the overlying surface was facing up and at an angle of 24 degrees from the horizontal. A section of the steel cable was installed above the specimen using steel guides. The hydraulic ram was used to push the cable into the material. The load on the hydraulic ram could be adjusted and recorded. A 10,000-pound load was used in testing the first test specimen which was a 5,000 psi portland cement concrete beam 12 by 6 inches. The angle of the test specimen caused the ram to deflect and could have damaged the hydraulic system.

Modifications of the testing device to eliminate the deflection of the hydraulic ram were investigated. The hydraulic ram was placed in a horizontal position. The specimen holder described above was mounted to the hydraulic ram. The hydraulic ram was used to push the test specimen into a piece of the steel cable, supported by a metal disk 3 inches wide. A portland cement concrete beam, 12 by 6 by 6 inches, was used as the test specimen for this evaluation. After 200 cycles with a load of 5,000 pounds, only a slight amount of abrasion was observed on the concrete specimen. Loads up to 10,000 pounds were used, with very little difference observed in the abrasion rate.

c. Drop Tower

A drop tower of a free-fall design was evaluated as a test method by dropping a 150-pound weight on the steel cable positioned above a concrete test specimen. The test specimens were prepared by cutting out 6-inch sections from a 6- by 6- by 36-inch concrete beam. One side of the concrete specimen was then cut at a 24-degree angle. The side of the concrete test specimen cut at the 24-degree angle was placed underneath the steel cable suspended 1/2 inch above the specimen. The cable was placed through two O rings attached to the uprights which support the drop weight. A steel ram, 2 by 2 by 7 inches, welded to a 1/4-inch-thick, 9-inch-diameter metal plate was attached to the drop weight. The ram was used to push the cable into the surface of the test specimen. An air cylinder bolted to the top of the drop tower was used to raise the drop weight. The drop weight was connected to the air cylinder rod by a 4-inch-long piece of heavy-duty chain. A three-way electronic solenoid valve with a latching relay was used to release and raise the air cylinder. Two electronic switches that detect metallic objects approaching the sensing face in any direction were attached to a metal pipe which was mounted to the floor and extended to the height of the drop tower. These electronic switches controlled the solenoid valve and the drop height could be adjusted by adjusting the distance between the two switches. A load cell was attached to the base of the drop tower beneath the drop weight. A metal platform for holding the test specimen was attached to the top of the load cell. An oscilloscope was used to monitor the load and load-rise time. An electronic counter was used to count the number of drops.

Concrete test specimens made from 4,200 psi concrete were used to evaluate the testing apparatus. A 5,000-pound load was applied to the test specimens. Severe abrasion and cracking were observed under this load.

The load-rise time was increased to 3 milliseconds. This was accomplished by placing a 1/2-inch-thick neoprene rubber disk 9 inches in diameter between the metal plate and the drop weight. A 1/8-inch-thick neoprene sheet was placed underneath the test specimen. The testing apparatus was evaluated a second time, using the same type of test specimen as before, applying loads of 5,000, 10,000, and 15,000 pounds with a load-rise time of 3 milliseconds. A very low abrasion rate was observed for 5,000- and 10,000-pound loads. The abrasion rate increased significantly when applying a 15,000-pound load. Concrete test specimens subjected to loads of 10,000 and 15,000 pounds are illustrated in Figure 3. Based on these evaluations it

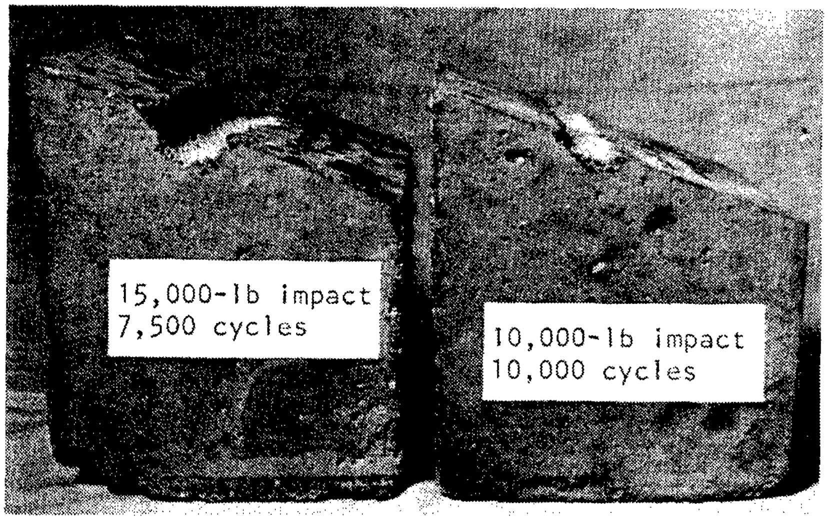


Figure 3. Comparison of Portland Cement Concrete Specimen after Different Impact Loadings.

was decided that this testing apparatus using a load of 10,000 pounds and a load-rise time of 3 milliseconds would be satisfactory for determining cable abrasion of barrier cable impact pad materials. All the initial tests were performed using the test apparatus described.

d. Modification of Drop Tower Test

The testing apparatus described above was modified for the following reasons: (1) poor abrasion due to the cable being attached to the uprights and not being free to turn, and (2) downtime due to maintenance because vibration caused the load cell beneath the test specimen to work loose from its mounting.

Two 1/4-inch-diameter U-bolts 4 inches long and 2 1/2 inches wide were welded to the sides of the ram. The U-bolts were tapered slightly to the backside so that the cable would roll to the same position each time the drop weight was raised. A section of the cable 14 inches long was then suspended through the U-bolts. Four-inch-diameter rubber washers were placed over the cable outside the U-bolts to prevent the cable from working through the U-bolts.

A strain gage accelerometer was used in place of the load cell to measure the force. The accelerometer was attached to the top side of the drop weight. A 4-inch-diameter steel rod was welded to a metal plate which was bolted to the base of the drop tower. The test platform was welded to the top of the steel rod. The detailed test method is presented in Appendix A.

3. Thermal Compatibility with Portland Cement Concrete

Concrete beams 11 by 3 by 3 inches were prepared by proportioning and mixing the concrete as prescribed in section 3 of ASTM C 672-76. The beams were moist-cured for 28 days before applying the test materials. Two test specimens were prepared for each material being tested. The test specimens were prepared by coating one surface of the beam with a 2-inch-thick layer of the material. The surface of the beam to be coated was first cleaned by sandblasting. The materials were mixed and proportioned following the manufacturer's recommendations. The materials were allowed to cure for 7 days in the laboratory at 73° F before testing.

After the completion of the curing period the test specimens were placed in a freezer at -6° ± 3° F for 24 hours and then removed to a conditioning cabinet at 120°± 3° F for 24 hours. This is one test cycle of 30 cycles. Delamination of the material from the concrete beams or the presence of horizontal cracks in the concrete near the interface constituted failure of the test specimens.

4. Thermal Compatibility with Asphalt

Asphaltic-concrete beams 15 by 3 by 3 inches were prepared as described under "Adherence to Asphalt." Asphalt beams were sawed in half to make beams 7 1/2 by 3 by 3 inches. Slots 2 inches wide and 1 1/2 inches deep were cut midspan in each beam. Retaining strips were attached to the sides of the beams to enclose the slot. The material was mixed and then poured into the slot. The retaining strips were removed after the material had hardened sufficiently, then the material was allowed to cure for 7 days in the laboratory before testing.

After curing, the test specimens were placed in a freezer maintained at -6° ± 3° F for 24 hours, and then removed to a conditioning cabinet maintained at 120° ± 3° F for 24 hours. This is one test cycle, and test specimens were tested for 30 cycles. The presence of any cracks in the asphaltic concrete next to the slot constituted a failure.

5. Gel Time and Peak Exotherm

The test material components and all equipment that they came in contact with were conditioned at 73.4° ± 3.6° F. The necessary amount of the two components to obtain 350 grams was weighed in a plastic beaker. The two components were then mixed with a wooden tongue depressor for 3 minutes. Three hundred grams of the mixed material were then poured into a 1-pint metal can approximately 3 1/4 inches in diameter by 3 3/4 inches in height to obtain a depth of 2 inches. for the material. A thermocouple was then placed into the center of the reacting mass to record the temperature. The time at which a soft, gelatinous mass forms in the center of the sample was noted by probing every 2 minutes with a wooden hospital applicator. The time interval between the beginning of mixing and the formation of the gelatinous mass was taken as the gel time. The peak exotherm was the highest temperature reached during the reaction.

6. Bond Strength of Systems to Damp Concrete Surfaces

The test specimens were prepared as described under "Adherence to Concrete" except that the concrete half cylinders were placed under water 24 hours before applying the materials to be tested. The materials were mixed before removing the half-cylinders from the water. A half-cylinder was removed from the water and excessive water was shaken from its surfaces. The freshly mixed material was then immediately applied to the damp elliptical surfaces using the stiff brush. The test specimens were then placed in the fog room for 14 days before testing.

7. Bond Strength Between the Freshly Mixed and the Hardened Material

The bond strength between the freshly mixed material and the hardened material was determined in accordance with ASTM C 882-78. One of the half-cylinder sections was the hardened material, and the other half section was the freshly mixed material.

The hardened half cylinders were made as specified in section 7.2 of ASTM C 882-78 except that the material being tested was placed into the mold rather than portland cement mortar. The half cylinders were removed from the molds after the materials had hardened sufficiently. The half cylinders were then cured in the laboratory for 7 days.

Three test specimens were prepared for each material tested. The elliptical surface (bonding surface) of the hardened half cylinders were sandblasted followed by cleaning with compressed air. The prepared surfaces to be bonded were then coated by brushing on some of the freshly mixed material. The half cylinders were then placed into the molds. (The molds were made by cutting 6-inch sections from a 3-inch-diameter rigid PVC pipe with a seam cut into one side of the section.) A quantity of the material necessary to fill the remainder of the molds was mixed and placed into the molds. The top surfaces were struck off with a trowel. After the material had hardened sufficiently, the cylinder was removed from the mold and allowed to cure for 7 days in the laboratory before testing.

The test specimens were capped and tested in compression in accordance with ASTM C 39-83b. The elastomeric polymers were compressed to 75 percent of the original height of the specimen and the total load recorded at that compressed height. The other polymers were tested until the maximum load was obtained.

8. Effect of Exposure to Fluorescent Sun Lamps and Heat

Test specimens were prepared by casting 1/4-inch-thick dumbbells having the dimensions given in ASTM D 638-82a for a Type I specimen. The materials were mixed and poured into silicone rubber molds to make the dumbbells. The test specimens were allowed to cure for 14 days in the laboratory before being tested. Ten test specimens were prepared from each material. Satisfactory test specimens could not be cast from the rubberized epoxy because of the irregular rubber particles in the material. A sample of the epoxy resin that did not contain the rubber particles was obtained from the supplier for preparing the test specimens.

Five specimens made from each material were placed in a weatherometer meeting the requirements of ASTM G 23-81. The remaining five specimens from each material were stored in laboratory air. The specimens placed in the weatherometer were exposed to the sun lamps and heat (130° F) for 300 hours. After the 300-hour exposure the specimens were removed and conditioned in laboratory air for 24 hours. All the test specimens were then tested for tensile strength and elongation in accordance with ASTM D 638-82a.

9. Effect of Temperature on Cure

The effect of temperature on the rate of cure of the different materials was determined by casting cylinders from each material and determining the compressive strength after 1, 2, 3, and 7 days at three different temperatures, 40°, 55°, and 75° F. Compressive strengths were also determined after 14 days for 75° F.

Test specimens were prepared by casting 2- by 2-inch cylinders. The molds were made by cutting 2-inch sections from a 2-inch-diameter rigid PVC pipe; a saw cut was then made longitudinally complete through the wall of the cylinder to facilitate the removal of cured specimens. Hose clamps were used to close the gap created by the saw cut while the specimens were being cast. The molds were placed on a Teflon®-coated aluminum plate and the bottom of the molds and the seams, created by the saw cut, were sealed with wax. The molds and the materials were conditioned to the testing temperature before casting the test specimens. The materials were mixed and placed into the molds. The top surfaces of the test specimens were trowelled to obtain a smooth surface. Three specimens were cast for each age and temperature. To eliminate batching error, a proper amount of each material was proportioned and mixed to make 12 specimens, the number needed for testing for a specific temperature.

Tests were conducted for compressive strength in accordance with ASTM C 39-83b. Test specimens made from the rubberized epoxy-resin system were compressed to 75 percent of their original height. The total load was recorded at that compressed height since the material was elastomeric and would not yield at that height.

10. Effect of Proportioning Error

The effect of proportioning error of the two components for each of the materials tested was determined by casting cylinders in which the two components were incorrectly proportioned by quantitatively varying from the manufacturer's recommended proportions. The compressive strengths of the cylinders were determined after allowing the test specimens to cure for 14 days.

Test specimens were prepared by casting 2- by 2-inch cylinders as described under "Effect of Temperature on Cure" above. The proportioning errors used in proportioning out both A and B components of the different materials are given below:

Proportioning Error, percent	
A Component	B Component
+5	-5
+10	-10
+20	-20
-5	+5
-10	+10
-20	+20

Three parts graded Ottawa C-109 sand to one part by volume of the incorrectly proportioned epoxy was the proportion used in making the test specimens for W-EP-7 and W-EP-4. Two parts graded Ottawa C-109 sand to one part by weight of the incorrectly proportioned polyurethane was the proportion used in making the test specimens for W-PU-7. The manufacturer's recommended proportion for the W-EP-3 was 86 percent of the filler supplied with the material to 14 percent of the epoxy resin by weight. This amount of the filler was added to the incorrectly proportioned epoxy components in making the test specimens.

The test specimens were allowed to cure for 14 days in laboratory air before testing. The specimens were tested for compressive strength in accordance with ASTM C 39-83b. The amount of deflection of each test cylinder was measured during compression.

D. TEST RESULTS

1. Gel Time and Peak Exotherm

The gel times for all the materials exceeded 30 minutes, which is considered satisfactory for field application. None of the materials generated an excessive amount of heat during curing. Of all the materials tested, W-EP-4 had the highest peak exotherm, 106° F. Test results are shown in Table 5.

TABLE 5. GEL TIME AND PEAK EXOTHERMIC TEMPERATURES OF MATERIALS

Material	Gel Time, minutes	Peak Exotherm, °F
W-EP-4	44	106
W-EP-7	60	97
W-EP-10	150	90
W-EP-3	120	81
W-PU-7	30	90

2. Effect of Temperature on Cure

The compressive strengths of the five materials after curing for 1, 2, 3, and 7 days at three temperatures, 40°, 55°, and 75° F, are shown in Figures 4-8. Each data point represents the average of strengths of three test specimens. Specimens were tested at 14 days at 75° F and are considered as the control or maximum strength in determining the cure rate. Results for the materials tested are given below.

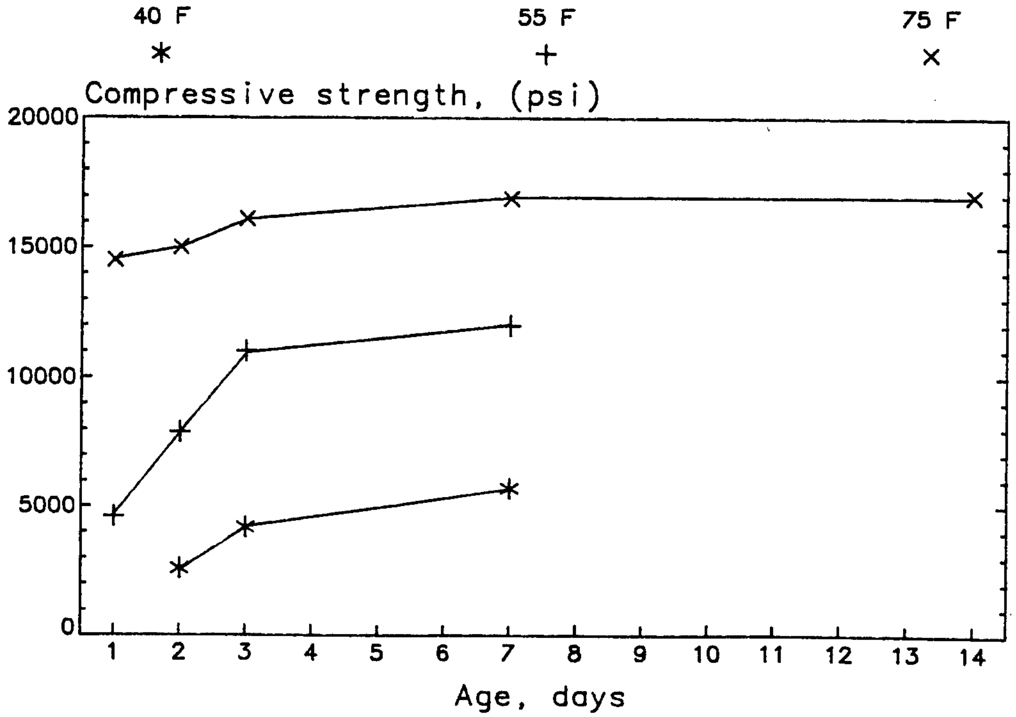


Figure 4. Effect of Temperature on Polymerization, W-EP-3.

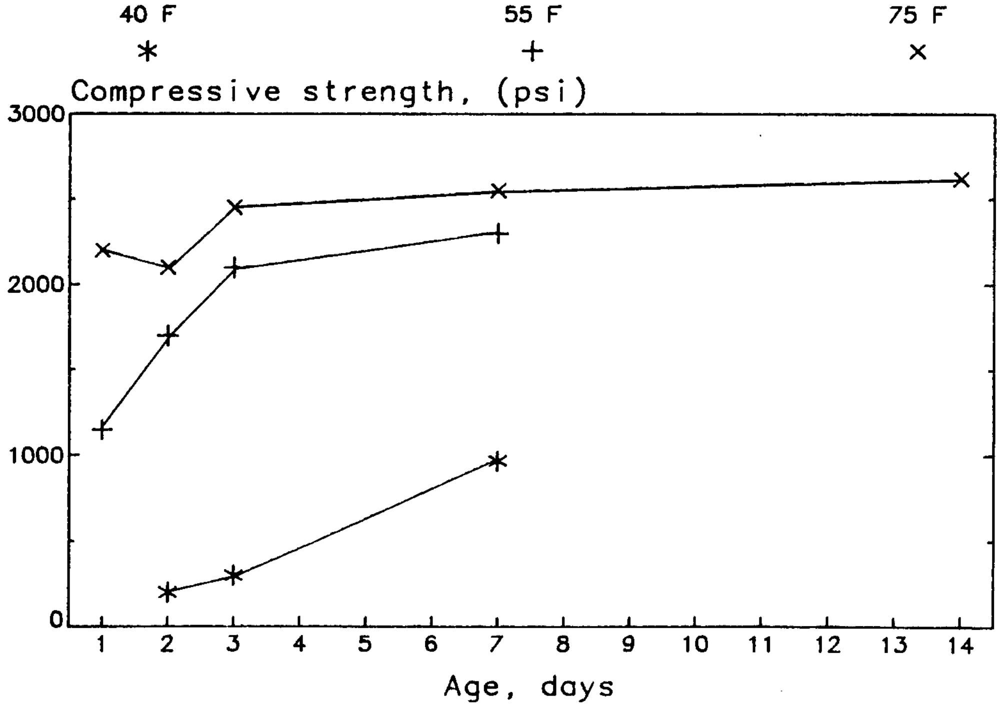


Figure 5. Effect of Temperature on Polymerization, W-EP-4.

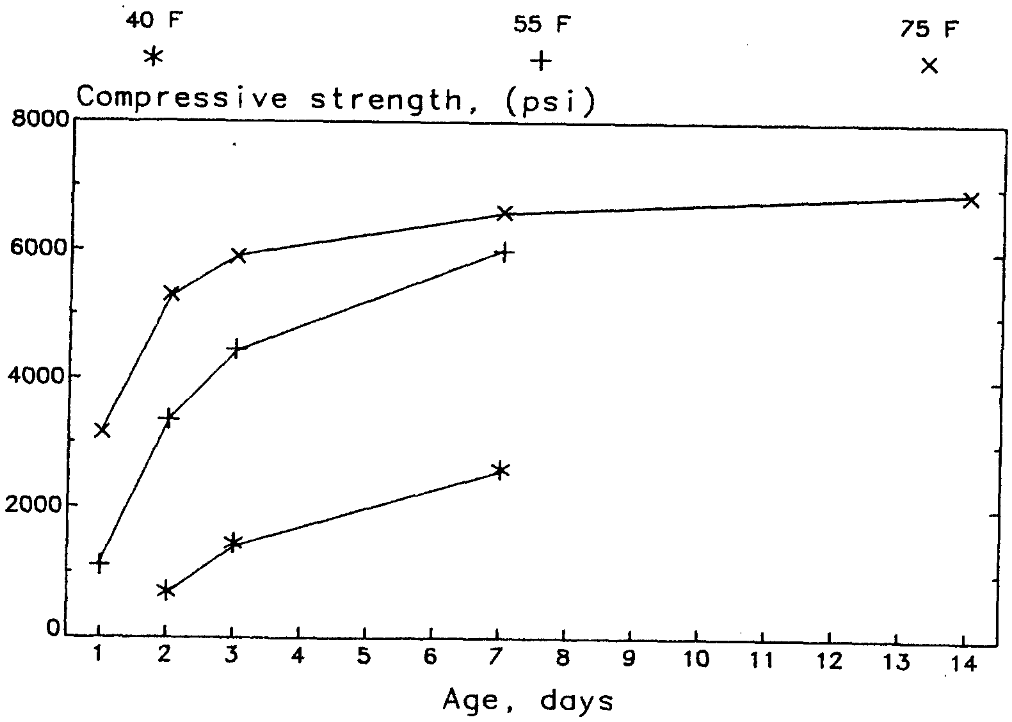


Figure 6. Effect of Temperature on Polymerization, W-EP-7.

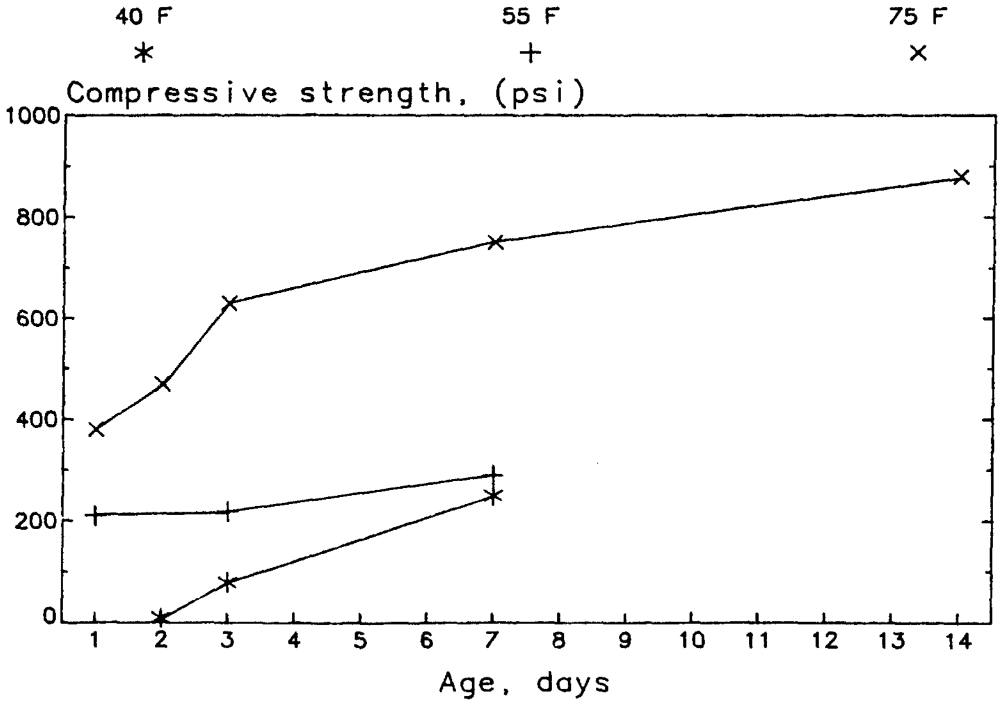


Figure 7. Effect of Temperature on Polymerization, W-EP-10.

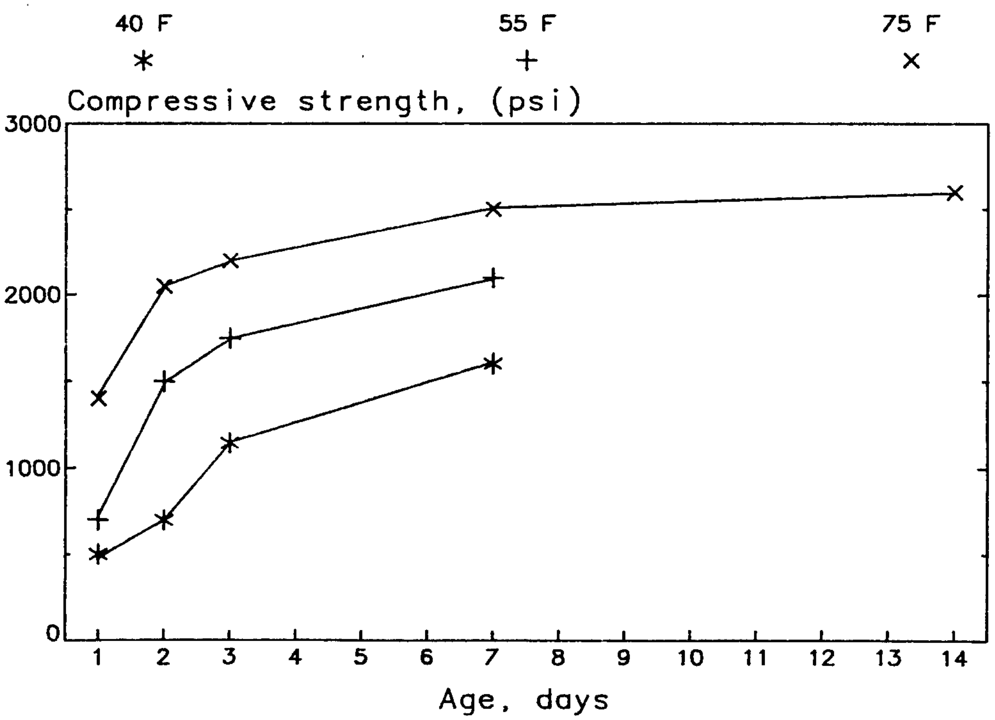


Figure 8. Effect of Temperature on Polymerization, W-PU-7.

a. W-EP-3

The effects of temperature on cure for this material are shown in Figure 4. This material could support aircraft traffic within 24 hours after placement at temperatures as low as 55° F. However, at 40° F this material would require an additional day of cure before traffic is allowed on the repair. Although the strength is relatively low (compared to 75° F cured material), the strength of the material is approximately that of the surrounding concrete.

b. W-EP-4

At a temperature of 75° F this material cured at a fast rate and would be satisfactory for service within 24 hours. The compressive strength after 24 hours was 2,170 psi or 83 percent of the compressive strength of the control (2,620 psi). At 55° F the material cured more slowly, as expected, but did cure at a fairly fast rate. After 3 days of curing at 55° F the compressive strength was 2,090 psi or 80 percent of the compressive strength of the control, which would be satisfactory for service. At 40° F the material cured very slowly. After 7 days at 40° F the compressive strength was only 970 psi. This material should not be applied at temperatures near 40° F unless the inlay area is maintained at a temperature above 60° F by heating.

c. W-EP-7

This material, like the others tested at 40° F, was slow in curing. The compressive strength after 7 days of curing at 40° F was 2,630 psi or 38 percent of the compressive strength of the control (6,880 psi). This material should not be applied at temperatures close to 40° F or lower unless heat is applied to the inlay area to accelerate curing. At 55° F, this material would support aircraft. The effects of temperature on cure for this material are shown in Figure 6.

d. W-EP-10

This material was found to have the slowest curing rate of all the materials tested. At the lower test temperatures of 40° and 55° F, the compressive strengths after 7 days of curing were 254 and 281 psi, respectively. These compressive strengths are 29 and 32 percent, respectively, of the compressive strength (878 psi) determined at 14 days at 75° F. Test results indicate that this material would not be satisfactory for installations at temperatures below 55° F unless the runway could be closed for periods longer than 7 days or heat could be applied. At 75° F this material was slower curing than the other materials and after 2 days of curing the compressive strength was only 54 percent of the control. After 3 days of curing at 75° F the compressive strength was 72 percent of the control. Based on these results, the material should not be applied at temperatures below 60° F if the runway is to be open for traffic within 2 weeks unless heat is used to expedite the curing rate. At temperatures above 75° F the material would support traffic after 3 days of curing.

e. W-PU-7

At a temperature of 75° F laboratory specimens reached 85 percent of ultimate strength in 3 days. However, at 70° F in field conditions, this material probably could be placed in service in 2 days because the polymerization of the polyurethane system is an exothermic reaction. Since larger quantities (field application) generate more heat than small quantities (laboratory application), the "extra" heat will accelerate the curing (or cross-linking process) resulting in higher strengths at an early age. At 55° F laboratory specimens in air reached about 85 percent maximum strength at 7 days; therefore, the time required for the material to be placed in service should be somewhat shorter than 7 days because of the temperature increase in the larger mass. This material should not be applied at temperature close to 40° F or lower unless heat is applied to accelerate the curing of the polymer.

3. Thermal Compatibility Test Results, Concrete and Asphalt

The specimens were visually inspected after each cycle for (1) delamination between the material being tested and the pavement material, (2) cracking in the concrete or asphalt, (3) cracking at the interface of the material, and (4) cracking in the polymer itself. Testing was stopped when a failure was apparent or after 30 cycles, whichever occurred first. Three of the specimens were cycled for the full 30 cycles, with no visual damage occurring. Since the W-PU-7 material could not sustain more than three cycles of freezing and thawing, the material should not be used where there is a chance of freezing. The W-EP-10 material performed poorly in the freeze-thaw test and could be considered for a barrier material only if the other material evaluated in this project fails to perform properly. The W-EP-7 material can be considered for a barrier pad material for concrete runways but should not be considered for asphalt runways. The results of the thermal compatibility tests are shown in Table 6.

4. Bond Strength, Damp Concrete Surfaces

The bond strengths of the test materials applied to damp concrete are shown in Table 7. The only material that bonded satisfactorily to damp concrete was W-EP-3. The concrete should be dry when applying the other test materials.

5. Adhesion of Freshly Mixed Material to Polymerized Materials

The bond strengths of the freshly mixed materials to the same material which has been previously mixed, cast, and fully cured are shown in Table 8; the averages of three specimens are presented. The compression testing on W-EP-10 was terminated when a 25 percent reduction in height of the specimen was reached. Satisfactory bond strengths were obtained for all materials except W-EP-7, which indicates that these materials could be used in the field to repair the same material.

TABLE 6. THERMAL COMPATIBILITY

	Concrete		Asphalt	
Material	No. of Cycles	Remarks	No. of Cycles	Remarks
W-EP-4	30	No damage	30	No damage
	30	No damage	30	No damage
W-EP-7	30	No damage	4	Cracks in asphalt
	30	No damage	8	Cracks in asphalt
W-PU-7	2	Adhesive failure	3	Cracks in asphalt
	3	Adhesive failure	3	Cracks in asphalt
W-EP-3	30	No damage	30	No damage
	30	No damage	30	No damage
W-EP-10	14	Adhesive failure[a]	3	Cracks in asphalt
	18	Adhesive failure	4	Cracks in asphalt

[a] Material pulled loose from concrete and cracked the concrete at the bond line.

TABLE 7. BOND STRENGTH BETWEEN SYSTEMS AND DAMP CONCRETE

Material	Bond Strength, psi	Failure Occurred In
W-EP-4	320	Adhesive
W-EP-7	580	Adhesive
W-EP-10	210	Adhesive
W-EP-3	>2,150	Concrete

TABLE 8. BOND STRENGTH BETWEEN FRESHLY MIXED MATERIAL AND HARDENED MATERIAL

Material	Bond Strength, psi	Failure Occurred In
W-EP-4	1,510	Adhesive
W-EP-7	560	Adhesive
W-EP-10	>660	No failure[a]
W-EP-3	>7,500	Material

[a] There were no bond failures; the test cylinders were compressed 25 percent of the original height.

6. Effect of Exposure to Fluorescent Sun Lamps and Heat

The effects on tensile properties of the materials exposed to fluorescent sun lamps and heat are shown in Table 9. Two of the epoxy-resin materials, W-EP-7 and W-EP-10, were greatly affected as indicated by the change in elongation and tensile strength. There was some change in the elongation of the polyurethane material, W-PU-7; however, this change was not as great as for the two epoxy-resin materials above. The epoxy resins, W-EP-3 and W-EP-4, showed very little change in the tensile properties after exposure, indicating that these materials would not be appreciably affected by light and heat.

TABLE 9. EFFECT OF EXPOSURE TO FLUORESCENT SUN LAMPS AND HEAT

Material	Exposure	Tensile Strength, psi	Elongation Percent
W-EP-4	Light and heat	730	67
	Laboratory conditions[a]	680	64
W-PU-7	Light and heat	2,150	88
	Laboratory conditions	2,300	132
W-EP-10	Light and heat	900	2
	Laboratory conditions	1,690	34
W-EP-7	Light and heat	4,340	17
	Laboratory conditions	2,670	35
W-EP-3	Light and heat	1,870	<1
	Laboratory conditions	1,840	<1

[a] Approximately 75° F with 50 percent relative humidity.

7. Effect of Improper Proportioning

The effects of improper proportioning of the two components for each material are shown in Figures 9-13. As expected, the improper proportioning did affect the properties when compared to the controls (specimens prepared with manufacturer's recommended mixture proportions). The epoxy resin, W-EP-3, was not significantly affected at the 20 percent proportioning error; the specimens had obtained approximately 75 percent of the compressive strength of the control, which was probably due to the small proportion ratio of component B used in the mixture. All other materials were affected even

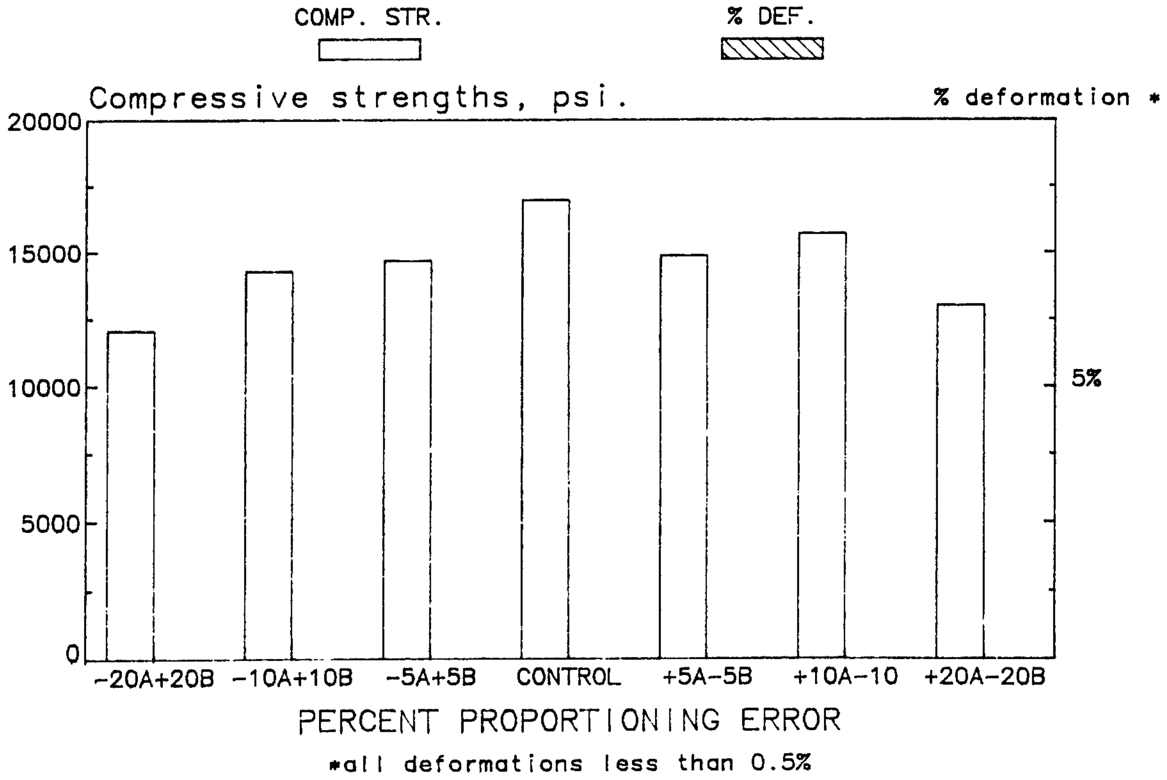


Figure 9. Effects of Proportioning Errors, W-EP-3.

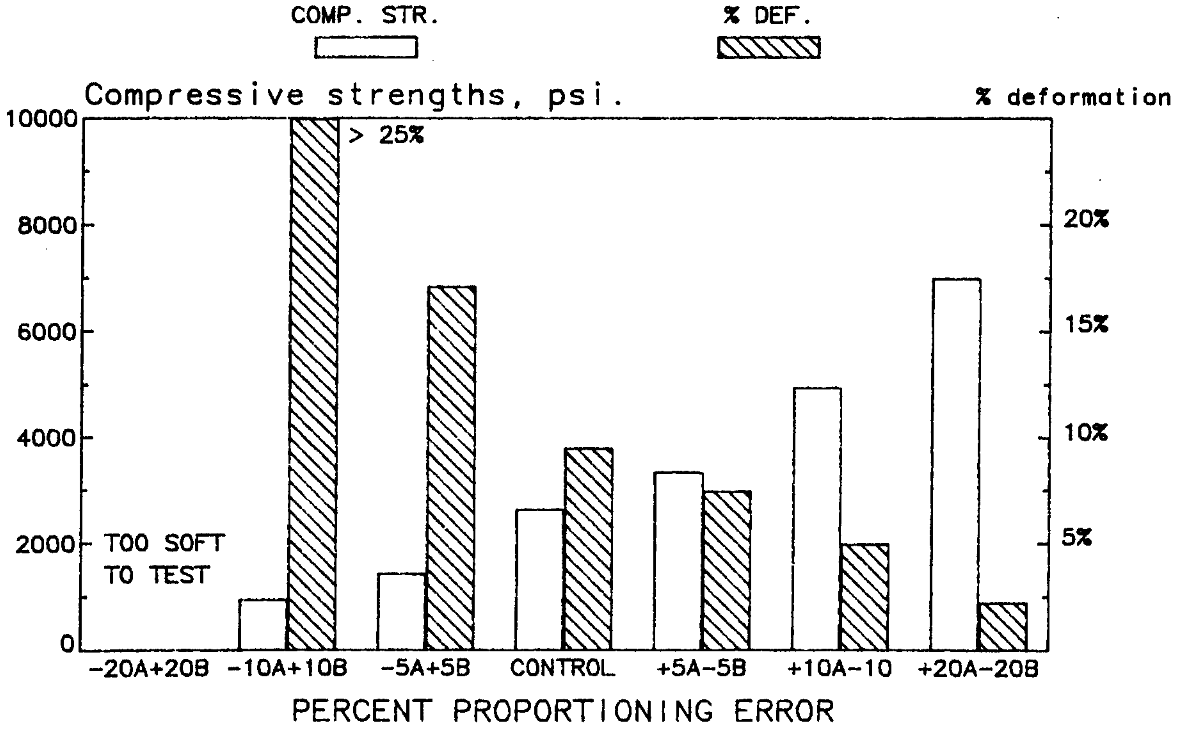


Figure 10. Effects of Proportioning Errors, W-EP-4.

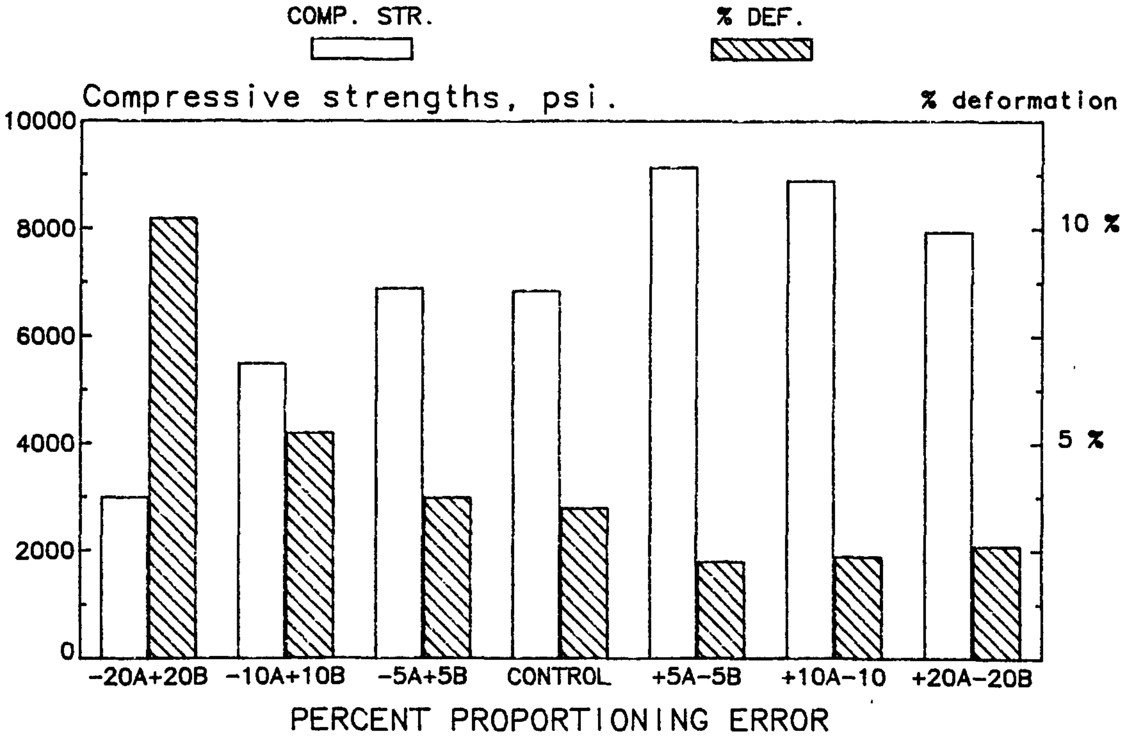


Figure 11. Effects of Proportioning Errors, W-EP-7.

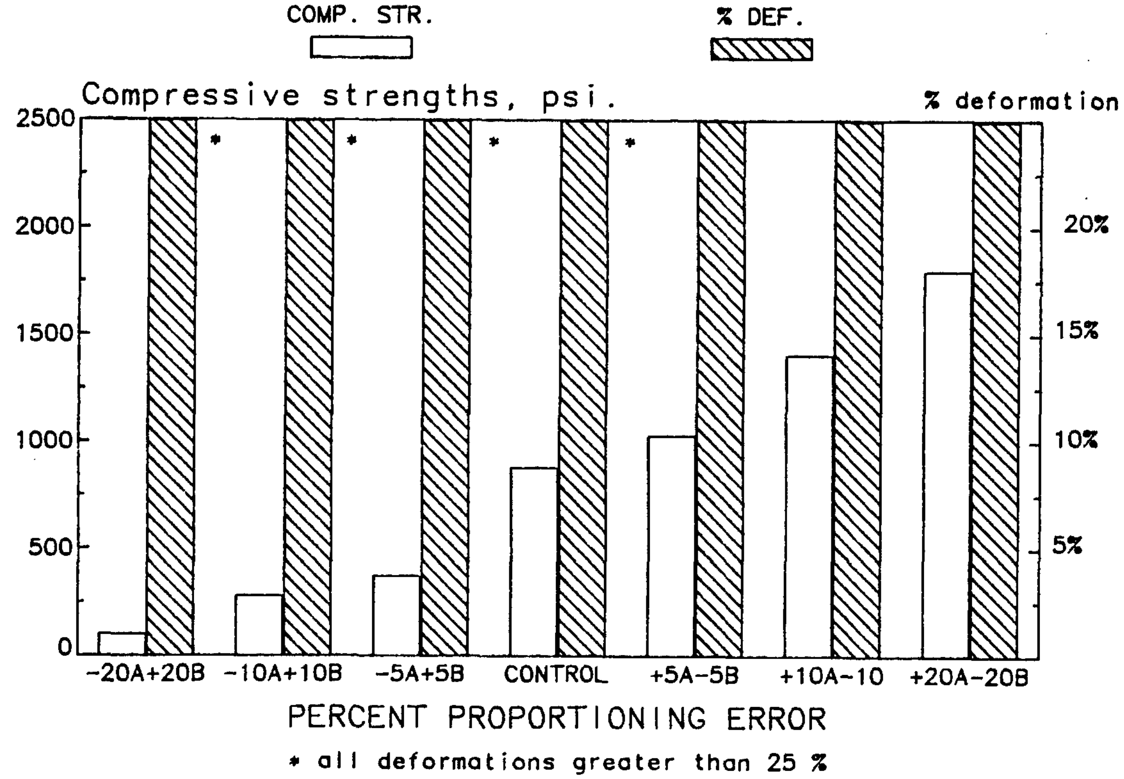


Figure 12. Effects of Proportioning Errors, W-EP-10.

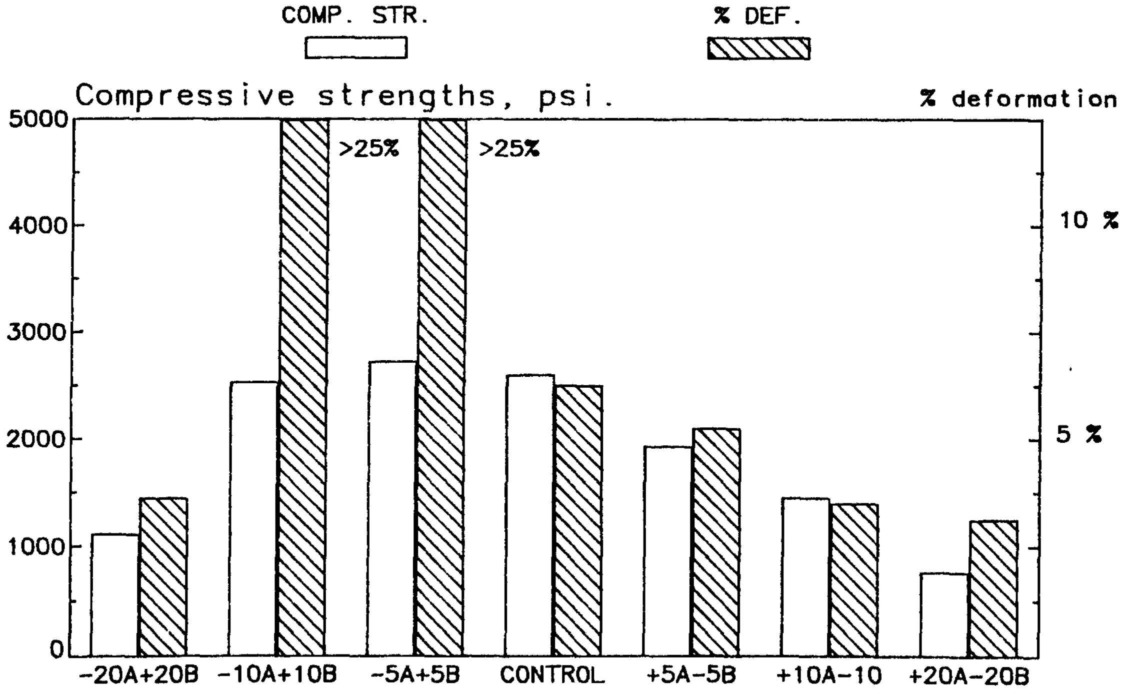
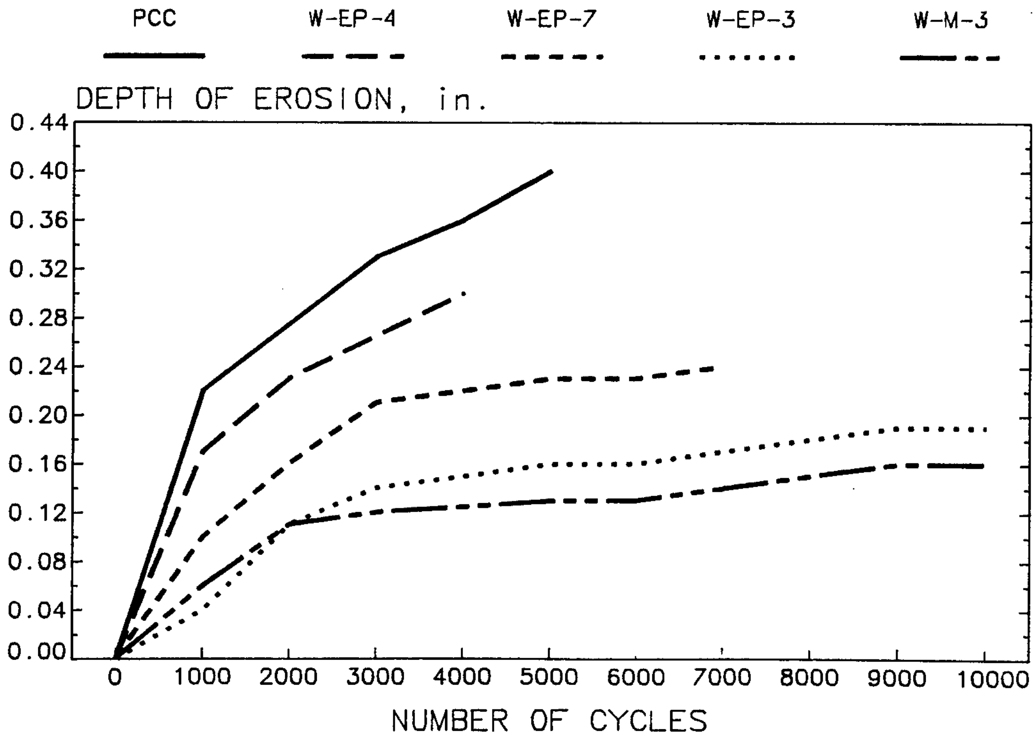


Figure 13. Effects of Proportioning Errors, W-PU-7.

at the 5 percent proportioning error, especially when the A component was decreased and the B component increased. The test results indicate that the correct mixture proportions are critical when obtaining the desired properties of the materials.

8. Cable Abrasion Testing

The materials were tested for cable abrasion as described in Appendix A. A 10,000-pound impact load was used for testing all specimens. The abrasion-erosion rate of the different materials is shown in Figure 14 along with a portland cement concrete control specimen. The control test specimen was cast from a 5,000 psi concrete containing a coarse dimension aggregate. Two other materials, W-M-3 and W-M-4, were also tested and the abrasion-erosion rate of W-M-3 is included in the plot. The material W-EP-10 failed before 1,000 cycles because of cracking and was not plotted. One of the other materials, W-M-4, also failed due to cracking. The material W-M-3 was found to have the highest abrasion-erosion resistance. W-EP-3 was also found to have good resistance to abrasion. The lower abrasion resistance of W-EP-4 was attributed to the sand which was added to the flexible epoxy resin. The sand appeared to cut the epoxy under the impact of the cable. All materials tested



10,000-lb. impact load with cable

Figure 14. Resistivity to Cable Abrasion.

except for W-EP-4 had a much lower abrasion-erosion rate than the portland cement concrete control.

E. ADDITIONAL MATERIALS AND TESTING

1. Testing

The AFESC requested laboratory testing of two fast-setting iron-filled cementitious materials (W-M-3 and W-M-4). The lab testing consisted of compressive strength, adhesion to concrete and asphalt, and the cable abrasion test. The compressive strength testing was done periodically to determine the time required before the material could be subjected to aircraft traffic. The adhesion capacity was determined by the slant shear test (ASTM C 882-78). The material was applied to a concrete specimen with and without an epoxy bonding agent. The impact-abrasion test was performed to determine which of the two materials was more durable.

2. Results

The time-strength relation is shown in Table 10. The testing revealed that after placing, 48 hours of curing is required before the material can be opened to aircraft traffic.

TABLE 10. COMPRESIVE STRENGTHS AT DIFFERENT CURE TIMES FOR W-M-3

Cure Time, hours	Compressive Strength, psi
24	4,840
48	9,990
168 (7 days)	12,400

To determine whether the material required a bonding agent, the material was applied with and without an epoxy adhesive and then tested after 7 days of curing. The results were: (1) the bond coat had a bond strength of 2,970 psi, and (2) the material placed directly onto concrete had a bond strength of 2,930 psi.

The abrasion-impact resisting ratios of W-M-4 were discontinued after 410 cycles because the specimen cracked. Because the material cracked, it was evaluated as a poor material and should not be tested in field applications. The abrasion-erosion rate of the W-M-3 material is shown in Figure 14. The W-M-3 material shows the higher abrasion resistance of all materials tested and was recommended for field applications.

F. FIELD APPLICATIONS AND PERFORMANCE

1. Homestead AFB

Based on the detailed testing results, the material W-EP-3 was recommended for field testing. The material was installed as a barrier pad on the secondary (23 end) of runway at Homestead AFB, Fla., on 14 August 1981. After 4 months in service the material appeared to be performing satisfactorily with a small amount of wear. The barrier pad inlay did contain four transverse cracks which developed shortly after placement of the material. A second installation of this material was made at Homestead AFB on the primary (05 end) runway on 9 January 1982.

On 15 May 1982, 9 months after the first installation and 4 months after the second installation, WES inspected the two barrier pad inlays. The condition of the barrier pad at the 23 end appeared to be about the same as it was on 9 January 1982, except for a few small spalls which developed in the concrete along the barrier pad. There were two locations where the material had buckled up, one at a longitudinal joint and the other at a crack. These areas were sounded with a metal rod and hollow sounds were obtained, indicating a loss of bond at these areas. The rate of wear of the material installed on the 05 end of the runway was greater than what had been expected for 4 months of service. The depth of abrasion of the material was measured by taking depth measurements every 5 feet across the barrier pad. The depth of abrasion ranged from a low of 4/32 inch for the north side to a high of 13/32 inch near the centerline. Only one transverse crack was observed, and this developed shortly after installation.

A second inspection of the barrier pads at Homestead AFB was made on 29 October 1982 because of bond failure of the material to the underlying concrete. The barrier pad at the 05 end had developed six additional cracks since the last inspection and a sounding indicated that the material had lost bond to the concrete in these areas. A few large pieces of the barrier pad material were removed and examined. Concrete was bonded to the bottom side of the material, indicating that good bond had been obtained during placement. The reasons for the bond failure could have been as follows:

a. Thermal skrinkage during cure. The inlay was divided into sections 12 1/2 feet in length by 58 inches wide and 3 1/2 inches deep. Each area was filled with the material in one application and high exotherms were observed.

b. Thermal incompatibility with concrete. The material was tested by WES for this problem; however, it is difficult to predict field applications of polymeric materials especially when the volume of the placed material is as large as the sections described above.

c. Weak concrete substrate. The concrete pavement contained a soft calcareous aggregate. Three concrete cores taken from this area were tested for tensile strength, and the average tensile strength of the three cores was 182 psi.

2. Tyndall AFB

On 28 May 1982, the material W-EP-3 was installed as a barrier pad on the northwest end of runway 13L. The material W-M-3 was also recommended for field testing and the material was installed as a barrier pad at Tyndall AFB on 25 September 1982. The material W-M-4 had previously been used as the barrier pad material underneath the arresting system located about midway of the length of the primary runway. W-M-4 had not performed satisfactorily because of cracks developing in the material shortly after placement and a higher abrasion rate than desired. This material was removed and replaced with W-M-3.

The manufacturer of W-M-3 furnished the material for this installation and the volume of material was slightly less than the volume needed because the depth of the inlay was 1/2 inch deeper than had been anticipated after removal of the old barrier pad material. There was a sufficient amount of the material W-EP-3 stored at the facility to complete filling the inlay. A decision was made on site to place the W-EP-3 material on one side of the centerline as a comparative test of the two materials. The section of the inlay filled with W-EP-3 was 12 1/2 feet long. The remainder of the inlay was partially filled with a fast-setting cementitious grout which was topped with a 1-inch-thick layer of W-M-3. The cementitious grout was recommended by the manufacturer to reduce cost. This cementitious grout was tested by WES and was found to have a 24-hour compressive strength of 4,100 psi.

The old barrier pad material was removed by making a saw cut 2 inches in depth around the perimeter of the pad and saw cuts 6-8 inches apart across the length of the pad. The barrier pad material was broken loose with air hammers and the loose pieces of material removed from the inlay. The inlay was cleaned by sandblasting followed by high-pressure water. The inlay was saturated with water by ponding overnight. The excess water was removed the following day by compressed air before placement of the cementitious grout. Saw cuts were made at the longitudinal joints and plyboard strips coated with polyethylene placed into the saw cuts to maintain the joint opening through the materials. A coated plyboard strip was also placed across the inlay to separate the two materials. The cementitious grout was mixed in a mortar mixer and placed into the inlay. The cementitious grout was screeded with a 2- by 4-inch board with grooves cut into the screed at each end 1 inch in depth to allow for the 1-inch overlay with W-M-3. The cementitious grout was allowed to stiffen for approximately 2 hours until it could support the W-M-3 overlay. The W-M-3 was mixed in a mortar mixer and each mixture consisted of three 55-pound sacks of W-M-3 and 1 1/2 gallons of water. The W-M-3 was compacted by tamping with a grill metal tamper followed by compacting and finishing with a Kelly float (Figure 15).

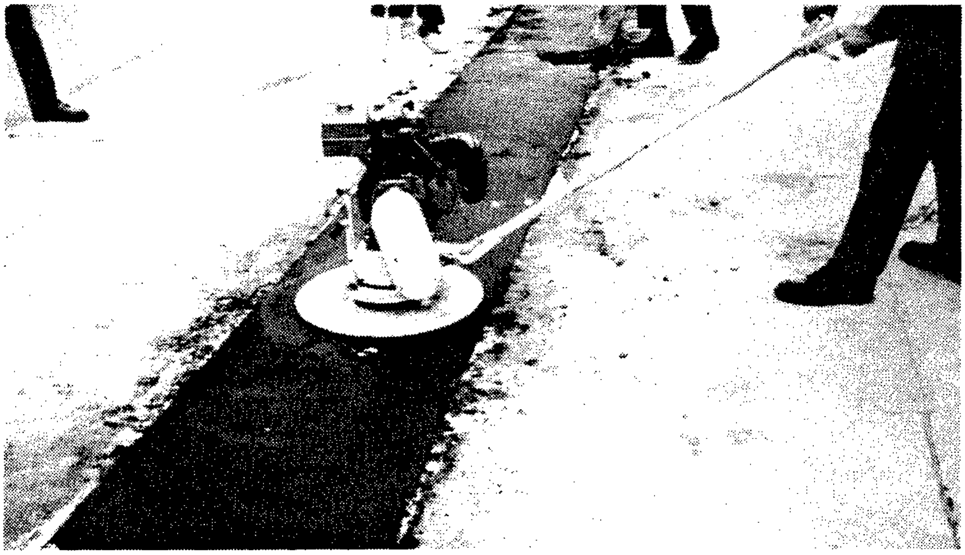


Figure 15. Compacting and Finishing with a Kelly Float.

On 12 March 1983, WES inspected the barrier pads of Tyndall AFB. Figures 16 and 17 illustrate the sections of the two pads that contain the W-EP-3. The cracks, spall areas, and the suspected delaminated areas are shown on the figures.

The inspection revealed cracking, suspected delamination in the W-EP-3 grout, minor surface scaling in the W-M-3, and surface abrasion in both systems. The problems encountered with the W-EP-3 product appeared to be the results of the epoxy shrinking or the difference in coefficient of thermal expansion. Figures 18-20 indicate that some lifting occurred, resulting in delamination. These areas and others next to the cracks were sounded by tapping with an iron rod. Areas that sounded hollow were labeled as delaminated. Figures 21-23 illustrate typical cracks in the pad. The scaling in the W-M-3 material is shown in Figures 24-26.

The erosion of the concrete adjoining the displaced west end of the northwest pad (Figure 18) indicates that the pad was level with the concrete before being displaced upward. This is indicated by the presence of the abrasion marks on both the pad (background, Figure 18) and the concrete (foreground, Figure 18). Figure 20 shows the apparent lifting of the end of the panel and the cracking of the corner. The corner broke loose and settled to its original level.

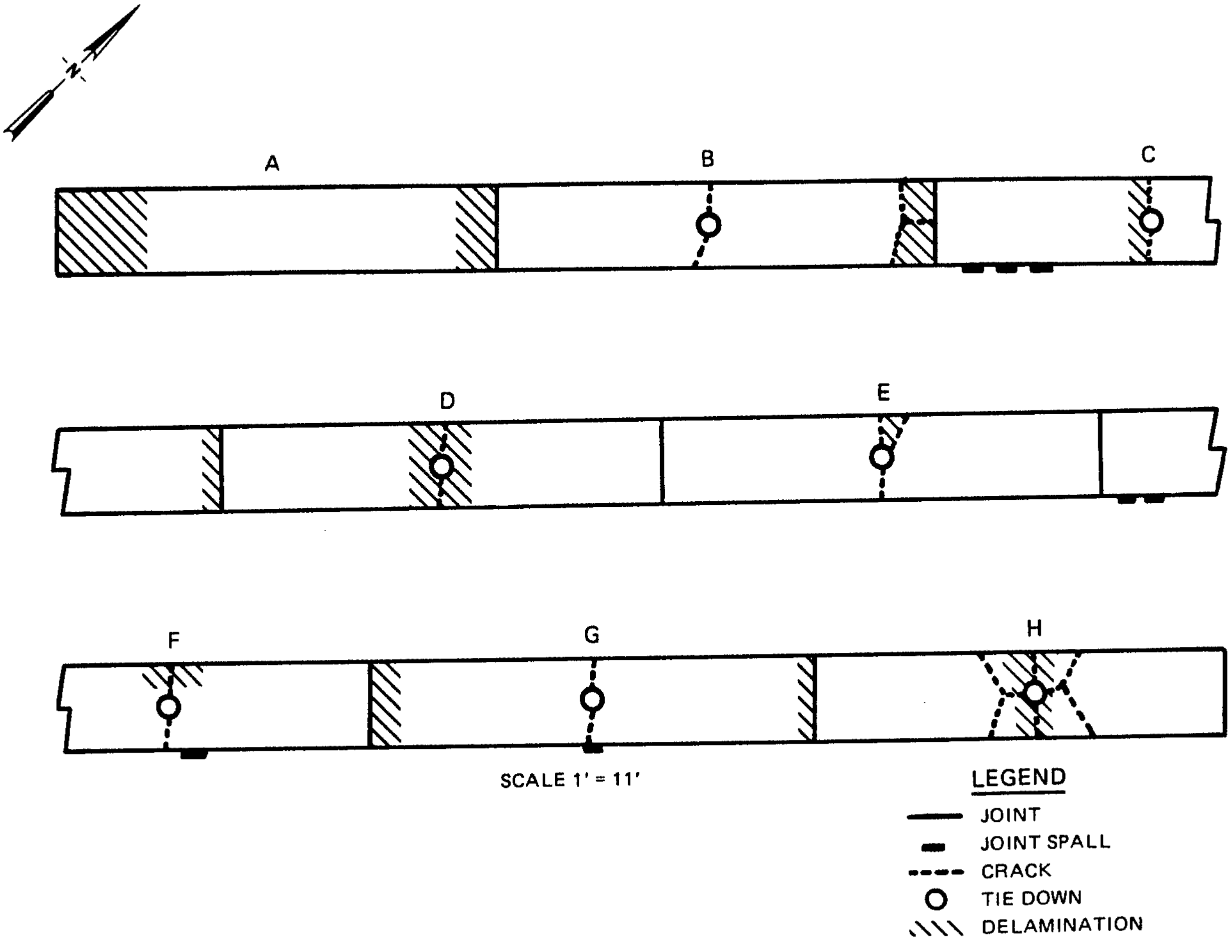


Figure 16. Plan View of W-EP-3 Pad on Northwest End of 13L Runway.

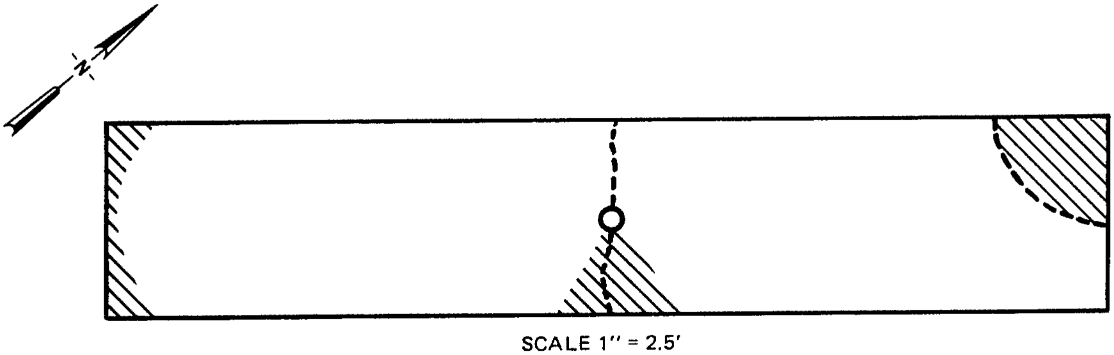


Figure 17. Plan View of W-EP-3 Pad in the Middle of Primary Runway.

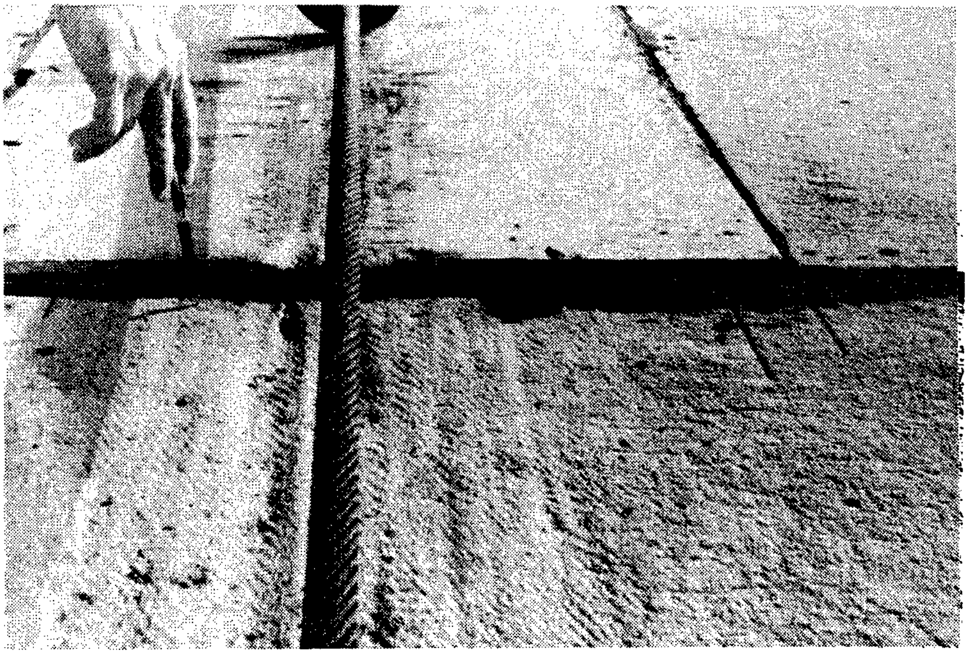


Figure 18. Lifting of the Ends of Panel A.

Figure 19. Lifting in Panel F.

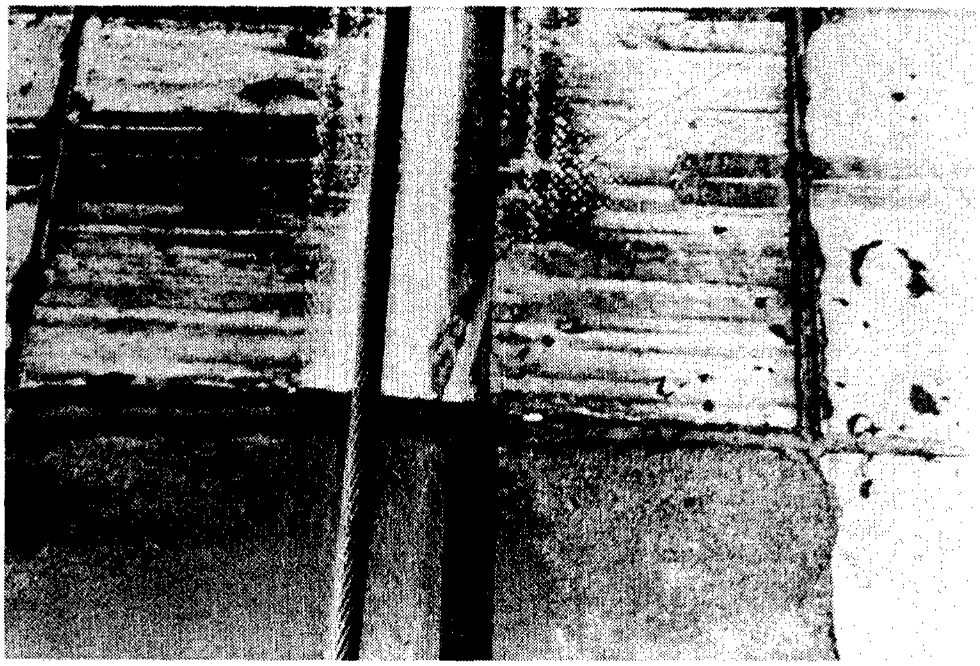


Figure 20. Lifting and Failure of the Corner of a Panel in the Middle Runway, Northwest End of the Panel.

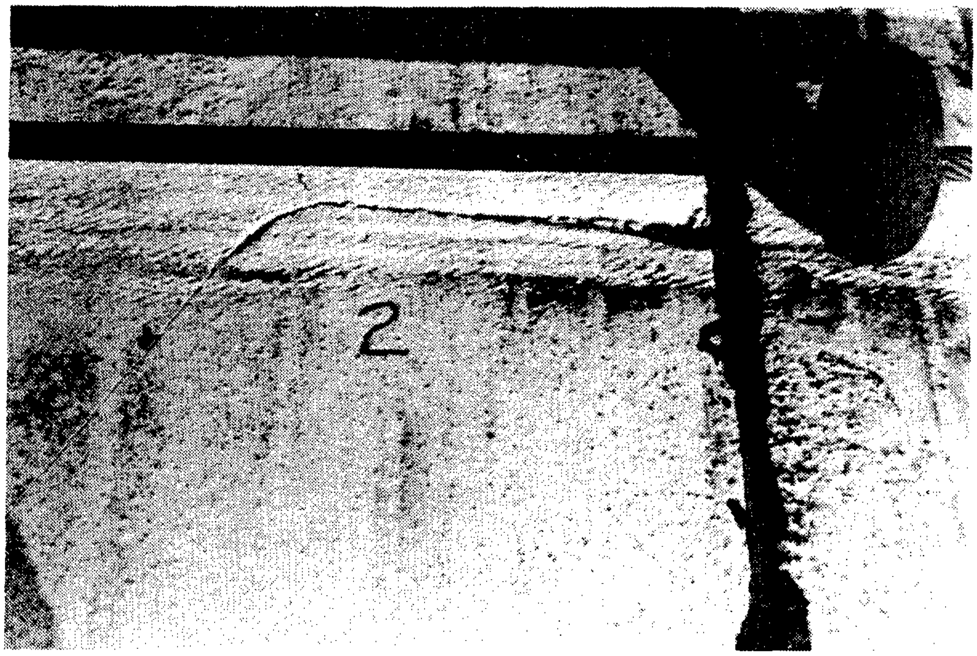


Figure 21. Diagonal Crack in Panel B.

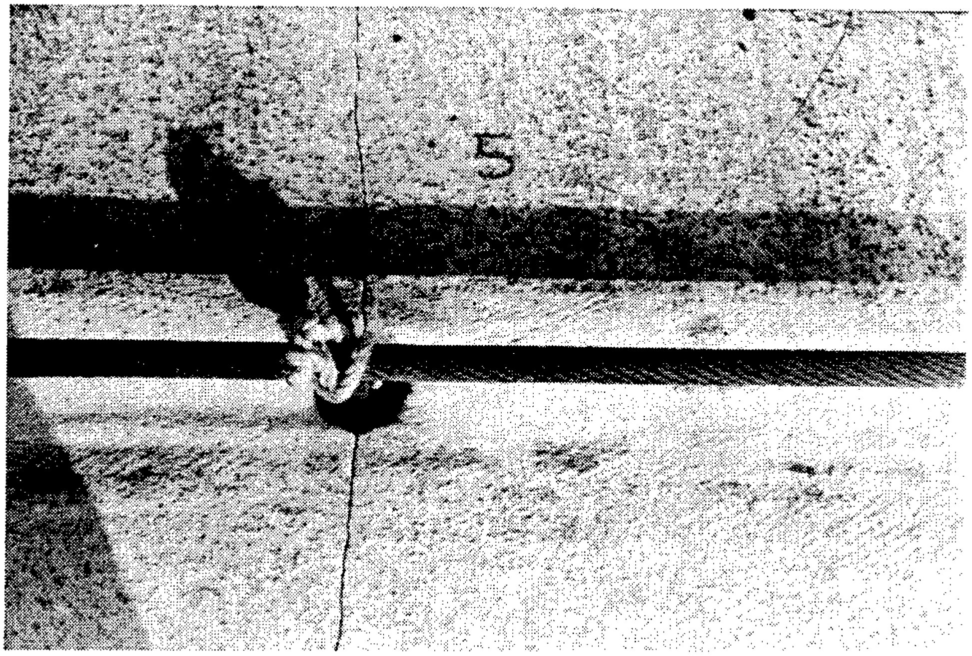


Figure 22. Transverse Crack in Panel E.

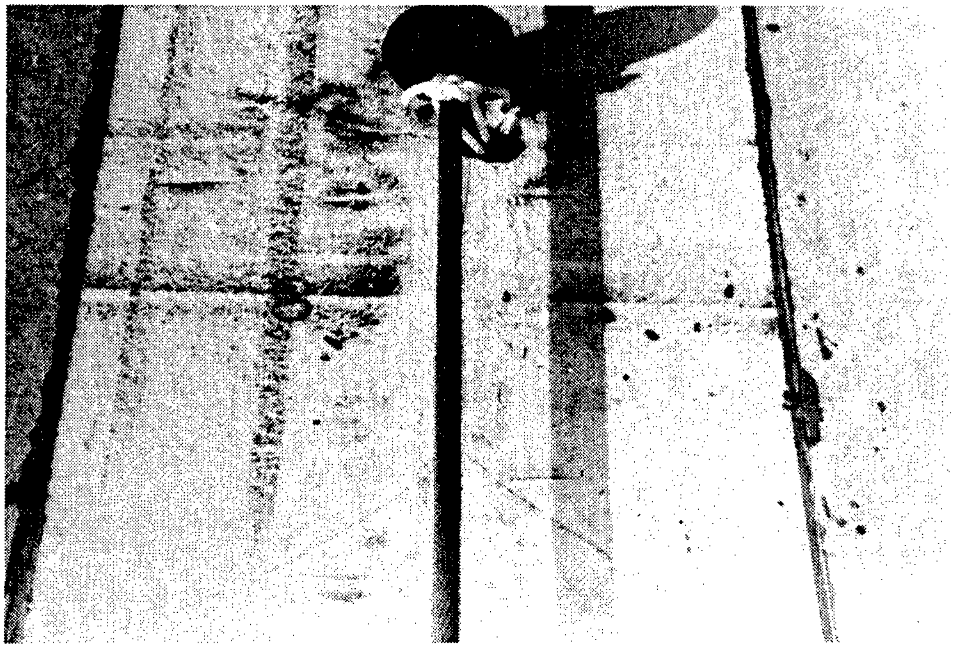


Figure 23. Diagonal Cracks in Panel H.

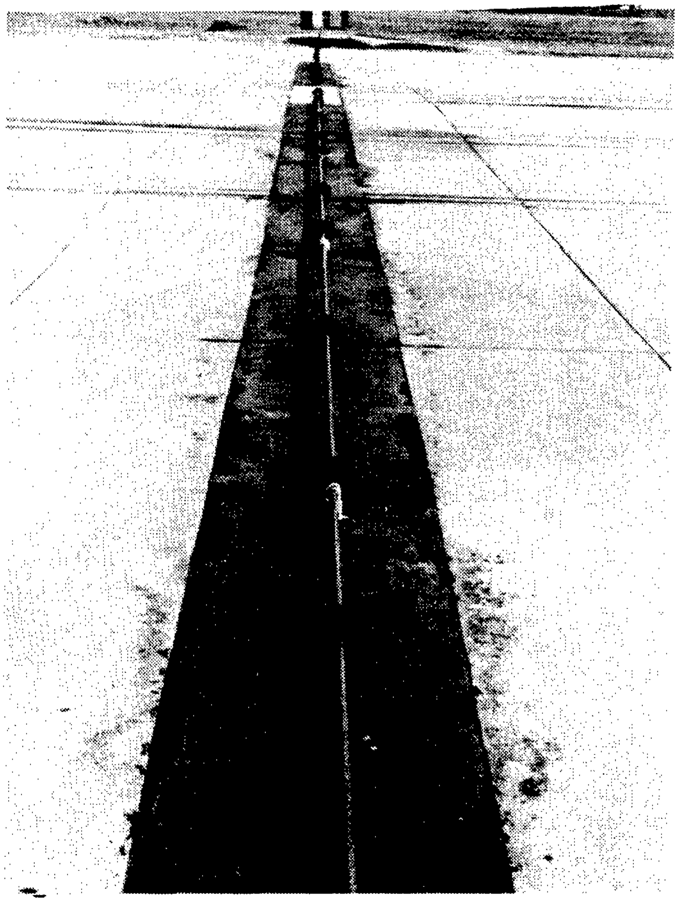


Figure 24. Scaling in W-M-3 Pad.

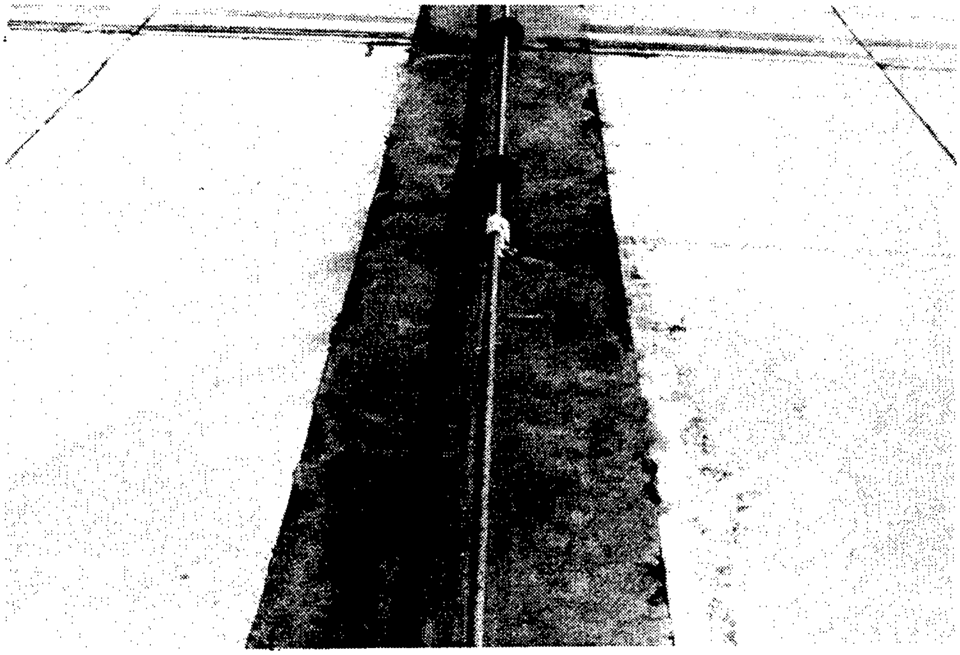


Figure 25. W-M-3 Pad.

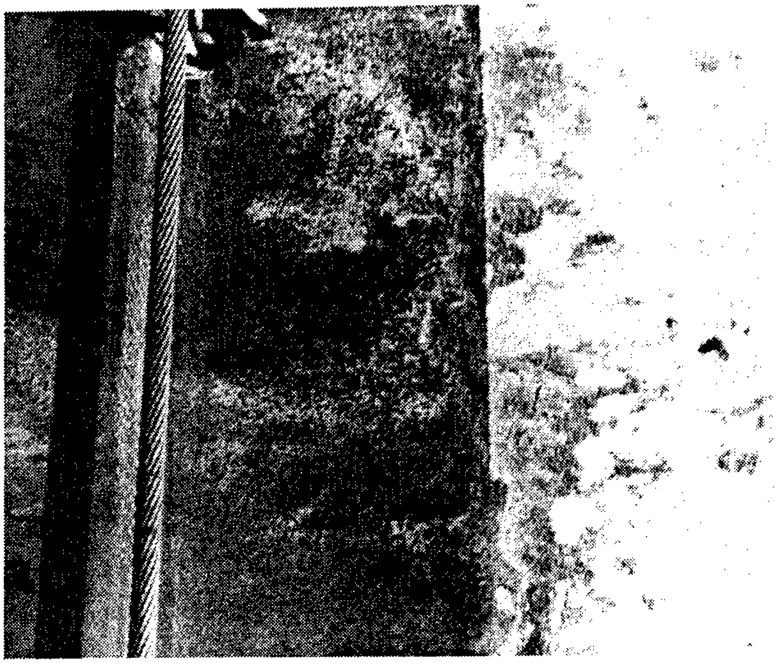


Figure 26. Scaling and Excess W-M-3 on Pavement.

The scaling of the W-M-3 occurred only in areas adjoining the concrete. When the W-M-3 is poorly consolidated, it is more susceptible to weathering and can be deteriorated faster than the properly consolidated material. It appears that the consolidation equipment, a Kelly float, could not properly consolidate the material next to the concrete because the concrete was partially supporting the equipment. This could be a reason why scaling only occurred in areas adjoining the concrete.

The abrasion resistance of the two materials was compared. Depth measurements were taken about 5 feet from the joint separating the two systems (which was the centerline of the runway). The W-EP-3 showed a depth of abrasion of about 7/32 inch, and the W-M-3 had a depth of abrasion of about 5/32 inch.

SECTION III
PHASE II STUDY

The AFESC requested that WES make another survey of materials for use as barrier cable impact pads and test those materials which appeared to be promising, based on the technical data received from the manufacturers. The survey was started in October 1983 and completed in March 1984. Twenty-one materials were tested to some degree, and the more promising were tested for cable abrasion, rate of cure, bond strengths, and thermal compatibility with concrete. Two of the more promising materials based on laboratory tests were installed at Seymour-Johnson AFB, North Carolina, for field evaluation.

A. SURVEY OF MATERIALS

Materials on the market that could meet the requirements necessary for barrier cable impact were sought by a letter survey. More emphasis was placed on elastomeric materials during the Phase II study since it was the desire of some Air Force command personnel because elastomeric materials reduce cable damage. The letters were sent to 108 manufacturers of materials. Forty-eight of the manufacturers submitted technical information. After reviewing the technical information, samples were requested for those materials which appeared to be promising. Materials received for testing are listed in Table 11.

Five of the materials were epoxy-resin systems; nine materials were polyurethanes, one was a preformed neoprene; five were cementitious materials; and two were acrylic polymer concrete systems. Seven of the polyurethane materials were preformed polyurethanes. The suppliers of the preformed materials were contacted and each supplier stated that their materials could be cast in widths up to 3 feet and lengths up to 10 feet at various thicknesses up to 3 inches. One of the preformed polyurethane materials, W-PU-15, was manufactured as a barrier pad material and the supplier had stated that this material had been installed at two commercial airfields. Two materials, W-PU-17 and W-M-9, were formulated by the manufacturer for this study.

Table 11. MATERIALS TESTED IN PHASE II

Material	Supplier	Material Classification
BP-1	Bailey-Parks	Preformed polyurethane
BP-2	Bailey-Parks	Preformed polyurethane
BP-3	Bailey-Parks	Preformed polyurethane
BP-4	Bailey-Parks	Preformed polyurethane
BP-5	Bailey-Parks	Preformed polyurethane
Brutem 800 Experimental	I. W. Industries	High molecular weight methacrylate polymer concrete
Ceva-Patch	Epoxy Industries	Epoxy-resin concrete
Concressive 2020	Adhesive Engineering Co.	Methyl methacrylate polymer concrete
CPR 2116	Upjohn	Preformed polyurethane
Densit	Elborg Technology Co.	Silica-fume concrete
Elborg shotcrete mix	Elborg Technology Co.	Silica-fume concrete
F-4067	Prime Polymers Corp.	Polyurethane
Hydrin	B. F. Goodrich	Preformed neoprene
Magma Quartz	Belzona Molecular Inc.	Epoxy resin
Master plate 100	Master Builders	Iron-filled cementitious grout
MB FT-878	Master Builders	Iron-filled cementitious grout
Purelast 208	Polymer Systems	Polyurethane
Quazite	Lone Star Industries	Epoxy resin
Runway Pendant Impact Pad Model 44	All American Engineering	Preformed polyurethane
Sika 51 SL	Sika Corp.	Epoxy resin
Super Quartz	Belzona Molecular Inc.	Epoxy resin
Silica Fume	WES	Silica-fume concrete

B. TEST METHODS

The materials were tested using the Phase I test methods described under "Preliminary Testing and Evaluation," except for adhesion to asphalt. The impact load for the cable abrasion test was increased to 16,000 pounds as requested by the AFESC. The adhesion to asphalt test specimen was made by bonding the material to the end of an asphalt beam described under "Adherence to Asphalt" in Part I. The beam was then tested in tension by applying a load to a metal rod which was placed on the bond line of the two materials. The load applied to fail the material was divided by the bonded surface area and reported as bond strength in pounds per square inch.

C. TEST RESULTS

1. Impact Resilience and Hardness

The elastomeric materials were tested for impact resilience and hardness, and the results are given in Table 12. Four of the materials, W-PU-11, W-PU-12, W-PU-13, and W-M-6, were found to have a Bashore rebound value in excess of 25 percent and therefore were not considered for further testing. Material W-PU-16 was considered too soft (40 Shore A). All other elastomeric materials were considered for further testing,based on Bashore rebound and hardness readings.

TABLE 12. IMPACT RESILIENCE AND HARDNESS

Material	Impact Resilience, Percent Rebound (Bashore)	Hardness Shore Durometer, A Scale
W-PU-10	10	78
W-PU-11	25	90
W-PU-12	38	96
W-PU-13	31	93
W-PU-14	14	80
W-PU-15	22	--
W-PU-16	--	40
W-PU-17	21	75
W-M-18	20	--
W-M-6	32	--

2. Adherence to Concrete

The bond strength between W-PU-17 (the liquid applied polyurethane system) and concrete was 280 psi when tested as described for Phase I testing. This bond strength was equal to or better than all but one polyurethane tested during Phase I. None of the preformed elastomeric systems were tested since they would be mechanically anchored to the concrete.

For the other materials, the bond strengths were obtained as described under "Adherence to Concrete" in Part II. The test results are shown in Table 13. All materials tested exhibited good bond strengths to concrete.

TABLE 13. BOND STRENGTH BETWEEN SYSTEMS AND CONCRETE

Material	Bond Strength, psi	Failure Occurred In
W-EP-11	>3,100	Concrete
W-EP-12	>8,650	Concrete
W-EP-13	>1,100	Adhesive
W-EP-14	>3,310	Concrete
W-M-1A	>3,040	Concrete
W-M-7	>3,400	Concrete
W-M-9	>3,300	Concrete

3. Adherence to Asphalt

The bond strength between asphalt and the additional four materials was determined. An epoxy resin formulated to bond freshly mixed concrete to hardened concrete was used as a bond coat for the cementitious materials W-M-7 and W-M-9. Only W-PU-17 was found to have a low bond strength to asphalt. The primer furnished by the manufacturer of this material appeared to soften the asphalt. Test results are shown in Table 14.

TABLE 14. BOND STRENGTH BETWEEN SYSTEMS AND ASPHALT

Material	Bond Strength, psi	Failure Occurred In
W-M-3	>125	Asphalt
W-M-7	>118	Asphalt
W-M-9	>132	Asphalt
W-PU-17	40	Adhesive

4. Compressive Strengths

The compressive strengths of three cementitious materials and one polymer system were determined periodically in accordance with ASTM C 109-80 to determine the amount of time required before the material could be subjected to aircraft traffic. All the cementitious test specimens were moist cured until tested. Test results are shown in Table 15. Test results indicated that all the cementitious materials could be subjected to aircraft traffic in 2 days after placement and the polymer system, W-M-9, could be put into service within 1 day. Test specimens made with material W-M-7 were moist cured for 2 days and then cured in laboratory air for an additional 7 days and tested for compressive strengths. This test was performed to determine whether the material would continue to gain strength after moist curing was stopped since the material would most likely be subjected to aircraft traffic within 2 days. The compressive strength of the material after 2 days of moist curing and 5 days of air curing was 18,100 psi, which is 6,670 psi higher than the 2-day moist curing test result (11,430 psi).

TABLE 15. COMPRESSIVE STRENGTHS AT DIFFERENT CURE TIMES

Material	Cure Time, days	Compressive Strength, psi
W-M-7	2	11,430
	7	19,100
	28	23,700
W-M-8	2	5,820
	7	8,620
W-M-10	2	5,960
	3	6,480
	7	8,360
W-M-9	1	17,710

5. Thermal Compatibility with Concrete

Four polymeric materials--W-M-9, W-EP-12, W-EP-15, and W-PU-17--were tested for thermal compatibility with concrete. All materials passed the test.

6. Resistance to Cable Abrasion

Sixteen of the materials were tested for cable abrasion as described in Appendix A. A 16,000-pound impact load was used for testing the materials. A control specimen made from a 5,000 psi concrete mixture containing 3/4-inch limestone aggregate was tested along with the materials for a comparison. Test results are shown in Figures 27-30.

Four polyurethane materials, three preformed and one liquid, were tested for cable abrasion. A comparison of the relative abrasion-erosion resistance of the polyurethanes, along with the better materials and the portland cement concrete control is shown in Figure 27. In general, all polyurethanes tested exhibited excellent abrasion-erosion resistance with essentially no depth of erosion. The material W-M-7 ranked first in abrasion-erosion resistance for all materials excluding the polyurethanes.

The relative abrasion-erosion resistance of the epoxy-resin systems is shown in Figure 28. None of the epoxy-resin systems exhibited satisfactory

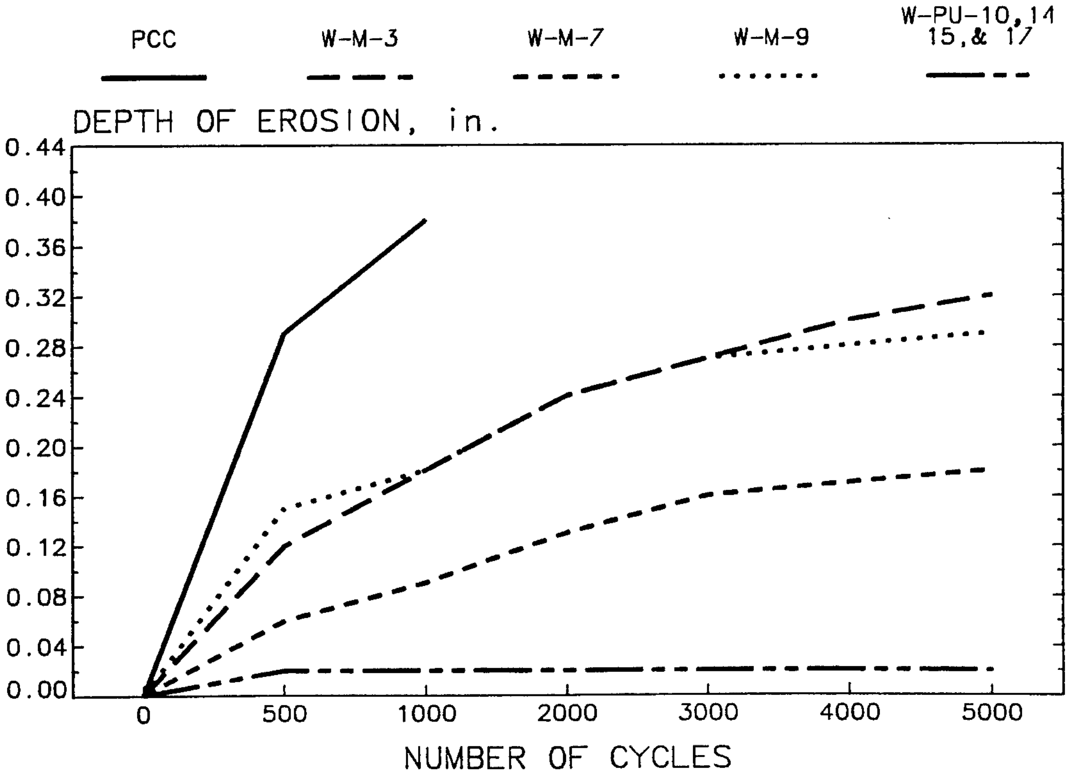


Figure 27. Comparison of the Resistance of Various Materials to Portland Cement Concrete.

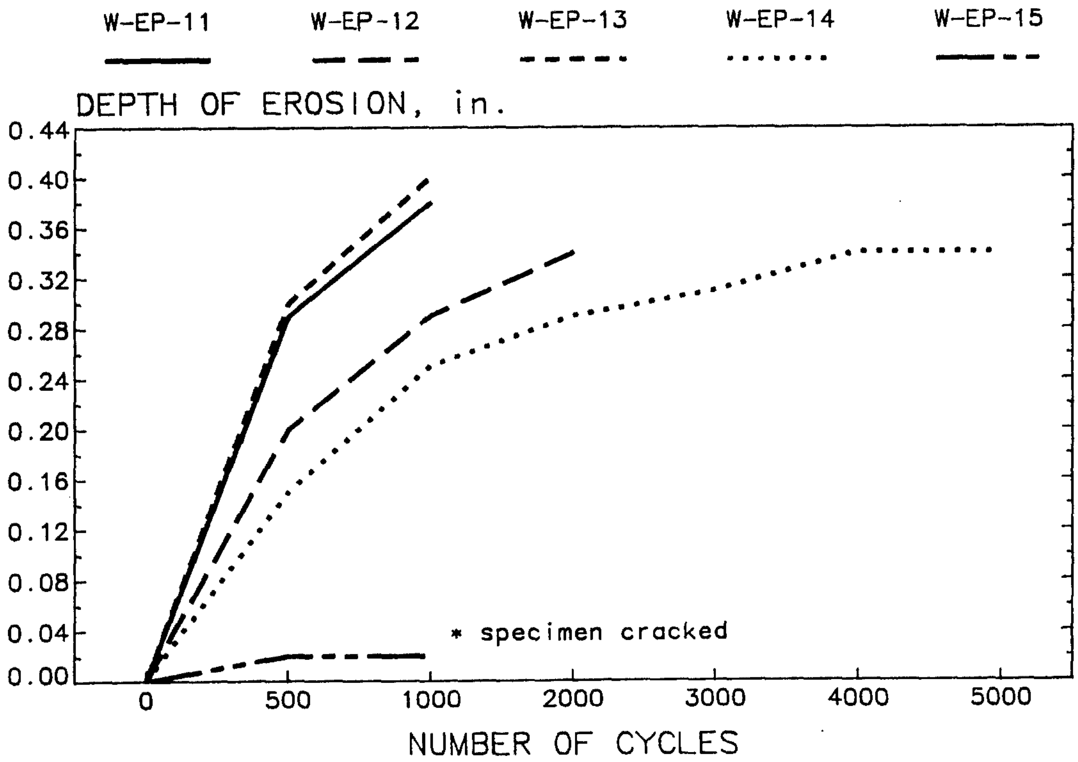


Figure 28. Resistance of Epoxy-Resin Materials to Cable Abrasion.

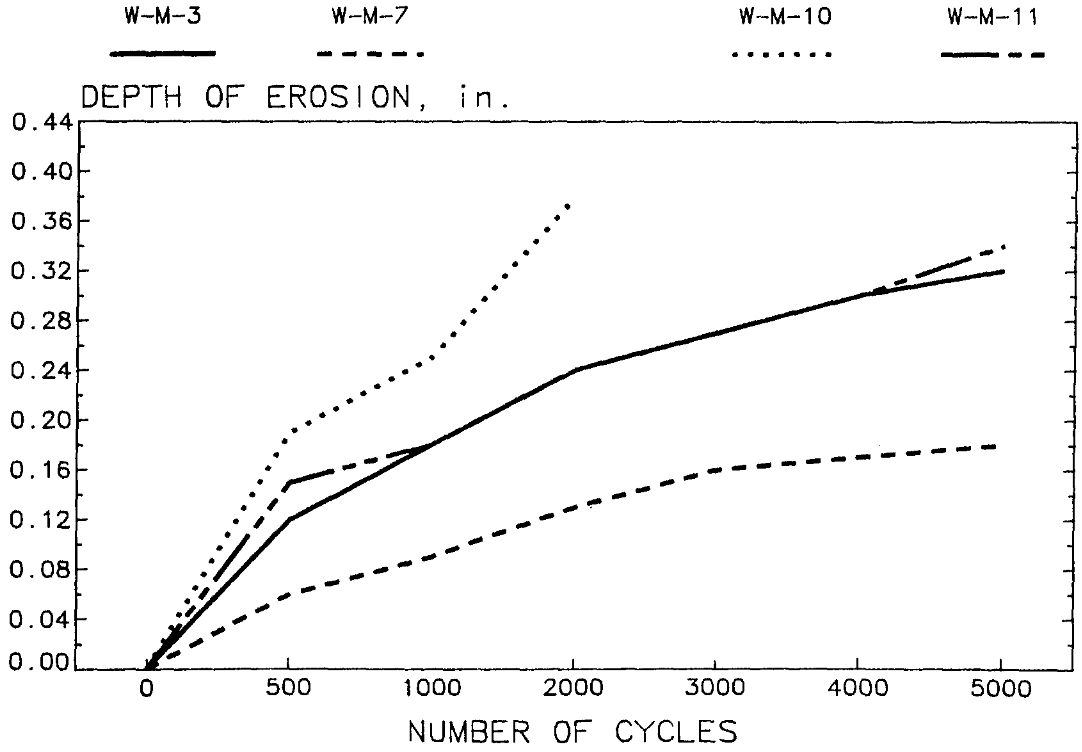


Figure 29. Resistance of Cementitious Materials to Cable Abrasion.

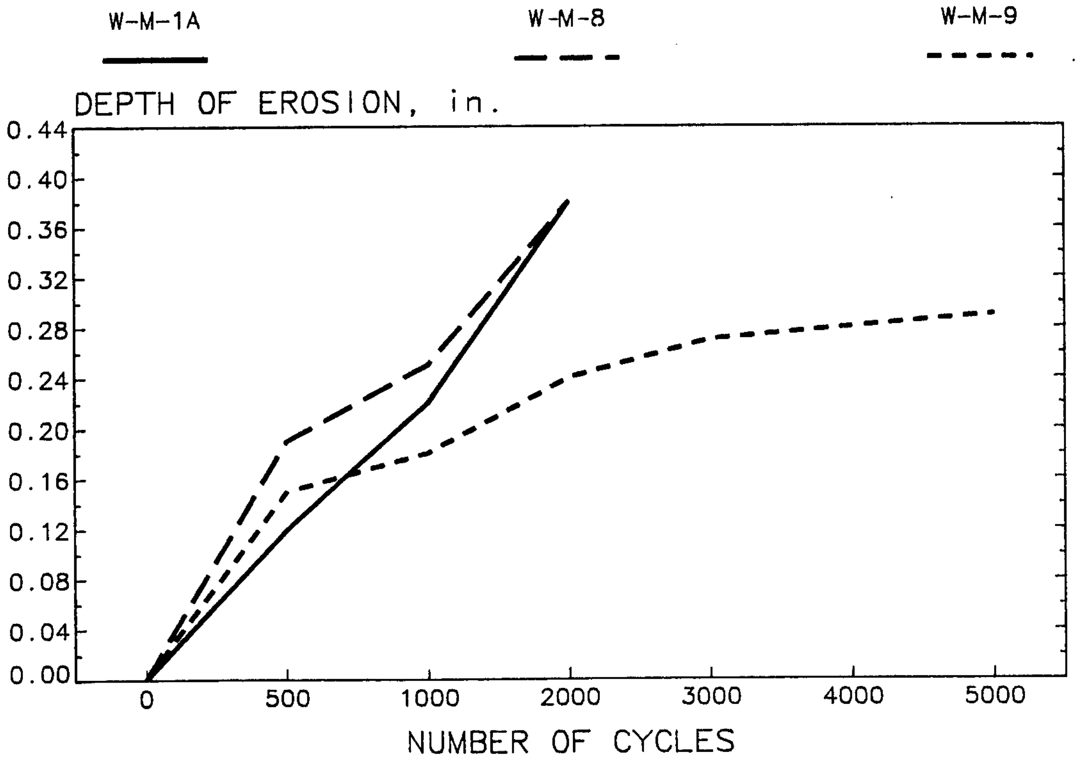


Figure 30. Resistance of Other Materials to Cable Abrasion.

abrasion-erosion resistance, when compared to the better cementitious materials and the acrylic polymer concrete W-M-9. W-EP-15 was highly abrasion-erosion resistant but cracked after 1,000 cycles from impact fatigue.

The relative abrasion-erosion resistance of the four cementitious materials is shown in Figure 29. Material W-M-7 had the highest abrasion-erosion resistance of the cementitious materials tested. The abrasion-erosion depth of this material after 5,000 cycles was 0.18 inch, which is nearly half of the abrasion-erosion depth of W-M-3 (0.32 inch) which had the next highest abrasion-erosion resistance. The silica-fume concrete W-M-11 prepared by WES had an abrasion-erosion resistance approximately equal to W-M-3. The abrasion-erosion resistance of the other two cementitious materials was lower than the other three materials.

The relative abrasion-erosion resistance of two acrylic polymer concretes, W-M-9 and W-M-1A, is shown in Figure 30. Material W-M-9 had good resistance to abrasion-erosion (slightly lower than W-M-3, which is shown as a comparison). W-M-1A did not exhibit good abrasion-erosion resistance.

D. FIELD TESTING AND PERFORMANCE

1. Field Testing at Seymour-Johnson AFB

Based on the test results and availability of materials tested, two materials were selected for field testing at Seymour-Johnson AFB, W-PU-15 and W-M-7. W-PU-15 is a preformed polyurethane pad measuring 3 feet by 59 3/4 inch by 1 inch thick reinforced with a heavy wire mesh. W-M-7 is a commercial silica-fume concrete mixture. The two materials were installed on 6-8 October 1984 under the BAK-12 arresting system cable located on the 26 end of the runway. Two of the preformed polyurethane pads were installed and the remainder of the inlay filled with the silica-fume concrete.

2. Field Installation

The old barrier pad materials, epoxy concretes, were removed by saw cutting around the perimeter of th, barrier pad. The saw cut was 2 inches in depth. The portion of the inlay south of the centerline on the east side was cut 7 inches wider so that a smooth surface could be formed next to where the polyurethane pads were going to be installed. A commercial fast-setting cementitious patching material was placed into this area to form the smooth surface. Additional saw cuts 2 1/2 inches deep were made the length of the barrier pad and these were spaced 6-8 inches apart. These saw cuts were made to help in the removal and control the depth of removal of the old barrier pad materials. Removal of the old barrier pad materials was accomplished by use of air hammers. After the old materials were removed, the area was sandblasted and washed with water followed by drying with compressed air. After cleaning and drying, an inspection of the prepared surface area was made to remove any visibly loose or cracked concrete.

The silica-fume concrete was applied on 6 October 1984. Before application of this material, the 121-inch-long area to receive the polyurethane pads was separated from the remainder of the prepared area by saw cutting two grooves 1/2 inches wide at each end and placing a strip of plyboard coated with a polyethylene sheet into the grooves formed by the saw cuts. W-M-7 was mixed in a mortar mixer. The placement of W-M-7 is shown in Figures 31 and 32. A bag of W-M-7 weighed 80 pounds and 3 quarts of water was added to a bag. Three bags of the W-M-7 material (240 pounds) and 9 quarts of water were used for each batch. Three mortar mixers were used in order to speed up the

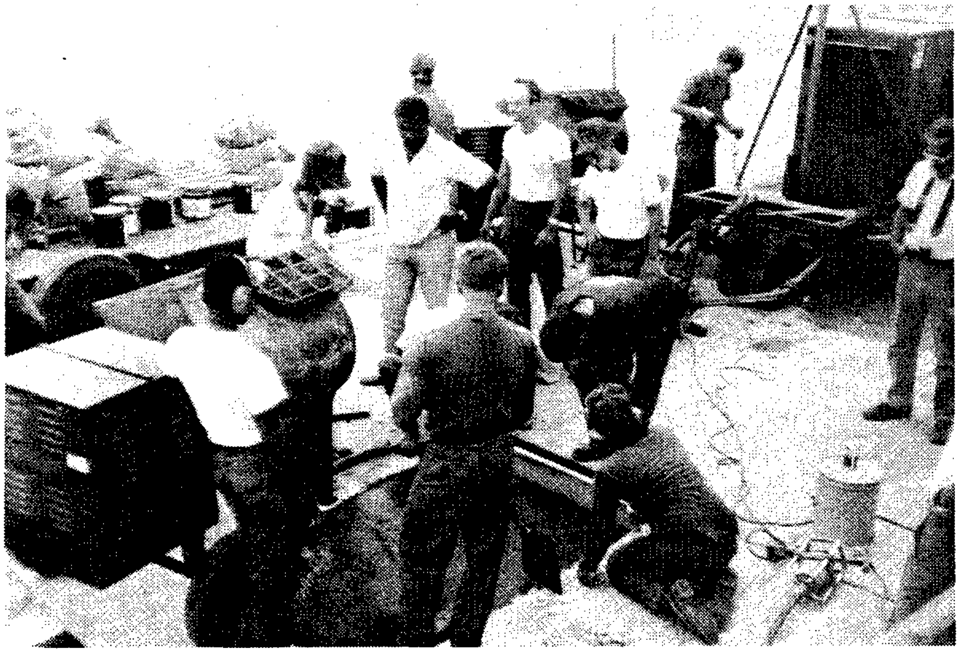


Figure 31. Placement of W-M-7.

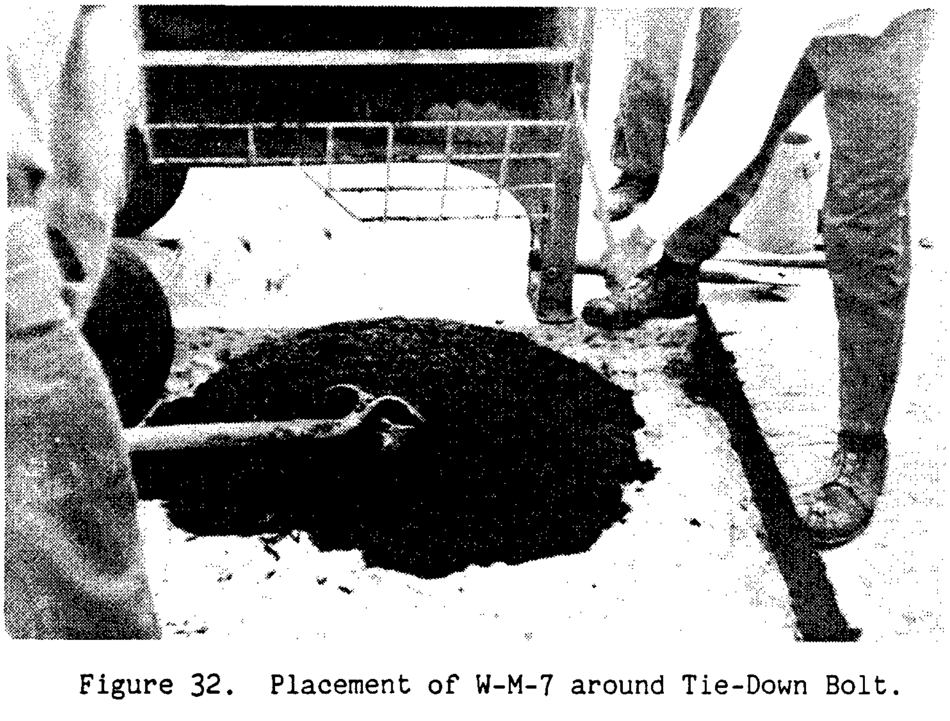


Figure 32. Placement of W-M-7 around Tie-Down Bolt.

application. The mixing time for each batch of the W-M-7 was 10 minutes. The mixed material was then poured into the prepared groove and consolidated with a vibrator. The material was then screeded with a wooden beam (2- by 4-inch wooden beam, 5 feet in length) and finished with a trowel. A white pigmented curing compound was sprayed onto the surface shortly after the finishing operation (Figure 33). The inlay of W-M-7 was covered with clear plastic sheets.

The material was difficult to finish because a hard film formed on the surface before the material was trowelled. This problem resulted because the material was spread over a long area and too much time elapsed before finishing. Also the material was not vibrated long enough. If W-M-7 is selected for use as a barrier pad material at another AFB facility, the following changes should be made for application of the material:

a. Set the mortar mixers about 10 feet away from the end of the groove and use wheelbarrows to transport the freshly mixed material to the groove.

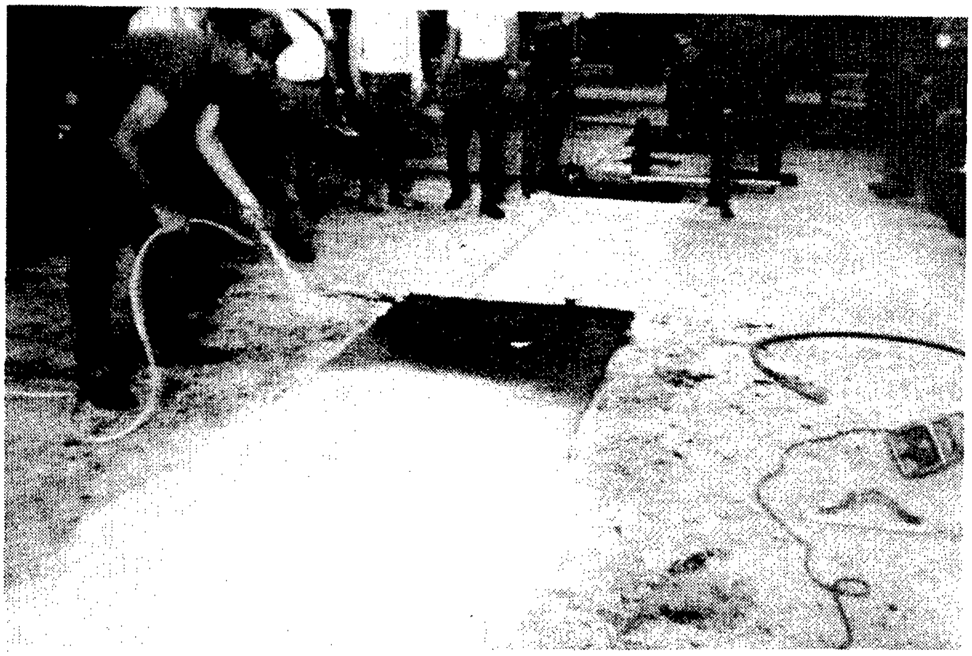


Figure 33. Application of Curing Compound.

b. Start placing the material at one end into the groove, working forward with placements.

c. Vibrate the material thoroughly and screed immediately after vibrating followed by trowelling.

Before polyurethane pads were installed, the pads were attached to a sheet of plyboard. Each preformed polyurethane pad was attached to a 1/2-inch-thick plyboard which was 4 feet wide and cut to the length of the polyurethane pad prior to the installation. The six steel anchors were installed and bolts placed into the anchors to hold the pad firmly against the plyboard. A 1/16-inch-thick washer was placed between the polyurethane pad and the plyboard so that the pad would be 1/16 inch below the surface when installed. Two other bolts were placed into the small tooling holes in the middle of the pad to hold the middle of the polyurethane pad firmly to the plyboard. Four wooden handles were constructed and attached to each corner. A polyethylene sheet was wrapped around the pad to prevent the pad from adhering to the epoxy levelling course. A polyurethane pad attached to the plyboard sheet is shown in Figure 34.

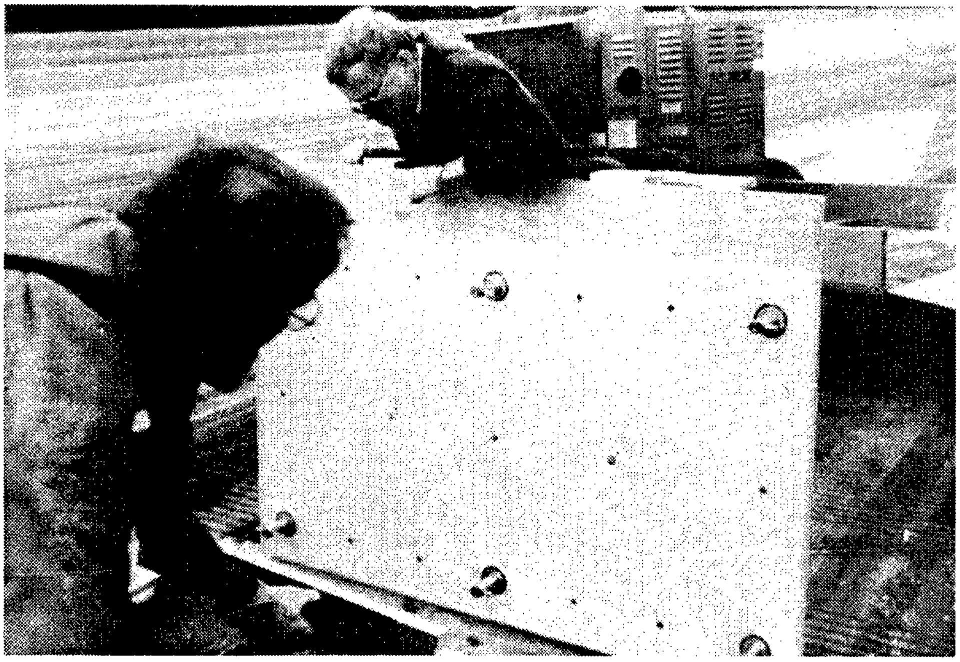


Figure 34. Applying Polyethylene Sheeting to Preformed Pad.

The polyurethane pads were installed 7-8 October 1984. A star drill was used to drill holes into the concrete where the anchors would be placed. The holes were drilled to a depth of 5 inches below the surface of the runway. A chipping hammer was then used to enlarge the holes to a diameter of at least 4 inches. The concrete surface was then coated with an epoxy resin by brushing the epoxy resin on the prepared surface. Epoxy-resin concrete was mixed with a mortar mixer. One part of the epoxy resin was mixed with four parts of sand and two parts of pea gravel by volume. The epoxy resin was a two-component system with a mixing ratio of two parts A component to one part B component by volume. The mixed epoxy-resin concrete was poured into the area and the height of the material levelled to 1 1/16 inches below the runway surface by use of a wooden screed. The screed was made by cutting a 1 1/16-inch notch into the ends of a 2- by 4-inch board. Steel trowels were then used to finish the surface of the epoxy-resin concrete. Placing and finishing of the epoxy-resin concrete levelling course are shown in Figure 35.

The polyurethane pads were placed on top of the freshly mixed epoxy-resin concrete as shown in Figure 36. Some of the epoxy-resin concrete that

Figure 35. Placing the Levelling Course.

Figure 36. Placing Polyurethane Pad over the Levelling Course.

was left from the last batch was poured into a 5-gallon plastic pail to a depth of 3 inches to observe the rate of hardening of the epoxy-resin concrete. Sandbags were placed on the edge of the plyboard sheets and in the middle to hold the polyurethane pads in place until the epoxy resin had hardened. Six hours after placement, the epoxy-resin concrete in the plastic pails was inspected and the material had hardened enough to remove the polyurethane preformed pads. The polyurethane pads were removed and the epoxy-resin concrete levelling course with the anchors embedded in the material is shown in Figure 37. There were some imprints of the polyethylene sheet on the surface of the epoxy-resin concrete. These imprints were shallow and should not affect the performance of the polyurethane pads. Spraying the bottom side of the pads with a wax or other suitable bond breaker should be investigated before any other applications are made using this material. There were also a few low areas (1/4 inch deep) near each end of the two pads. These low areas were caused by the epoxy-resin concrete flowing into the grooves cut for the plyboard forms. The grooves should have been sealed before placement of the epoxy-resin concrete. These areas were roughened and some freshly mixed epoxy mortar was placed into these areas to level the surface with the surrounding surface. Some of the rough edges of the epoxy-resin concrete were removed with a side arm grinder.

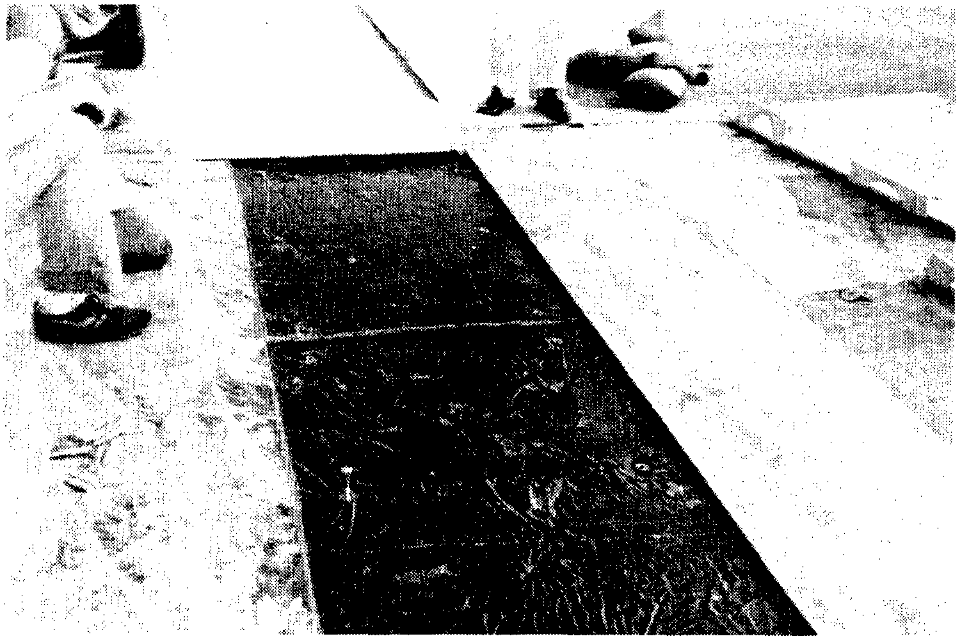


Figure 37. Levelling Course with Anchor Embedded.

The two polyurethane pads were placed onto the prepared surface. One grommet was placed above each of the large holes in the pad and one washer below each hole. A flathead socket screw was then placed into each hole and tightened into the anchors with an allen wrench. The anchoring of the polyurethane pad by tightening the flathead socket screws is shown in Figure 38. Figure 39 shows the installed polyurethane pads. The 1/2-inch joint around each pad was sealed with a joint sealant material meeting the requirements of Federal Specification SS-S-200D (Reference 4).

3. Field Performance

Approximately 1 month after the installation of the preformed polyurethane pads, it was reported that the pads had started to warp (Figure 40). The two pads were turned over and the warping was eliminated for a time but could reoccur. The pads were being turned over at least once a month. After 9 months of service the pads had started to warp to such an extent as to justify removal. Torn places in the pads below the cable were also observed (Figure 41). The tears in the polyurethane pads were due to metal plates that were installed at form holes during the manufacturing process to center the wire mesh. The cable had started to bow the small metal plates causing the plates to protrude through the pads.

Figure 38. Anchoring the Polyurethane Pad.

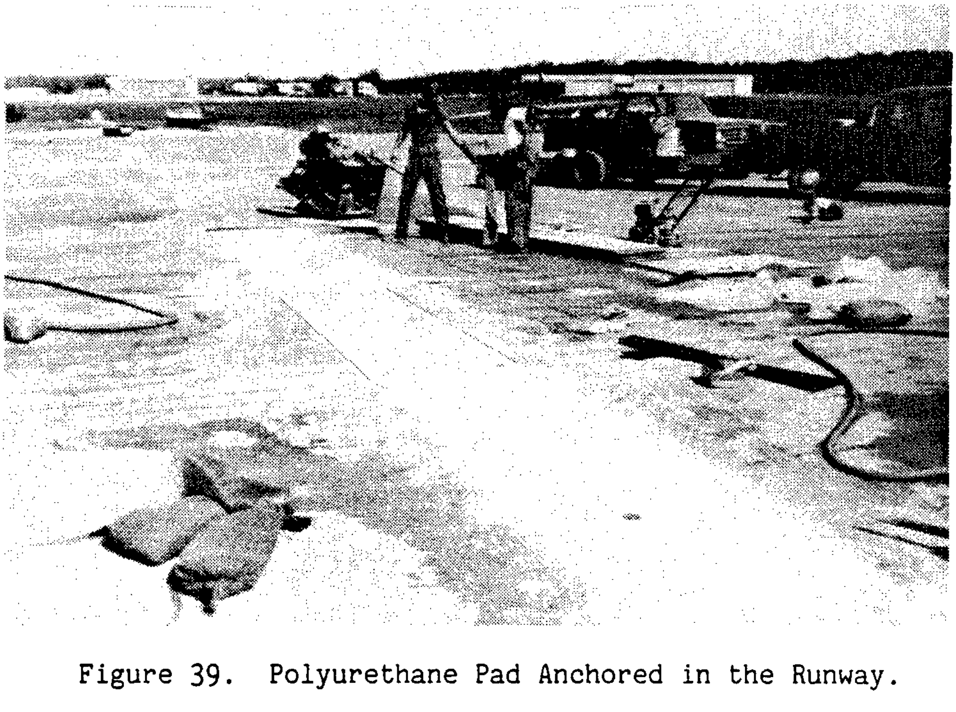


Figure 39. Polyurethane Pad Anchored in the Runway.

Figure 40. Warpage in the Polyurethane Pad.

Figure 41. Deterioration within the Polyurethane Pad.

The silica-fume concrete was performing satisfactorily after 9 months of service with a slight amount of erosion present. There was no evidence of spalling due to impact of the cable and no delamination to the sides or bottom of the inlay. This material shows promise as a barrier pad material based on the laboratory and field tests, but it may be difficult to repair. The hardness and types of fillers incorporated in the mixture could be troublesome while preparing the material for the repairs.

When contacted, the manufacturer of the polyurethane pads recommended that the design of the wire mesh be changed slightly and the metal plates removed. The manufacturer also recommended that the bolts be tightened with a torque wrench to obtain 25 foot-pounds and then the force reduced by turning the wrench one-fourth turn in the opposite direction. Two of the polyurethane pads having the new design were ordered for replacement of the two placed in service earlier and were installed on 19 October 1985.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Five materials, four epoxy resins and one polyurethane, were selected from the survey and screen tests during the Phase I study for detailed testing. The material W-EP-3, an epoxy-resin grout, was selected for field tests based on the test results. W-EP-3 obtained high bond strengths to concrete and asphalt (bond strength greater than the concrete and asphalt). High bond strengths (strengths equal to the material) were obtained when bonding the freshly mixed material to the hardened material. Although this material had a gel time of 120 minutes at 75° F, it developed 90 percent of its compressive strength in 24 hours at this temperature. The material passed the thermal compatibility test when applied to both concrete and asphalt test specimens. The material was not affected by the ultraviolet light and heat test and exhibited the highest abrasion resistance of the four epoxy-resin systems tested. The epoxy resin, W-EP-4, showed promise based on all the tests except for abrasion resistance, and this material exhibited the lowest abrasion resistance of all epoxy resins tested. The polyurethane material, W-PU-7, was eliminated as a candidate material for field testing because it failed the thermal compatibility test.

Two iron-filled cementitious materials, W-M-3 and W-M-4, were tested as requested by AFESC. W-M-4 cracked when tested for cable abrasion, indicating poor impact strength. W-M-3 was found to have an abrasion resistance greater than W-EP-3. Early compressive strength test results (10,000 psi in 48 hours) indicated that the material could be opened to aircraft traffic within 48 hours after placement. W-M-3 was recommended for field testing.

Six materials--three preformed polyurethanes, one liquid polyurethane, one polymethacrylate polymer concrete, and one silica-fume concrete--showed promise based on the laboratory test during the Phase II study. None of the polyurethane materials exhibited any wear or cracking when tested for 5,000 cycles upon completion of the cable abrasion test. W-PU-15 was chosen over the other two preformed polyurethanes for field testing since this material was already being manufactured as a commercial barrier pad. The liquid polyurethane, W-PU-17, had a viscosity that was higher than most of the liquid polyurethanes tested causing air to be entrapped in the material during mixing. This material also had a slow cure rate at temperatures below 70° F. The silica-fume concrete, W-M-7, exhibited the highest abrasion resistance of all materials tested except for the polyurethanes. Early compressive strength test results (11,400 psi in 48 hours) indicated that this material could be opened to aircraft traffic within 48 hours after placement. W-M-9, the polymethacrylate polymer concrete, had an abrasion resistance equal to W-M-3. This material also developed high early strength (17,700 psi in 24 hours) and could be opened to aircraft traffic in less than 8 hours. The material was considered for field testing but the cost for the material, $200 per cubic foot, was much greater than W-M-7.

The epoxy-resin grout, W-EP-3, installed as a barrier pad at Homestead AFB and Tyndall AFB did not perform satisfactorily in service. The rate of abrasion was greater than anticipated. The material lost bond to the underlying concrete and started to crack. These failures are believed to be caused by thermal incompatibility of the material with the concrete.

The iron-filled cementitious material, W-M-3, which was installed as a barrier pad at Tyndall AFB performed satisfactorily, but did wear from cable abrasion. The rate of abrasion wear was less than the epoxy-resin grout. The barrier pad made with the W-M-3 material was repaired after 2 1/2 years of service due because of the depth of abrasion under the cable. No excess spalling of the pavement around the perimeter of the barrier pad and no bond failures to the underlying concrete were observed. The W-M-3 material was later installed as a barrier pad at Langley AFB, Virginia, on 28 April 1984 and was performing satisfactorily as of September 1985 except for some abrasion.

The commercial silica-fume concrete, W-M-7, and two preformed polyurethane pads, W-PU-15, were installed as barrier pads at Seymour-Johnson AFB in October 1984. Approximately 1 month after the installation, the preformed polyurethane pads started to warp. The warping was eliminated for a short period of time by turning the pads over. After 9 months of service the pads warped to such an extent as to justify removal. Tears in the pads were also observed. The silica-fume concrete was performing satisfactorily after 9 months of service with only a slight amount of abrasion.

The two preformed polyurethane pads were removed and two new preformed polyurethane pads from the same supplier with changes in the design were installed on 19 October 1985. Both preformed polyurethane pads started to warp after 2 months in service. The pads had to be turned over as before to eliminate warpage. No tears were observed when removed in March 1986. The warpage is believed to be from the steel reinforcement embedded in the polyurethane.

B. RECOMMENDATIONS

The barrier pad material, W-M-3, will most likely need repairs because of wear after having been in service for 1 1/2 to 3 years. When this material is repaired, an epoxy resin conforming to the requirements of ASTM C 881-78 (1983), Type II, Grade 2 should be used for bonding the freshly mixed material to the hardened barrier pad material. A saw cut 1 inch deep should be made outside the worn area and the unsound material inside the saw cut removed. The freshly mixed W-M-3 material should then be placed inside of the cavity and compacted with a metal tamper and finished with a trowel. Material W-M-9, tested in Phase II, should be a satisfactory patching material for repairing materials W-M-3 and W-M-7. This material can support aircraft within 3 hours, has good abrasion resistance, and bonds well to itself and cementitious materials like those above.

The two preformed polyurethane pads installed 19 October 1985 at Seymour-Johnson AFB should be inspected monthly until they are removed. If the new design and installation techniques eliminate the warpage problem and the pads do not show any excessive warpage or cracking after 6 months of service, barrier pads like those should be installed at another facility to determine long-term performance.

The silica-fume concrete, W-M-7, appears to be a promising barrier pad material based on the laboratory and field testing. Very little wear was observed in the W-M-7 material as of March 1986 after 17 months of service. The depth of abrasion was measured before removal and the depth was approximately 1/8 to 3/16 inch. A small section of the pad was removed by saw cutting to determine the ease and time of repair for this material.

A number of the materials evaluated in the Phase II study show promise and the possibility of field testing should be considered. Preformed polyurethanes, W-PU-10 and W-PU-14, should be outstanding materials for a barrier pad; however, a design of the pads made from these materials and installation techniques would have to be developed. The liquid applied polyurethane, W-PU-17, shows promise, based on the laboratory study but good field conditions such as an ambient temperature above 60° F and a dry concrete would be necessary for satisfactory application.

REFERENCES

1. American Society for Testing and Materials, Annual Book of ASTM Standards, Philadelphia, Pa., 1985.

   "Bond Strength of Epoxy-Resin Systems Used with Concrete," Designation: C 882-78 (CRD-C 596).

   "Method of Making and Curing Concrete Test Specimens in the Laboratory," Designation: C 192-81 (CRD-C 10).

   "Recommended Practice for Operating Light and Water-Exposure Apparatus (Carbon-Arc Type) for Exposure of Nonmetallic Materials," Designation: G 23-81.

   "Specification for Concrete Aggregates," Designation: C 33-84 (CRD-C 133).

   "Specification for Epoxy-Resin-Base Bonding Systems for Concrete," Designation: C 881-78 (Reapproved 1983) (CRD-C 881).

   "Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes," Designation: C 511-80 (CRD-C 202).

   "Specification for Portland Cement," Designation: C 150-84 (CRD-C 201).

   "Standard Method of Test for Impact Resilience of Rubber by Vertical Rebound," Designation: D 2632-68.

   "Standard Method of Test for Indentation Hardness of Rubber and Plastics by Means of a Durometer," Designation: D 2240-68 (CRD-C 569).

   "Standard Test Method for Tensile Strength of Hydraulic Cement Mortars," Designation: C 190-82 (CRD-C 260).

   "Test Method for Compressive Strength of Cylindrical Concrete Specimens," Designation: C 39-83b (CRD-C 14).

   "Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-inches or 50-mm Cube Specimens)," Designation: C 109-80 (CRD-C 227).

   "Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals," Designation: C 672-76 (CRD-C 47).

   "Test Method for Tensile Properties of Plastics," Designation: D 638-82a.

2. Headquarters, Department of the Army, Bituminous Pavements Standard Practice, Technical Manual TM 5-822-8, Washington, DC, 1971.
3. American Concrete Institute, Use of Epoxy Compounds with Concrete, ACI 503-R-80, 1980.
4. Federal Specification SS-S-200D (CRD-C 526), Sealing Compounds, Two-Component, Elastomeric, Polymer Type, Jet-Fuel-Resistant, Cold Applied, 1971.

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APPENDIX A

TEST METHOD FOR CABLE ABRASION AND IMPACT RESISTANCE OF BARRIER CABLE PAD MATERIALS

A. SCOPE

This method covers determination of the abrasion and impact resistance of barrier cable pad materials by subjecting the materials to dynamic loading with a steel cable.

B. SIGNIFICANCE

The testing apparatus consists of a drop tower in which a known weight with a cable suspended below is dropped on a concrete test specimen coated with a 2-inch layer of the material being tested. The test surface is sloped at a 24-degree angle from the horizontal. This test simulates aircraft landing gears rolling over the cable, forcing the cable into the material below and causing the material to abrade or crack. The severity of the abrasion or damage to the material can be controlled by adjusting the test load or load-rise time.

C. APPLICABLE DOCUMENTS

The following ASTM standards, are applicable to this test method:*

- ASTM C 33-84, "Specification for Concrete Aggregates."
- ASTM C 150-84," Specification for Portland Cement."
- ASTM C 192-81, "Making and Curing Concrete Test Specimens in the Laboratory."
- ASTM C 511-84, "Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes."

D. TEST APPARATUS

The test apparatus (Figure A1) consists of the components discussed in the following paragraphs.

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* References cited in this appendix are included in the References section at the end of the main text.

1. Drop Tower

A drop tower of a free-fall design which enables it to produce predictable loads shall be used. Below are the mechanical specifications:

Height	6 1/2 feet
Floor area	18 by 34 inches
Weight	Approximately 1,450 pounds
Test load	150 pounds, maximum
Drop height	40 inches, maximum

Note: A varipulse impact loader (drop tower) Model VP-150 manufactured by Barry Controls has been found satisfactory for this test.

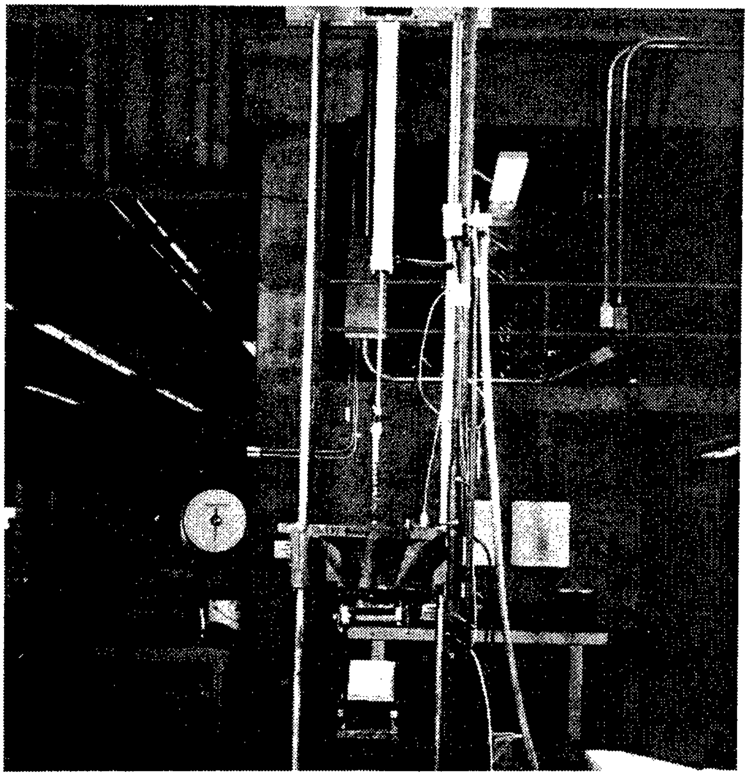

Figure A1. Test Apparatus.

2. Metal Ram and Cable Attachment

The dimensions of the steel ram used to push the cable into the surface of the test specimen shall be 2 by 2 by 7 inches. The ram is welded to a 1/4-inch-thick metal plate 9 inches in diameter. A neoprene rubber disk approximately 1/2 inch thick, 9 inches in diameter is placed between the metal plate and the drop weight.* The metal plate and ram are connected to the drop weight by 4 bolts. Two 1/4-inch-diameter U-bolts 4 inches long and 2 1/2 inches wide are welded to the sides of the ram. The U-bolts are tapered slightly to the back side so that the cable will roll to the same position each time the drop weight is raised. A 1-inch-diameter cable 14 inches (356 mm) long is suspended through the U-bolts. The cable is welded on both ends to prevent raveling. Four-inch-diameter rubber washers are then placed over the cable outside the U-bolts to prevent the cable from working through the U-bolts. The washers are held in place by clamps. This attachment is shown in Figure A2.

3. Test Platform

The test platform shall consist of a metal plate 8 by 10 1/2 inches by 1 inch which is bolted to the base of the drop tower. A 4-inch-diameter steel rod 12 inches high is welded to the plate. A metal plate 8 by 8 1/2 inches by 1 inch is welded to the top side of the rod. A metal plate 5 by 8 inches by 1/2 inch is welded to the back side of this plate to support the back side of the test specimen. The side supports shall consist of two pieces of angle iron 1 inch in height and 6 inches in length. The front support shall be an adjustable steel plate 4 by 8 inches by 1/2 inch with a right angle cut into both bottom corners 1 1/4 by 1 1/4 inches. Two 1/2-inch-diameter bolts 9 inches long with 4 nuts are placed into two holes drilled into the back support and front to tighten the front support plate against the test specimen. The test platform is shown in Figure A3.

4. Air Cylinder

The air cylinder used to raise the drop weight shall have a 2 1/2 inch bore, with a 30-inch stroke, 5/8-inch-diameter rod. The air cylinder is bolted to the top of the drop tower. The drop weight is connected to the rod by a 4-inch-long piece of heavy-duty chain.**

5. Solenoid Valve

A three-way electronic solenoid valve with a latching relay shall be used to release and raise the air cylinder. A compressed air line with an air

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* The thickness of the neoprene pad helps control the load-rise time and this thickness may be varied to obtain the proper load-rise time.

** A Sheffer Series A Clevis Mount, Model Number 2 1/2 AC30, Style C (MP1) air cylinder or equivalent has been found to be satisfactory.

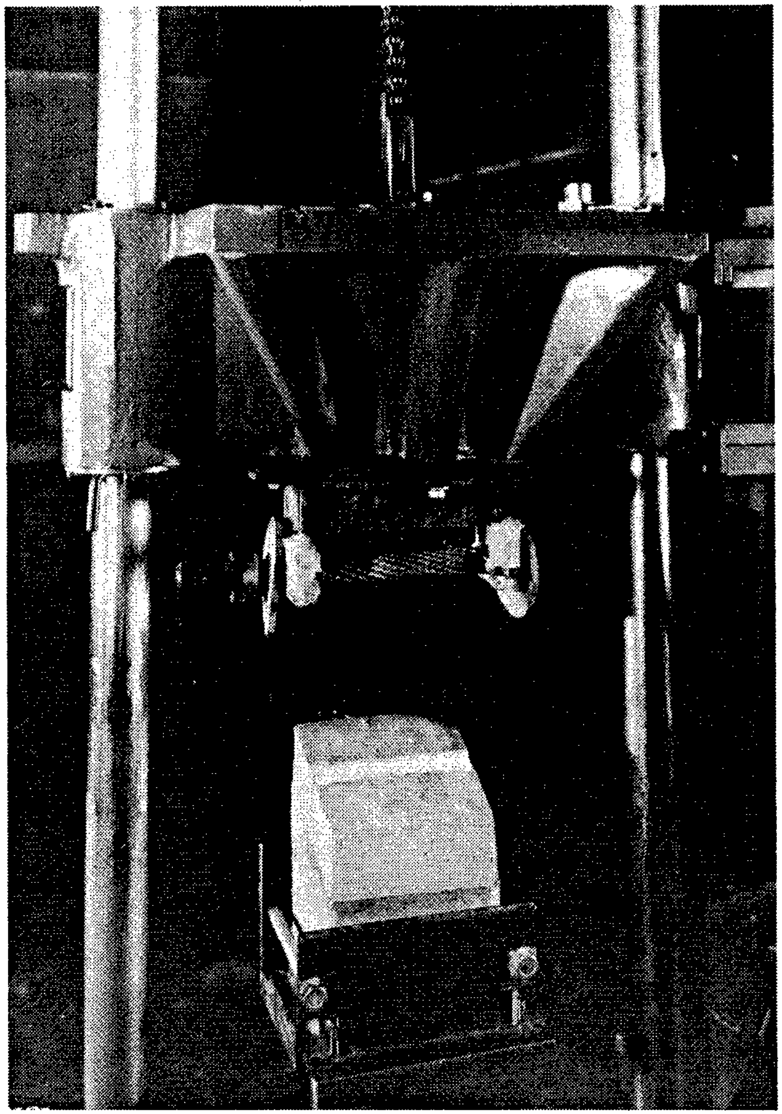

Figure A2. Drop Weight with Metal Ram and Cable Attachment.

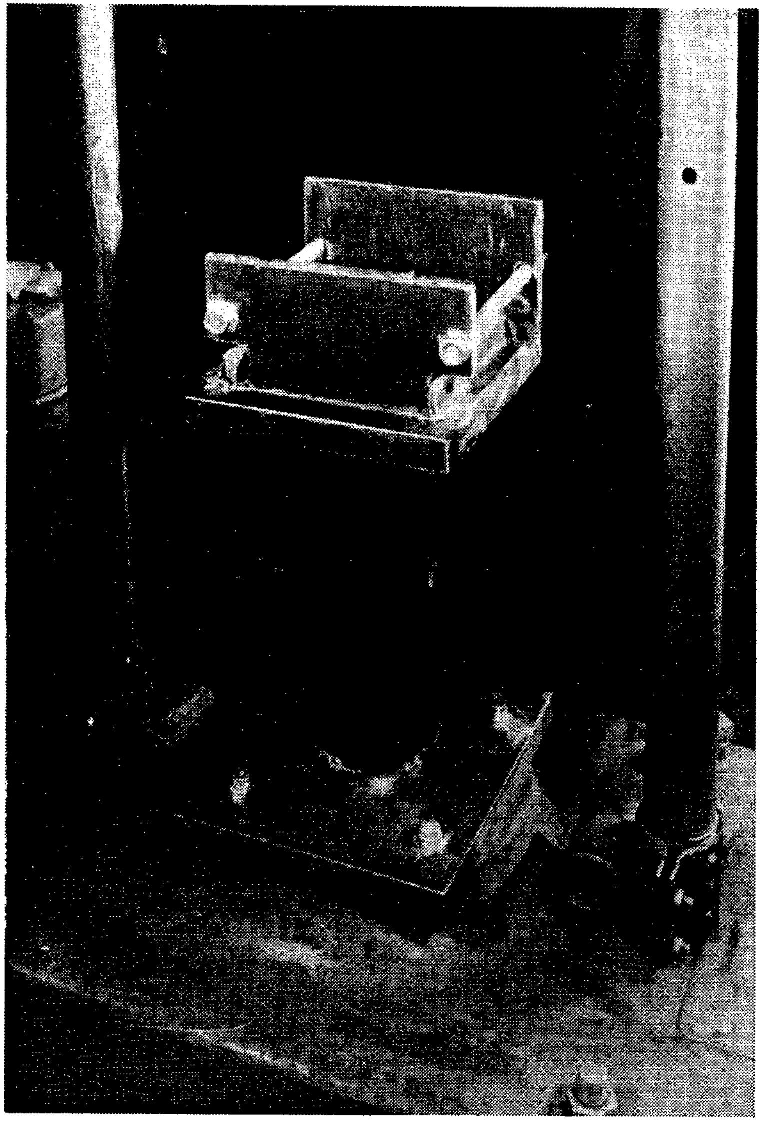

Figure A3. Test Platform.

regulator is connected to the valve. The rate of the drop time is controlled by the air regulator.

6. Electronic Switches

Two electronic switches shall be mounted on a metal pipe which is mounted to the floor and is approximately the height of the drop tower. The electronic switches* shall be the type that detects metallic objects approaching the sensing face in any direction. The solenoid valve is controlled by these switches; therefore, the drop height can be adjusted by adjusting the distance between the two switches.

7. Accelerometer

A strain gage accelerometer shall be attached to the top side of the drop weight to measure the force. The accelerometer shall be calibrated to a load cell. The test platform shall be removed and a load cell with a platform attached to the top placed beneath a concrete test specimen for calibration.

8. Oscilloscope

Shall be used to monitor the load and load-rise time.

9. Electronic Counter

Shall be used to automatically count the number of drops.

E. PREPARATION OF TEST SPECIMENS

1. Materials

The following materials shall be used:

a. Portland Cement

Type I or Type II meeting the requirements of ASTM C 150-84.

b. Aggregates

Fine and coarse aggregates meeting the requirements of ASTM C 33-84. The coarse aggregate shall have a maximum size of 1 inch. The fine aggregate shall be a natural sand.

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* FYS-FYT proximity limit electronic switches manufactured by Micro Switch, Freeport, Illinois, or equivalent shall be used.

c. Test Material

An appropriate amount of material for preparing two test specimens.

2. Preparation of Concrete Base

The concrete base shall be 6- by 6- by 6-inch cubes in which the top surface is sloped at a 24-degree angle. A side view is shown in Figure A4. The concrete shall have a slump of less than 2 inches and a cement content of 6 ± 0.1 bags per cubic yard. The minimum compressive strength of the concrete after 28 days of moist curing shall not be less than 4,000 psi. Molds of the proper dimensions given above for the concrete base conforming to the requirements of ASTM C 192-81 shall be used in casting the concrete. Molds may also be in the forms of beams 6 by 6 by 24 inches. Specimens made from the beam shall be cut with an appropriate masonry saw to the dimensions shown in Figure A4. Mixing, placing, and consolidation of the concrete shall be done in accordance with ASTM C 192-81. The specimens shall be moist cured for 28 days in a moist room or cabinet meeting the requirements of ASTM C 511-80. The top surface of the concrete base shall be sandblasted before application of the test material.

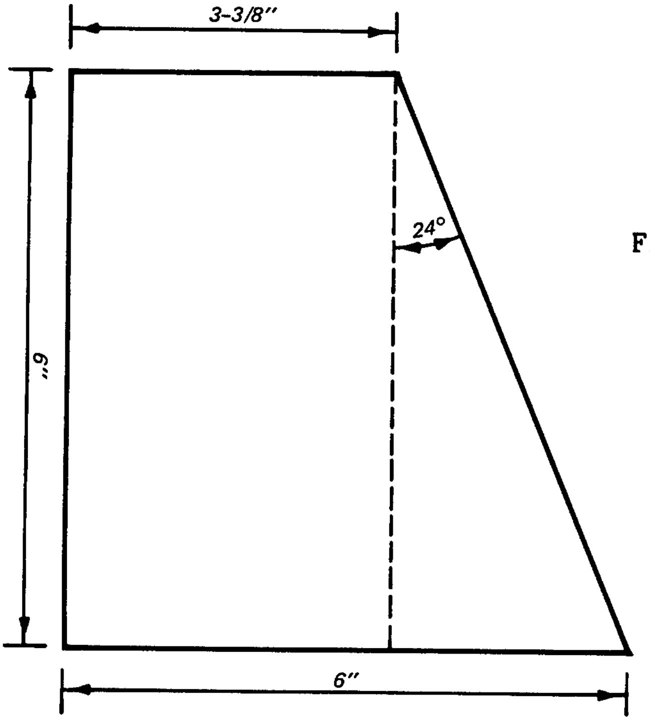

Figure A4. Schematic of Concrete Base for Test Specimen.

3. Fabrication of the Test Specimen

To retain the test material on top of the concrete base, wooden forms coated with a bond-breaking material were attached to the concrete base so as to enclose completely the top surface of the concrete base and rise above it a uniform distance of 2 inches.

The bottom surface of the concrete base shall be placed on an angled surface so that the top surface will be perpendicular to the surface of the workbench. The material shall be proportioned and mixed in accordance with the instructions of the manufacturer or formulator. The material shall be applied in a layer flush with the top of the retaining strips. Consolidation and surface finishing of the material may be varied to simulate the conditions of placement.

Polymers shall be cured for 7 days at 73° ± 1.8° F (23° ± 1° C). All materials requiring moist curing shall be cured for 28 days in a moist room or cabinet.

F. CALIBRATION OF APPARATUS

A concrete base as described above shall be used for the calibration. The concrete base shall be placed into the apparatus platform. The drop height shall be adjusted by the electronic switches to obtain a test load of 10,000 ± 500 pounds. The load-rise time shall be 3 ± 0.2 milliseconds.* The compressed air regulator shall be adjusted so that the rate of the drop time is 20 ± 3 per minute.

G. PROCEDURE

The test specimen shall be placed into the test platform with the test surface on the top side below the cable and ram. The support plates should be tightened against the test specimen. The top of the test specimen and the metal ram shall be checked with a level before starting the test. The cable shall be dropped on the surface of the test specimen for a designated number of drops. The rate of abrasion is determined by taking depth readings every 1/2 inch across the surface of the test specimen. Readings may be taken by a

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* The load-rise time is controlled by the thickness of the neoprene disk and the sheets of neoprene under the test specimen.

depth micrometer or by laying a straightedge over the abraded surface and using a ruler graduated in 0.01 inch. The average of the 11 readings will be taken as the depth of abrasion.

H. REPORT

Report the depth of abrasion to the nearest 0.01 inch. Also, it should be noted whether the material failed by cracking or delamination.

APPENDIX B

CONCRETE MIXTURE PROPORTIONING DESIGN FOR PHASE I TESTING

JOB NAME Tony Husbands	**CONCRETE MIXTURE PROPORTIONS** (WORK SHEET) (CRD-C 3)	DATE 1-19-82
JOB. NO. / MIXTURE SER. NO. 5000 psi		INITIALS FS

PORTLAND CEMENT TYPE	POZZOLAN SER. NO.	A. E. ADMIX: SER. NO.
SER. NO. ADDITION	TYPE	NAME Hunts Air - in
BRAND AND MILL Marquette	SOURCE	AMOUNT % ML

OTHER CEMENT SER. NO.	CHEMICAL ADMIX SER. NO. % ML
BRAND AND MILL	NAME

FINE AGGREGATE		COARSE AGGREGATE	
TYPE Limestone	SER. NO.	TYPE Limestone	SER. NO.
SOURCE Lab Stock		SOURCE Lab Stock	SIZE 3/4"

MATERIALS

MATERIAL	SIZE RANGE	BULK SPECIFIC GRAVITY	UNIT WEIGHT (SOLID), LB/CU FT	ABSORPTION, PERCENT	TOTAL MOISTURE CONTENT, PERCENT	NET MOISTURE CONTENT, PERCENT
CEMENT						
		3.15	196.56			
F. AGGREGATE			169.73	0.5		+1.7
C. AGGREGATE (A)		2.72	170.98	0.4		-0.3
C. AGGREGATE (B)		2.74				
C. AGGREGATE (C)						
C. AGGREGATE (D)						
POZZ/OTHER CEMENT						

PROPORTIONS

	CALCULATED BATCH DATA (1 CU YD)			ACTUAL BATCH DATA CU FT		
MATERIAL	SOLID VOLUME CU FT/BATCH	SAT. SURF DRY BATCH WT, LB	FACTOR	SAT. SURF DRY BATCH WT, LB	WATER CORRECTION, LB	ACTUAL BATCH WT
CEMENT	2.586	508.3 (13)	0.148	75.2		75.2
F. AGGREGATE	7.942	1348.0		199.5	+3.5	203.0
C. AGGREGATE (A)	10.968	1875.3		277.5	-0.8	276.7
C. AGGREGATE (B)						
C. AGGREGATE (C)	(11)					
C. AGGREGATE (D)	(10)					
POZZ/OTHER CEMENT						
WATER	4.154	259.2 (3)		38.4 (1)	-2.7	35.7
AIR	1.350					
TOTAL AIR FREE	27.000 (5)	(4)		(2)		
TOTAL YIELD	(14)					

MIXTURE DATA

12 ml AEA

SLUMP 1 1/4" IN.	AIR CONTENT (D) 5.0 %	MIXING WATER F	TH CF LB CU YD
REMOLD EFF DROPS	AIR CONTENT (E) %	AMBIENT F	ACT CF 508.3 LB CU YD
TH UW LB/CU FT	AIR CONTENT (F) %	CONCRETE F	W/C 0.51 WT
ACT UW LB/CU FT	BLEEDING %	S/A 42.0 PERCENT VOL.	

WES FORM NO. 476
REV MAR 1972

(OVER)

APPENDIX C

CONCRETE MIXTURE PROPORTIONING DESIGN FOR PHASE II TESTING

JOB NAME Tony Husbands	**CONCRETE MIXTURE PROPORTIONS** (WORK SHEET) (CRD-C 3)	DATE 9 Dec 83
JOB. NO. / MIXTURE SER. NO. 5000 psi		INITIALS BN

PORTLAND CEMENT TYPE I SER. NO. ADDITION BRAND AND MILL Lab Stock	POZZOLAN SER. NO. TYPE SOURCE	A. E. ADMIX: SER. NO. NAME AMOUNT % ML

OTHER CEMENT SER. NO. BRAND AND MILL	CHEMICAL ADMIX SER. NO. % ML NAME

FINE AGGREGATE		COARSE AGGREGATE	
TYPE Natural	SER. NO.	TYPE LS	SER. NO.
SOURCE		SOURCE	SIZE 3/4

MATERIALS

MATERIAL	SIZE RANGE	BULK SPECIFIC GRAVITY	UNIT WEIGHT (SOLID), LB/CU FT	ABSORPTION, PERCENT	TOTAL MOISTURE CONTENT, PERCENT	NET MOISTURE CONTENT, PERCENT
CEMENT		~~3.15~~	~~196.56~~			
F. AGGREGATE		2.63	164.11	0.5		-0.4
C. AGGREGATE (A)		2.69	167.86	0.4		-0.3
C. AGGREGATE (B)						
C. AGGREGATE (C)						
C. AGGREGATE (D)						
POZZ/OTHER CEMENT						

PROPORTIONS

		CALCULATED BATCH DATA (1 CU YD)			ACTUAL BATCH DATA CU FT		
MATERIAL		SOLID VOLUME CU FT/BATCH	SAT. SURF DRY BATCH WT, LB	FACTOR	SAT. SURF DRY BATCH WT, LB	WATER CORRECTION, LB	ACTUAL BATCH WT
CEMENT		2.798	550.0 (13)	0.056	30.6		30.6
F. AGGREGATE		7.152	1,173.6		65.2	-0.3	64.9
C. AGGREGATE (A)		11.668	1,958.6		108.8	-0.3	108.5
C. AGGREGATE (B)							
C. AGGREGATE (C)		(11)					
C. AGGREGATE (D)		(10)					
POZZ/OTHER CEMENT							
WATER		5.112	319.0 (3)		17.7 (1)	+0.6	18.3
AIR		0.270					
TOTAL	AIR FREE	(5)	(4)		(2)		
	YIELD	27.000 (14)					

MIXTURE DATA

SLUMP ______ IN.	AIR CONTENT (D) ______ %	MIXING WATER ______ F	TH CF ______ LB CU YD
REMOLD EFF ______ DROPS	AIR CONTENT (E) ______ %	AMBIENT ______ F	ACT CF ______ LB CU YD
TH UW ______ LB/CU FT	AIR CONTENT (F) ______ %	CONCRETE ______ F	W/C 0.58 WT
ACT UW ______ LB/CU FT	BLEEDING ______ %	S/A 38 PERCENT VOL	

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REV MAR 1972

(OVER)