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**REPAIR OF BRIDGE DECK STRUCTURES
IN COLD WEATHER**

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16. Abstract The research project presented in this report addresses the problem of concrete bridge deck repair in cold weather. Five materials were selected for in-depth investigation: M1 - TRANSPO - a methyl methacrylate based polymer concrete M2 - CONGRESIVE - Nominally identical to M1 P1 - SET 45 - A water based magnesium phosphate mortar P2 - BOSTIK 276 - A liquid (non-water) based magnesium phosphate concrete U - PERCOL - A polyurethane based polymer concrete The investigation identified methyl methacrylate (MMA) and magnesium phosphate based materials as performing satisfactorily under the test conditions. The MMA based materials show somewhat superior performance over the magnesium phosphate materials, particularly with regard to durability. The water based magnesium phosphate material demonstrated inferior durability. When, on the other hand, handling of the materials is taken into account, the magnesium phosphate based materials and particularly the water based variety, show a distinct advantage over the volatile and malodorous methacrylates. It is recommended to adopt methyl methacrylate or liquid based magnesium phosphate as long-term patching materials. Water based magnesium phosphate can be used for short term patching (less than 5 years) or when protected from deterioration due to freezing and thawing.					
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PREFACE

The research reported herein involved the identification of appropriate patching material for bridge-deck cold weather concreting. It was necessitated by the nationwide increase in the deterioration of bridge decks and the infrastructure in general.

This project was initiated in 1985 by the New Jersey Department of Transportation in conjunction with the Federal Highway Administration, Washington, DC, at Rutgers-The State University of New Jersey for conducting both analytical and experimental research to address the problem of cold weather. The project was staffed by the following investigators from Rutgers University, Department of Civil and Environmental Engineering:

Principal Investigators

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Dr. P.N. Balaguru, Associate Professor

Dr. Edward G. Nawy, Professor and Project Director

Graduate Assistants:

Prasad Kudlapur, Ph.D. Candidate

Several Graduate and Undergraduate Students and Laboratory Technicians.

The research was conducted in the Civil Engineering Laboratory experimental and computational facilities.

The Advisory Committee of the Department of Transportation of the Project comprised:

Mr. John J. Quinn, Research Engineer and Project Officer

Mr. Jack Croteau, Chief Research Engineer

Mr. Eugene F. Reilly, Director of Research

Grateful acknowledgement is extended to each member of the Advisory Committee for the advice, enthusiasm, interest and support accorded and for the several conferences held during the duration of the project as well as the numerous telephone conferences, particularly with the Project Officer, Mr. John Quinn.

Thanks are also due to Senator John H. Ewing for his interest from the outset in the importance of this research to the State of New Jersey in particular. Last, but not least, thanks are due to the Commissioner and Deputy Commissioners of the New Jersey Department of Transportation, under whose jurisdiction the project was initiated.

Respectfully submitted, .

A handwritten signature in black ink, appearing to read "Edward G. Nawy", with a long, sweeping underline that extends to the right.

Dr. Edward G. Nawy, P.E.

Project Director

EXECUTIVE SUMMARY

Resources are increasingly being devoted to maintenance and rehabilitation of the infrastructure. In order to utilize available resources efficiently, procedures are needed for year round, all weather repair and maintenance operations. The research project presented in this report addresses this problem in the area of concrete bridge deck repair in sub-freezing winter conditions.

The report consists of two major parts. Part I contains mainly a survey of the literature pertinent to concrete patching with particular emphasis on cold weather operations. The objective of this part of the investigation is to narrow the scope of the experimental investigation to potentially effective procedures by identifying materials and methods which show promise for satisfactory cold weather applications.

Part II contains the results of an extensive experimental program, testing the performance of promising materials identified in Part I. The program involves two major phases: a preliminary screening phase aimed at further condensation of the list of potentially suitable materials for in-depth investigation, and a follow-up phase of in-depth performance study of the selected systems.

The preliminary screening investigation of seventeen commercially available products identified four generic materials for investigation in the second phase. These materials are: methyl-methacrylate (MMA), two types of magnesium-phosphate and a polyurethane based composite. The investigation included early strength development of patching material, slant shear bond strength to existing concrete, flexural strength of patched specimens under static and fatigue loading, freeze-thaw durability of patched specimens.

corrosion across patch boundary and the effect of moisture on patch bond. All patching materials were cast and cured at temperatures of 15°F to 20°F, prior to testing.

Based on the results of the initial phase, the following materials were selected for in-depth investigation

M1 - TRANSPO - a methyl methacrylate based polymer concrete

M2 - CONCRESEIVE - Nominally identical to M1

P1 - SET 45 - A water based magnesium phosphate mortar

P2 - BOSTIK 276 - A liquid (non-water) based magnesium phosphate concrete

U - PERCOL - A polyurethane based polymer concrete

These materials were evaluated for strength (compression, bond and flexure) and durability. The properties studied include:

- cylinder compressive strength
- cylinder slant shear bond strength
- static and cyclic flexure of patched prism specimens
- freeze-thaw durability of patched prism specimens
- corrosion of reinforcement in patched prism specimens, and
- static and cyclic flexure of patched slab specimens.

For cylinders, two loading modes were of particular interest; direct compression and shear bond. Cylinder compression tests were conducted on neat patch material and shear bond tests were conducted using patched slant shear specimens. The total number of cylinders tested in the program exceed 310. The 24 hour compressive strength of cylinders of various products investigated ranged between 1760 and 9800 psi and the slant shear strengths ranged between 2110 and 4230 psi.

For flexure, static and cyclic (fatigue) tests were conducted on patched prisms of size 3 x 3 x 14 in. Three patch depths, namely: shallow, half and full depths were investigated. A total of 108 prisms were tested to failure.

Fourteen slab specimens (6 long patch, 6 wide patch and 2 control) of size 20 in x 48 in. were also tested to failure to assess the two-dimensional effects relating to patch plan dimensions and boundaries. The parameters investigated were: aspect ratio (width to length of 6" / 10" and 10" / 6") and roughness of the bonded surface.

The polyurethane material was not used for slab tests due to its inferior performance in the prism tests. In view of the low significance of the patch depth in the prism tests, only one patch depth, i.e., half depth was used in the slab tests. Slab tests consisted of loading the specimens under slow cyclic loading of 4 cycles per second to 100,000 cycles, followed by static loading to failure. The tests showed no two-dimensional effects on patch performance in the form of bond or shrinkage cracks and no delamination of patches during the cyclic or ultimate loading for the selected patching materials. In general, cracks at failure occurred at patch boundary for wide patches and at the center for long patches.

Transpo, M1, performed best under most of the test conditions, followed by concrete, M2. However the compound has a strong odor.

The performance of SET 45, P1, was comparable to M1 in terms of compressive and flexural strength. Its performance under freeze-thaw conditions was poor. BOSTIK 276, P2, which is also a magnesium phosphate based material performed better under freeze-thaw conditions.

In summary, the investigation identified methyl methacrylate (MMA) and magnesium phosphate based materials as performing satisfactorily under the test condition. The MMA based materials show somewhat superior performance

over the magnesium phosphate materials, particularly with regard to durability. The water based magnesium phosphate material demonstrated inferior durability. When on the other hand handling of the materials is taken into account, the magnesium phosphate based materials and particularly the water based variety, show a distinct advantages over the volatile and malodorous methacrylates.

It is recommended to adopt methyl methacrylate or liquid based magnesium phosphate as long-term patching materials. Water based magnesium phosphate can be used for short term patching (less than 5 years) or when protected from deterioration due to freezing and thawing.

PART I - STATE OF THE ART

1 INTRODUCTION

1.1 Background

The widespread deterioration of the overall infrastructure, and of bridge structures, in particular, has become an acute problem, necessitating the development and implementation of remedial measures, as bridges approach the limits of their design life spans. Concrete bridge decks are particularly sensitive to the effects of freezing and thawing, wetting and drying and the attack of chemical de-icing salts. Development of techniques for year-round maintenance and repair of bridge deck structures with minimum obstruction to traffic flow has, thus, become a goal of high priority. This goal, however, has remained elusive, to a large extent. Although development of new materials and technologies has provided a range of potentially promising solutions, the range and extent of constraints and requirements are such that no single technique has, thus far, been found completely satisfactory. As an illustration, the requirement for fast setting of concrete, on the one hand, and high durability, on the other, are often irreconcilable as are high ductility and low thermal expansion-contraction.

Investigations into methods for repair of concrete bridge decks have, thus far, concentrated predominantly on mild and warm temperature conditions. Although no solution which satisfies ideally all the requirements has been found, some satisfactory results have been reported and with ever-improving technology, the problem of bridge deck maintenance under such conditions can be expected to be mostly under control.

The problem of sub-freezing temperature operations, on the other hand, has received little attention, largely due to its increased complexity. This is an important aspect of the overall maintenance problem, whose treatment is essential for the development of year-round maintenance procedures.

Development of satisfactory cold weather repair procedures is necessary both on technical and logistical-economic grounds. It is during winter that most of the deterioration takes place. Attacking the problem as soon as it develops, would ensure minimizing the extent of damage and thus the cost of repair. On the logistical side, keeping highly skilled and trained maintenance-crews all year-round would ensure an efficient and smooth operation.

The present project is aimed at addressing the issue of cold weather repair of concrete bridge decks. This first part of the report is concerned primarily with surveying the relevant literature and with laying the groundwork for an experimental program on the development of cold weather concreting procedures.

2. OUTLINE OF THE PROPOSED INVESTIGATION

2.1 Scope

The investigation is limited to the development of patching materials and procedures for localized patches ("potholes"). It does not include replacement of large deck portions or whole decks, the stabilization of spalled or cracked areas or preventive measures, such as overlays. It is assumed that spalled or damaged areas have been thoroughly cleared and prepared in accordance with established procedures prior to commencement of the patching operations proposed in the investigation.

The major problems which need to be addressed in patching, in general and winter patching, in particular are:

- (1) strength development of the patch material within reasonable time limits
- (2) bond strength between new and existing concrete
- (3) compatibility of the patch material and the parent concrete in terms of stiffness and thermal expansion
- (4) long-term durability of the patch itself and the effect of the patch on the deterioration of adjacent areas.

2.2 Methodology

The following major factors have to be considered in the investigation:

- (1) Patch size and shape (area and depth): It is possible that no single method will be capable of handling satisfactorily all sizes and shapes. Material composition will also be affected by these factors.
- (2) Temperature range: Any particular method will be suitable for a limited range of temperatures of application. The

lower the temperature to which the patch is subjected during the setting time, the harder it would be to find a satisfactory material and the more costly the procedure is likely to be.

- (3) Setting and curing time: This is an important factor which impacts both on traffic flow obstruction and on temperature effects. Fast setting materials are clearly desirable but they often affect long term performance unfavorably.
- (4) Strength: Short-term and long-term strength targets for patch material and for bond to existing concrete have to be set and met. It may also be possible to trade-off excess strength for setting rate/temperature range.
- (5) Other factors include ease and simplicity of handling procedures and equipment, applicability under varying conditions - especially under wet conditions, availability, shelf life, storage requirements. etc.

These are some of the major, universal factors affecting the investigation. In addition, each method/material will have its own list of factors which affect its performance (e.g., water/cement ratio, aggregate type, size, etc.).

In view of the complexity of the investigation, a two tier procedure was used:

- (1) Preliminary tests aimed at screening a relatively large number of materials for potential suitability as patching materials. Specimens are tested primarily for material strength development.
- (2) Extensive laboratory tests of a limited number of promising materials/methods (suggested by the preliminary investigation) using patched specimens. Here, effects of

patch geometry as well as material and bond strength and durability are to be assessed.

2.3 Materials and Methods

2.3.1 Materials

Materials can be classified under three major categories: (a) Portland cement based materials, (b) polymer based materials, and (c) miscellaneous and proprietary products.

(a) Portland cement based materials

Portland cement (PC) requires water for hydration and is therefore susceptible to freezing. Some admixtures would be required to use Portland cement in sub-freezing temperatures. These admixtures perform the function of lowering the freezing temperature and/or raising the temperature by accelerating the exothermic hydration process. External heating can also be used (see Methods) but its use is expected to be only in a secondary, supporting role due to technical and economic constraints.

PC based materials are characterized by two major components: cement type and admixtures. Aggregate type may play some role, particularly in affecting long-term behavior.

Cement Type

Three types are to be investigated:

- (1) regulated set cement
- (2) high early strength cement (Type III)
- (3) shrinkage compensating cement (Type K).

This might prove to be significant for the development of bond strength to existing concrete.

Admixtures

- (1) Air entraining agents have to be used as a rule, unless other admixtures provide adequate entrained air, or in polymer modified concrete which is intended to be void free (and therefore impermeable).
- (2) Accelerating admixture - particularly CaCl_2 (calcium chloride). These often serve a triple purpose of accelerating the set time, raising set temperature (exothermic processes) and lowering freezing temperature (anti-freezing agents).
- (3) Anti-freezing agents, e.g., sodium nitrite. These are nonaccelerating agents whose sole purpose is to lower the freezing temperature.
- (4) Polymer modifiers. The purpose of such modifiers is to reduce water content (and thus sensitivity to freezing). They may also be associated with exothermic processes and may improve bond to existing concrete. High thermal expansion coefficients and curing shrinkage need to be monitored, however. Heating may be required to accelerate curing.
- (5) Water reducing agent (superplasticizers) may be used in conjunction with other agents to reduce water content and drying shrinkage while maintaining workability.
- (6) Miscellaneous admixtures, e.g., silica fume, which has been shown to increase early strength.

(b) Polymer Concrete

In polymer concrete, cement is replaced with a polymer which acts as the binding agent for the aggregate. A large number of polymer materials are available but they all have some problems. These problems are primarily

associated with high curing shrinkage and high coefficient of thermal expansion/contraction which tend to cause cracking in the patch or in the surrounding concrete. Very few polymers will cure at low temperatures at a sufficient rate and heating may therefore be required. The following is a summary list of some generic materials or classes of materials which may be investigated:

- (1) Methyl Methacrylate based materials: Systems involving Methyl Methacrylate (MMA) with various compositions of accompanying materials (promoters, retarders, cross-linking, etc.) have been widely tested with varying degrees of success. The attraction of this material, particularly for low temperature applications is its rapid setting and highly exothermic characteristics. It is highly sensitive, however, to accurate composition and handling procedure and requires dry conditions.
- (2) Polyester resins have been used with moderate degrees of success at ambient temperatures.
- (3) Polyurethane has been reported to have some good low temperature properties, but only limited data is available.
- (4) Various epoxy resins have been used. Most would require heating to accelerate curing time but some can be used in wet conditions.
- (5) Various acrylics have been mentioned in the literature but only very limited data is available.

(c) Miscellaneous Products

Some non-Portland cement based materials are available or have been reported, often marketed as pre-packaged proprietary products. Very little

information is available on their low temperature applications. Some examples of these products are the various magnesium phosphate based products which are generally fast-setting and exothermic, lime silico-phosphate cements and various proprietary products of undisclosed composition (see Literature Survey).

2.3.2 Methods

Methods fall under two general categories - material related methods and applications related methods. In the current project, only materials related methods are considered: fiber reinforcement and heating. Fiber reinforcement has been shown to favorably affect bond characteristics and crack control. If properly used, it can also be applied for electric heating by modifying the electrical resistance of the patch.

Application related methods include precast patch panels, shotcrete application and general heating methods. Such methods are not considered as part of the present project but may feature in a follow-up program upon successful completion of the current phase.

3. LITERATURE SURVEY

The literature survey and the bibliography at the end of this report follow the pattern outlined in the preceding chapter. The material is divided under the headings "General" which include general patching materials and procedures, "Portland Cement Based Materials", "Polymer Based Materials", "Miscellaneous Products" and, finally, "Methods" which include both material and application related methods. The bibliography is comprehensive but only what are considered to be key references are reviewed in this chapter.

3.1 General

This section starts with a general review of some typical aspects of bridge deck deterioration and methods for its detection. This is followed by some references dealing with general repair procedures and factors affecting patch durability and further deck deterioration, with special considerations to cold weather. Finally a general survey of rapid setting materials and particularly polymers is reviewed.

ACI Committee 201 - in its "Guide to Durable Concrete" (1977), reviews the causes of concrete deterioration, including the mechanism of frost action in freezing and thawing cycles, abrasion and wear, corrosion of steel and chemical reaction of aggregate. It also makes general recommendations for repairs and for preventive measures.

Carrier and Cady (1975) carried out an extensive survey of bridges in Pennsylvania. That survey provides useful guidelines for the detection and classification of deterioration and the factors affecting it. It also suggests measures for prevention, though not for treatment of deterioration.

Clear (1975) suggests chloride analysis as a means of identifying the extent not only of existing but also of potential damage (particularly corrosion of

reinforcement) and recommends that remedial operations (removal of existing concrete and repair) be carried out over the whole area thus identified. Full details of methods for carrying out this analysis are given.

ACI Committee 546 in its report "Guide for Repair of Concrete Bridge Superstructures" (1980) suggests methods for evaluation of damage and for the selection of repair methods. Among the methods covered are ordinary Portland cement mortars and concrete, with or without bonding agents, shotcrete, latex modified concrete and polymer concretes using epoxy resins or Methyl Methacrylate. The report outlines criteria for the selection of repair method/material as well as guidelines for their application.

Kliethermes (1972), evaluates factors affecting the durability of patches and reviews a number of techniques, including the use of polymer concrete, protective coating of reinforcement and cathodic protection. He points out the important fact that the patch itself may cause further deterioration of surrounding areas by producing corrosion cells. The use of chloride and other accelerators, in particular, promotes reinforcement corrosion. Like other sources, the author recommends removal of concrete substantially beyond the damaged area as well as coating of cleaned reinforcing steel with epoxy resin prior to patching. A method for detecting the extent of corrosion in reinforcement is also provided.

Darter (1984) outlines general procedures for patching with Portland cement concrete. His recommendations include extensive removal of concrete in excess of damaged areas and bonding to dry concrete, using cement grout as bonding agent. He also recommends use of superplasticizers to reduce water content and limiting the amount of calcium chloride to no more than 1%. Similar recommendations with regard to preparation and bonding are made by Felt (1960).

Numerous references deal with general cold weather concreting. These relate mostly to provisions for new construction but some of the provisions are also relevant to repair. The central issue is the development of adequate strength in cold conditions, namely sufficient strength for the prevention of frost damage.

ACI Committee 306, "Cold Weather Concreting" (1978, 1980) lays out guidelines for minimum protection and heating requirement for concrete for new construction. These requirements are stringent and impractical for bridge repair application.

Berwanger and Malhotra (1974) investigated strength development of air-entrained concrete at sub-freezing temperatures. They found that concrete cured for 3 days at 50°F and then subjected to sub-freezing temperatures, continues to develop strength and no long term effects on strength were measured.

Shideler et al. (1951) found that adding between 1% and 2% calcium chloride to air entrained concrete improves its short and long term strength and reduces heating requirement in sub-freezing temperatures.

Litvan and Sereda (1978) have indicated that the use of porous aggregate improves freeze-thaw behavior of concrete. Such aggregate acts in a similar way to air entrainment but with a more favorable pore size distribution.

The following is a review of several sources relating to various general classes of patching materials. A more detailed review of specific materials is included in the sections that follow.

ACI Committee 548 special publication, "Application of Polymers in Concrete" (1981) is a compilation of papers dealing with various applications of polymer materials related to concrete. Among other applications, use of polymers in pavement patching material and properties of polymer concrete and

polymer modified concrete are included. Also included are general reviews of research in progress and current practices. Some of the papers dealing with specific materials are reviewed separately under the appropriate headings.

NCHRP Synthesis Report 45 "Rapid Setting Materials for Patching Concrete" (1977) is a general report on patching practices and on the performance of various rapid setting patching materials, mostly Portland cement based but some epoxy and polyester resins and magnesium phosphate and sulfur are also included. This is a useful, quick reference guide to some commonly used materials giving data on handling times and compressive strength development at temperatures ranging from 20°F to 100°F.

Indhal et al. (1975) reported performance of several bituminous patching material and three fast setting concrete patching materials: Octocrete, Speedcrete and Fast-Set-Precrete. The report is dedicated predominantly to the bituminous material. Experience with the concrete commercial patching compounds was disappointing and due to failures, operations were limited to application at above 40°F with "speedcrete" performing best of the three compounds tested.

A report by Hartvigas (1979) lists a number of commercial patching compounds together with long-term (over 2 years) performance. Some of the compounds (Acmaset, Darex 240, Minute Patch 1-2-5, Set Instant, Speed-Crete, Texas Mix) were applied in winter, overall performance was mediocre and all the four winter patches deteriorated within 12 months.

Cowan et al. (1975) presented some data on a variety of techniques involving polymers, primarily Methyl Methacrylate (MMA) based material (see Polymer Concrete for more details on this material). The techniques are: Polymer Impregnated Concrete in various applications, polymer concrete and

polymer shotcrete. The two last mentioned are relevant to bridge patching and are reviewed in more detail under Polymer Concrete and Methods, respectively.

The report by Popovics (1974) is a thorough review and experimental investigation of the properties and behavior of polymer materials with concrete. Two classes of materials were investigated - polymer impregnated concrete (PIC) and polymer modified concrete (PMC).

Polymer impregnation of concrete can be used as a preventive measure in reducing its permeability to water and de-icing salts and as a means of stabilizing loose or partially spalled and cracked concrete. This technique, however, is not included in the present investigation. Polymer modified concrete has high ductility, high tensile strength, low permeability and good bonding characteristics and is therefore potentially suitable as a patching material. Popovics reviews and investigates in-depth the effect of various polymers and their aqueous suspensions or solutions on the properties of the modified concrete. He found that increase in compressive strength for most polymers tested is marginal but improved tensile strength and reduced permeability are achieved (particularly with Urea-Formaldehyde polymer). A potential problem, however, is increased shrinkage. Use of epoxies as modifiers resulted in reduced compressive strength though other properties (tensile strength, bond, impermeability) were enhanced. Some limited tests with Furfuril Alcohol (FA) showed promise, particularly for cold weather applications (although this was not tested) as it polymerizes very rapidly. A drawback, however, would be a retarding effect on the hydration of the cement. These two materials, Urea-Formaldehyde and Furfuril Alcohol, as modifiers may deserve further attention.

3.2 Portland Cement Based Materials

This section deals with patching materials based primarily on Portland cement as the binding material and aggregate as the filler. This basic mix can be modified to achieve the required performance by the addition of various admixtures. The review begins with accelerators/anti-freezing agents as the main active admixtures. Accelerating admixtures (e.g., calcium chloride) often act also to lower freezing temperatures, which makes them suitable for low temperature application. Following this sub-section some special types of cements are viewed: regulated-set cement and shrinkage compensating cement. Finally some polymer modified concrete mixes are surveyed.

3.2.1 Accelerating/Anti-Freezing Agents

Ross (1975) has conducted tests on a large number, mostly Portland cement based rapid set mixes for Louisiana D.O.T. Performance of the various mixes was tested (at mild temperatures) in the laboratory as well as in the field immediately after casting as well as after one year. The author stresses the need for thorough preparations to achieve lasting repairs. He points out that the six hours compressive strength (which ranged from 890 psi to 3044 psi, averaging 2600 psi) gives no indication of the durability of the patch. Based on performance after one year of exposure to traffic, the report recommends four patching mixes, but these are all non-Portland cement based and are reviewed separately. Of the four Portland cement based materials tested two contained unspecified accelerators and the other two were P.C. Type III. Both types appear to have performed reasonably well after one year. Debonding may be a problem.

Macadam et al. (1984) tested five different accelerating compounds and mixes containing Portland cement Type III, air entraining agent and superplasticizer. The five materials were: (1) "Acceleguard 80" - calcium nitrate

($\text{Ca}(\text{NO}_3)_2$) based, (2) "Darex" - a calcium nitrite ($\text{Ca}(\text{NO}_2)_2$) based, (3) "LA-40" - a sodium thiocyanate (NaSCN) based material, (4) "Hydra Set" - a calcium chloride (CaCl_2) based material, and (5) "Daraset" - a mixture of calcium nitrate and calcium nitrite. Tests included compressive and tensile strengths, bond, set time, length change (shrinkage), freeze-thaw durability and corrosion potential at various temperatures. Lowest casting temperatures tested was 40°F . Mortar specimens tested after 24 hours at this temperature all failed to reach sufficient strength, except "hydraset" which reached 1340 psi. Concrete specimens performed better. Of all materials "Darex" appears to have performed best overall. It seems that some heating would be required for sufficient performance at sub-freezing temperatures.

Calcium Chloride

Calcium chloride is the most commonly used and well documented accelerating admixture, yet it is highly controversial. This material can act both as an anti-freezing agent, accelerating agent and heating agent, due to the highly exothermic hydration process. The main drawback in its use is its putative deleterious effects on corrosion and sulphate attack resistance. This is the reason that most codes limit CaCl_2 content to 2% or less (by weight) of cement. Most sources dealing with the use of CaCl_2 in cold temperatures relate to structural concrete and require heating for 3 days, typically, at 50°F (ACI Committee 306 - "Cold Weather Concreting", 1978). Both the restriction of 2% and the requirement for heating may not be relevant to pavement patching.

Shideler (1952) conducted a thorough research on the effects of CaCl_2 . He found particular advantages in its use at low temperatures, but warns of possible long term negative effects on durability. Some increased shrinkage was also observed. CaCl_2 content was limited to 2% in these tests. Tuthill (1956) found

that 1% of CaCl_2 in air entrained concrete does not affect durability adversely, but heating at 50°F for 3 days is required.

Keeton (1970) used Portland Cement Type III with 2% CaCl_2 and 5-7% entrained air in foundations and slabs in Antarctica. Heating at 50°F - 70°F for 3 days was maintained.

Anti-Freezing Agents

A departure from the 2% limit on CaCl_2 content was reported by a Soviet group, led by Mironov. Mironov et al. (1968) tested a number of anti-freezing agents, including CaCl_2 on mixes cast at temperatures as low as 5°F . The minerals they used were NaCl , KCl , CaCl_2 , FeCl_3 , $\text{Ca}(\text{NO}_3)_2$, NaNO_2 and K_2CO_3 . FeCl_3 and $\text{Ca}(\text{NO}_3)_2$ did not accelerate curing. NaNO_2 appears to delay curing. K_2CO_3 accelerates curing in amounts between 7% and 15% of cement weight. A combination of CaCl_2 and NaCl of up to 7.5% of cement weight is also recommended. In their 1956 paper, Mironov and Krylov followed up the use of combinations of calcium and sodium chloride. The CaCl_2 accelerates setting while NaCl is used to lower freezing temperature and control the rate of acceleration of CaCl_2 to prevent excessive acceleration. The amount of additives depends on the temperature. The authors provide a guide of total salt content as percentage of mix water rate for temperatures ranging from 32°F down to -4°F . The total average amount of salt required per degree (Fahrenheit) of temperature fall below freezing is approximately 0.64% of mixing water weight (e.g., for casting temperature of 20°F salt content should be approximately 7.5% of water weight). The report deals with structural concrete and data on very early strength are scant. It is likely that proportions of NaCl to CaCl_2 should change for faster setting. Results on durability effects are ambiguous, some deleterious effects were observed particularly under dry conditions. Long term tests (up to 2.5 years) indicated little corrosion of

reinforcement and this was attributed largely to cracks and insufficient cover. The authors claim that chlorides from the added salts do not enter into reaction with reinforcing steel and do not affect its corrosion. On the other hand salt content does affect freeze thaw durability. The effect, according to the authors, depends on the alumina content with cements with low alumina content showing improved durability.

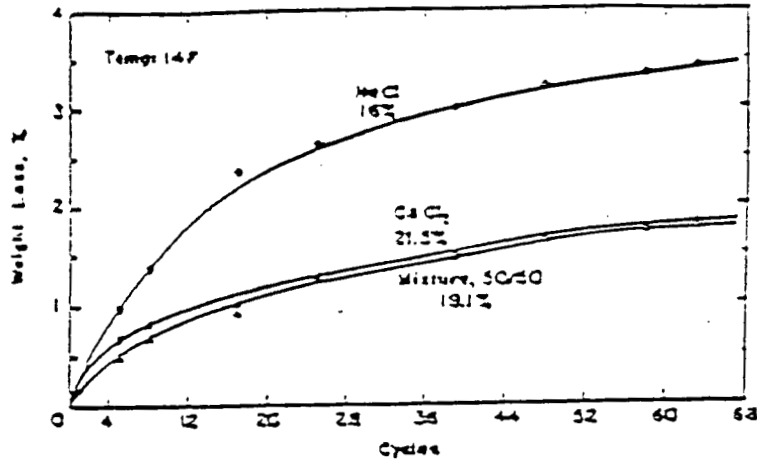
Stormer (1970) repeated essentially the experiments of Mironov and Krylov in an attempt to confirm them and his results are similar. In his mixes he used Portland Cement Type I and no entrained air. With typically 12% CaCl_2 by weight of water at 23°F he reached strength of 580 psi at 3 days, which is inadequate for bridge application. Using Type III cement with some heating could considerably improve this performance. Figures 3.1 and 3.2 illustrate some of his results. It should be noted that with some air entrainment, freeze-thaw resistance would improve. These results suggest that the 2% restriction on CaCl_2 content may be conservative and that substantial increase can be applied at no significant risks, subject to further experimental verification.

Mironov and Demidov (1978) used sodium nitrite as an anti-freezing agent in concrete used in foundations. Addition of 10% NaNO_2 by weight of cement at 5°F produced concrete of sufficient strength and with good bonding to existing (cold) concrete, but strength development is slow.

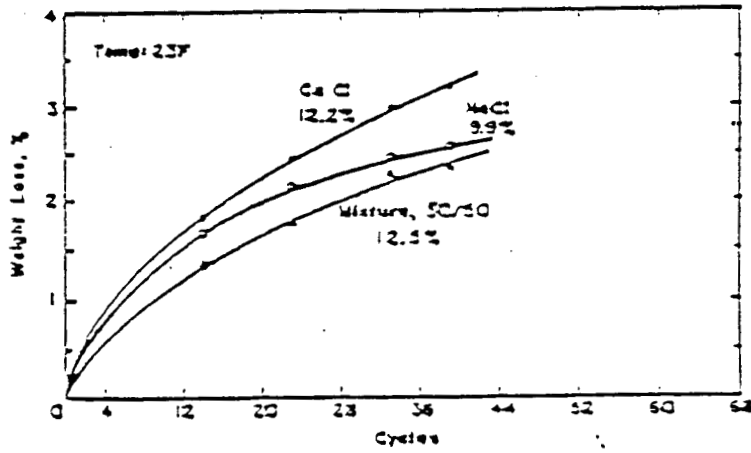
Meyer (1952) reports some tests on the use of alcohol as an anti-freezing agent. Results with 2% alcohol by weight of water showed marginal improvement as compared to concrete without alcohol, cast and cured at 41°F and cycled between 41°F and 14°F for 7 days.

3.2.2 Regulated Set Cement

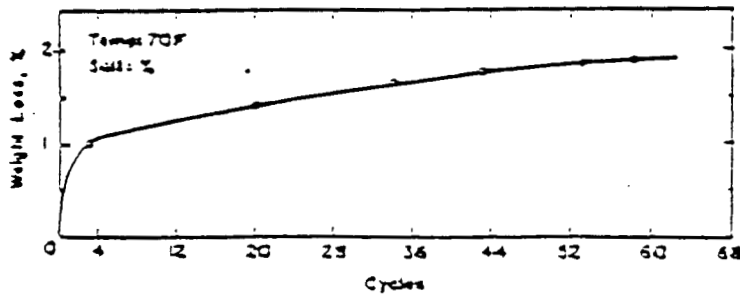
Hoff et al. (1975) investigated the effect of a number of factors on the strength development and heat development of some regulated set cements. The



Average weight loss percentages for given numbers of freeze-thaw cycles.

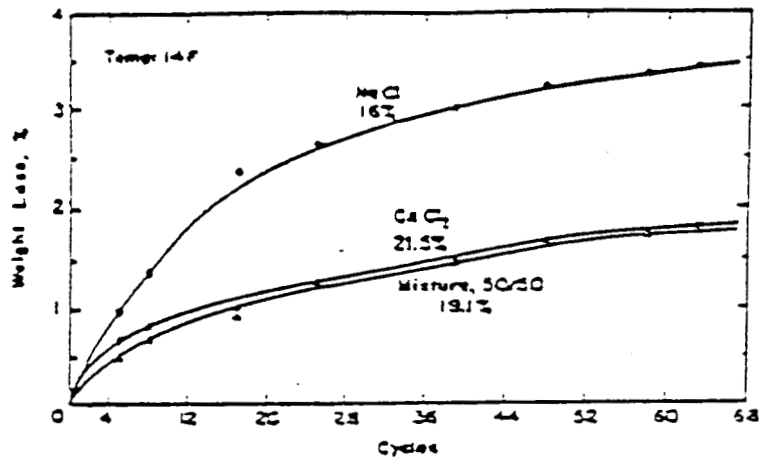


Average weight loss percentages for given numbers of freeze-thaw cycles.

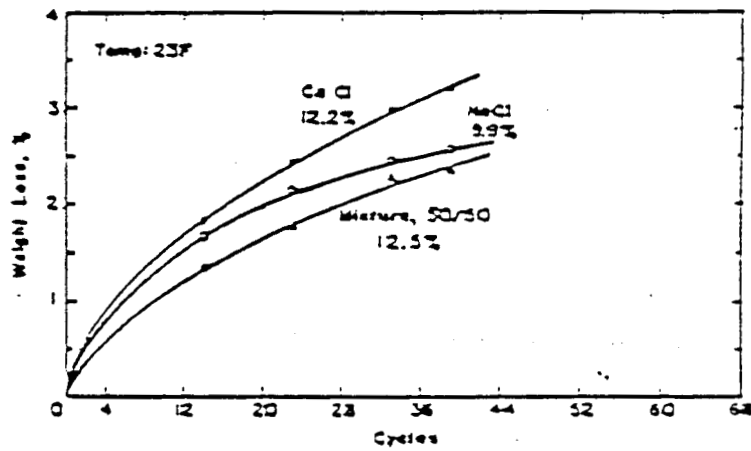


Average weight loss percentages for given numbers of freeze-thaw cycles.

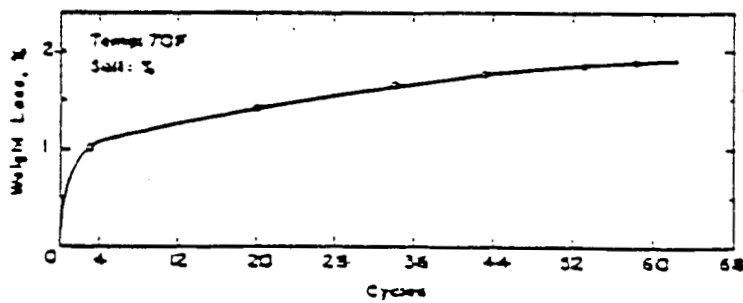
Fig. 3-1: Compressive Strength of Mixes with CaCl₂ and NaCl (Stormer, 1970)



Average weight loss percentages for given numbers of freeze-thaw cycles.



Average weight loss percentages for given numbers of freeze-thaw cycles.



Average weight loss percentages for given numbers of freeze-thaw cycles.

Fig. 3-2: Durability of Mixes with CaCl₂ and NaCl (Stormer, 1970)

high early strength of this cement is due to the calcium fluoro aluminate content. Among their major findings are:

- Specimens mixed at 35-40°F and placed immediately at 15°F developed a strength of 1000 psi in 3 days and reached only 60% of the 28 days compressive strength of the control (cast and kept at 70°F).
- Temperature of slabs cast and exposed to 15°F, rose, then fell again. The plate temperature and time to reach it depended on slab thickness and ranged from 46.5°F at 1 hour 20 minutes for 3 inch thick slab (on sand base) to 69°F at 1 hour 40 minutes for 12 inch thick slab.
- Maintaining the mix at above freezing temperature (heating) prior to exposure to sub-freezing temperatures substantially improves strength development.

Houston and Hoff (1981) carried out some field tests on slabs cast at temperatures varying between 0°F and 32°F. The average temperature inside the slabs was approximately 20°F. The results were somewhat disappointing, strength at one day was only 200 psi. The authors attribute this to faulty batch of regulated set cement.

Osborne and Smith (1977) tested regulated set cement for strength and durability. Specimens cast at 20°C (68°F) displayed 22-29 Mpa(3100-4100 psi) compressive strength at one day (and about double this value at 28 days). Sulphate resistance of regulated set cements proved poor but was improved with the inclusion of PFA (pulverized fuel ash). This inclusion, however, retards setting and reduces early strength.

It appears that regulated set cement is very variable in its behavior and sensitive to various parameters. Some short-term heating may be necessary together with some protective measures for long term durability (e.g., polymer inclusion).

3.2.3 Shrinkage Compensating Cement

Shrinkage compensating cement may be desirable to prevent shrinkage and debonding cracks in the patch. At cold temperature it could be used with other admixtures - e.g., accelerators.

Cusik and Kesler (1976-77) carried out extensive laboratory testing on simulated bridge deck specimens. They measured the effect of various factors on the amount of expansion of the cement. The amount of expansion is sensitive to mixing time, admixtures (air entraining, water reducing) and temperature as well as curing method, reinforcement, etc. Some typical effects are presented in Figures 3.3-3.6. Durability tests indicated that corrosion of reinforcement is due to cracks and since cracking is reduced with expansive cement the extent of corrosion is reduced accordingly.

Polivka et al. (1975) carried out freeze-thaw tests on air entrained specimens. They concluded that freeze-thaw durability of concrete made with expansive cement, in terms of weight loss was comparable to Portland Cement Type II specimens.

3.2.4 Polymer Modified Concrete

As stated earlier, the objectives of using polymer modified concrete would be primarily to reduce water content and to improve bond characteristics but other measures may be required to cope with low temperatures, e.g., heating, use of accelerators, etc. The work by Popovics, which deals with polymer modified concretes and polymer impregnation of concrete has been reviewed in the

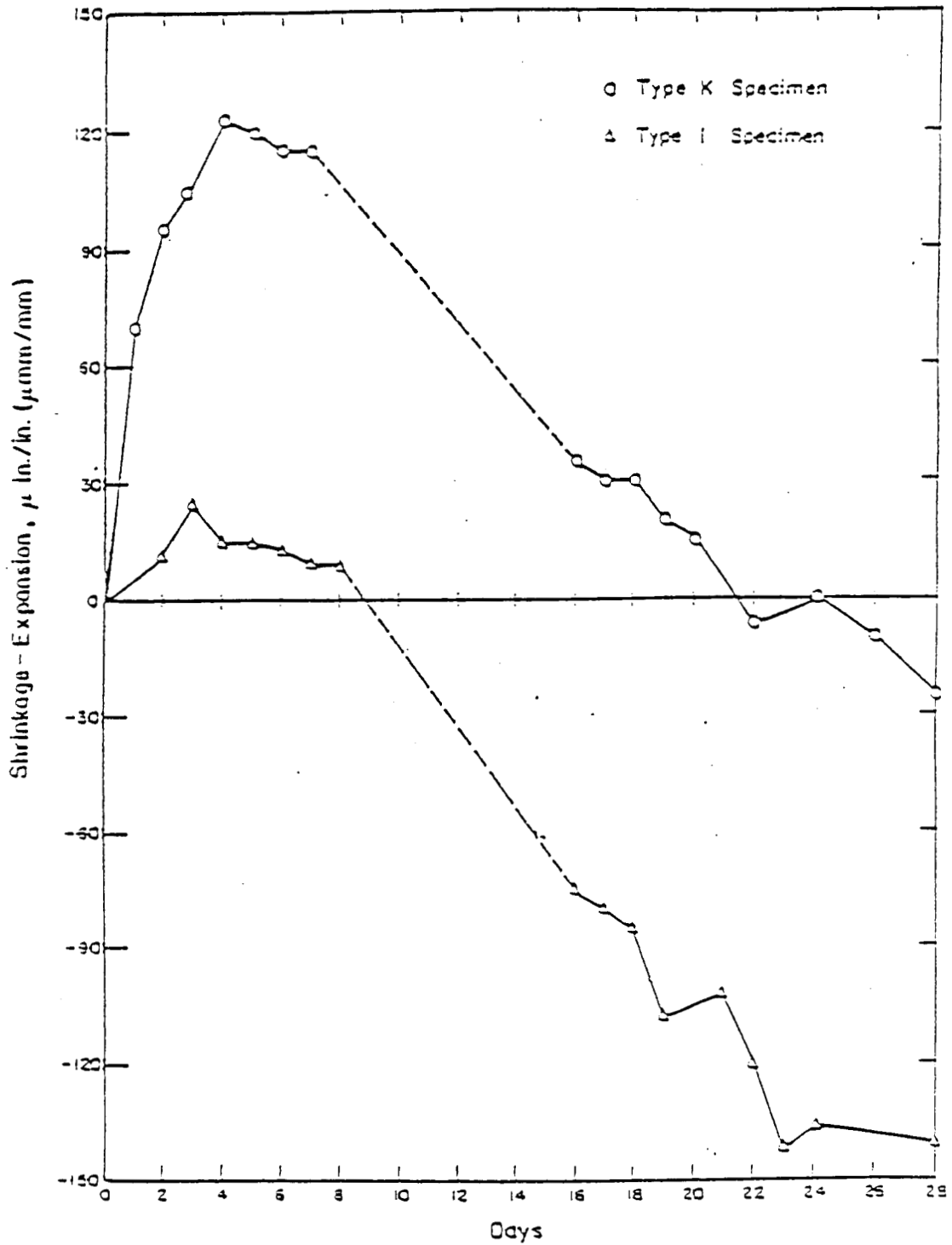


Fig. 3-3: Expansion and Shrinkage Behavior (Kusick and Kesler, 1976)

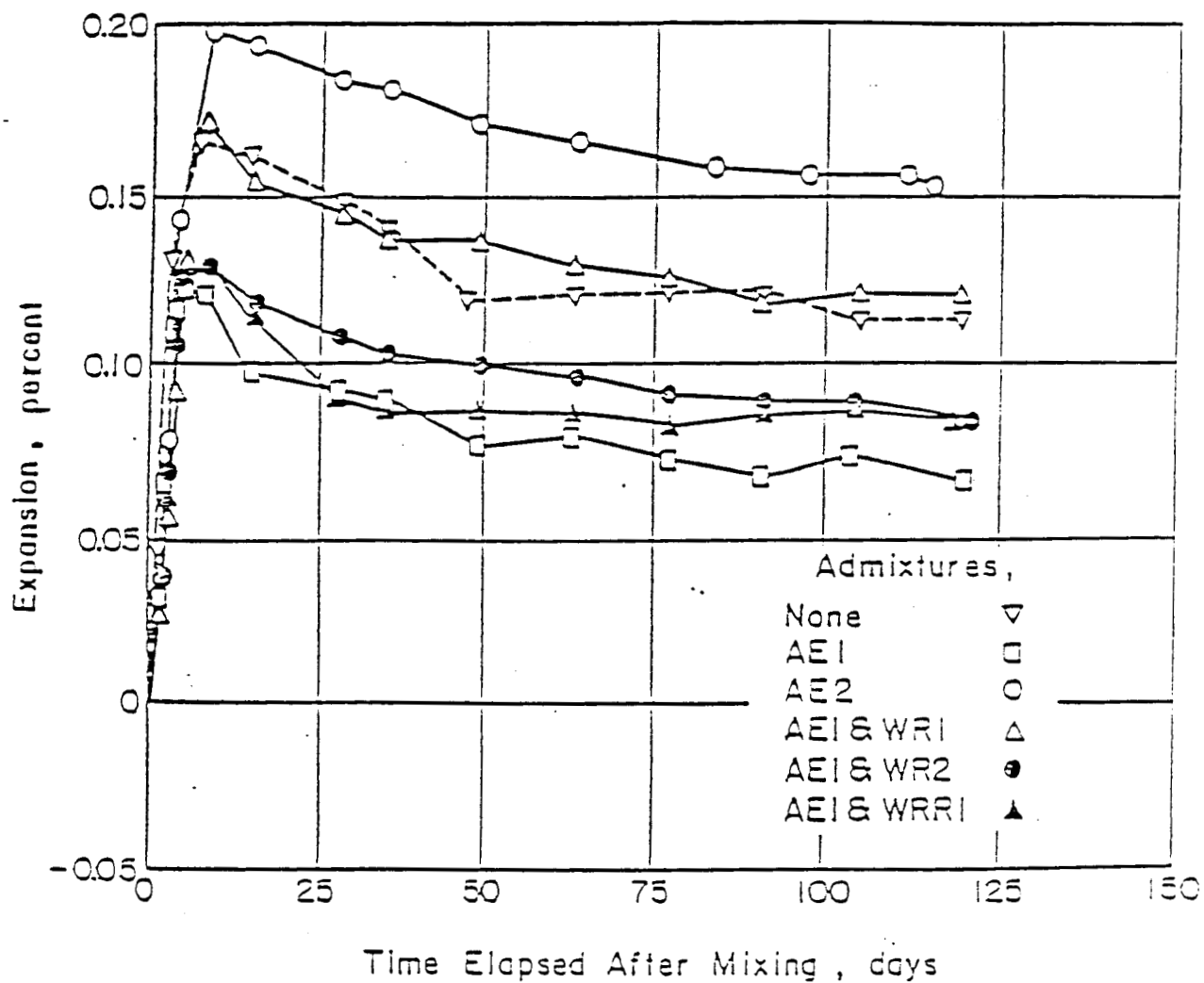


Fig. 3-4: Effect of Admixtures on the Expansion of a Highly Expansive Concrete Made with Type M Cement (Kusick and Kesler, 1976)

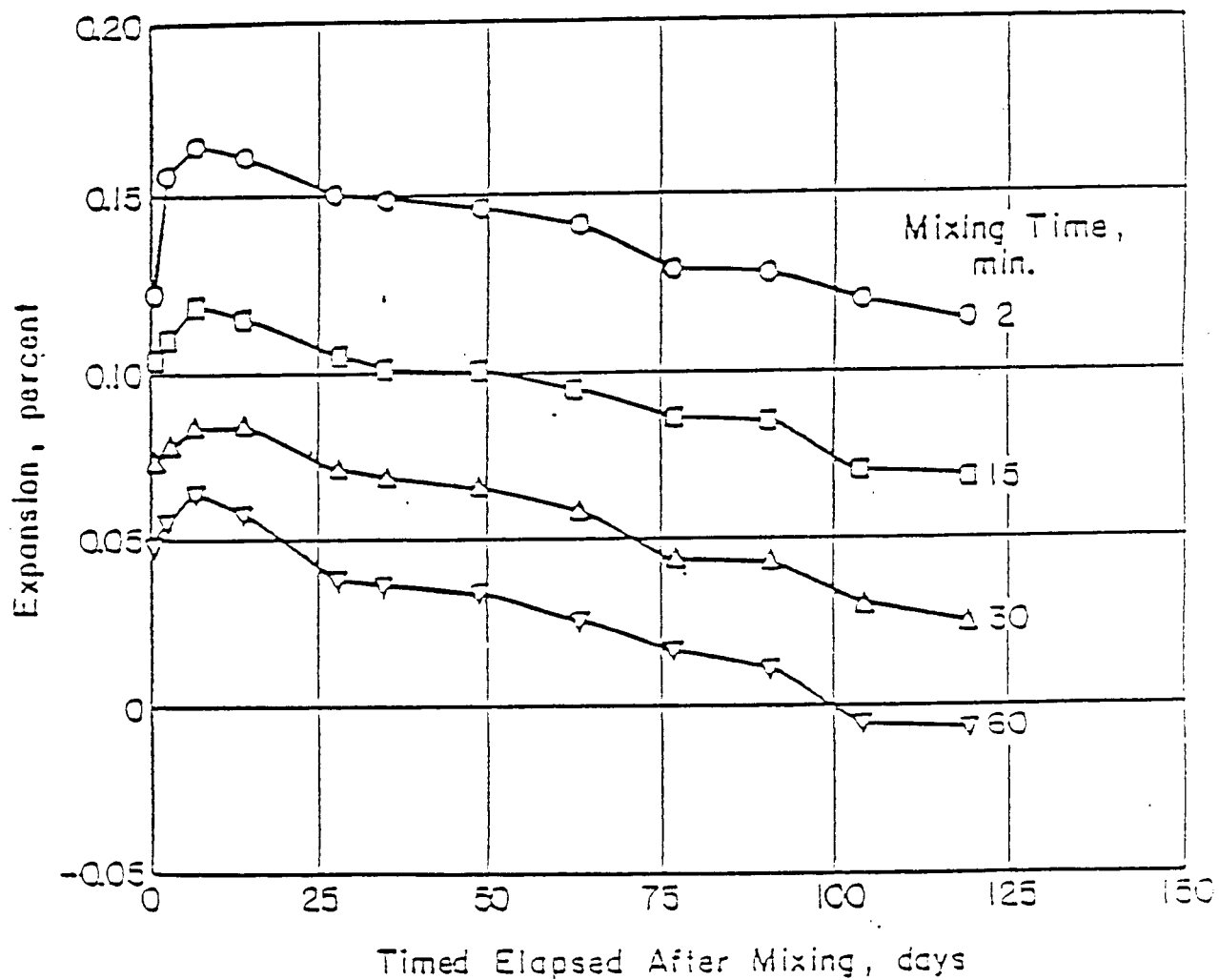


Fig. 3-5: Effect of Length of Mixing Time of Expansion of Concrete Made with a Highly Expansive Type K Cement (Kusick and Kesler, 1976)

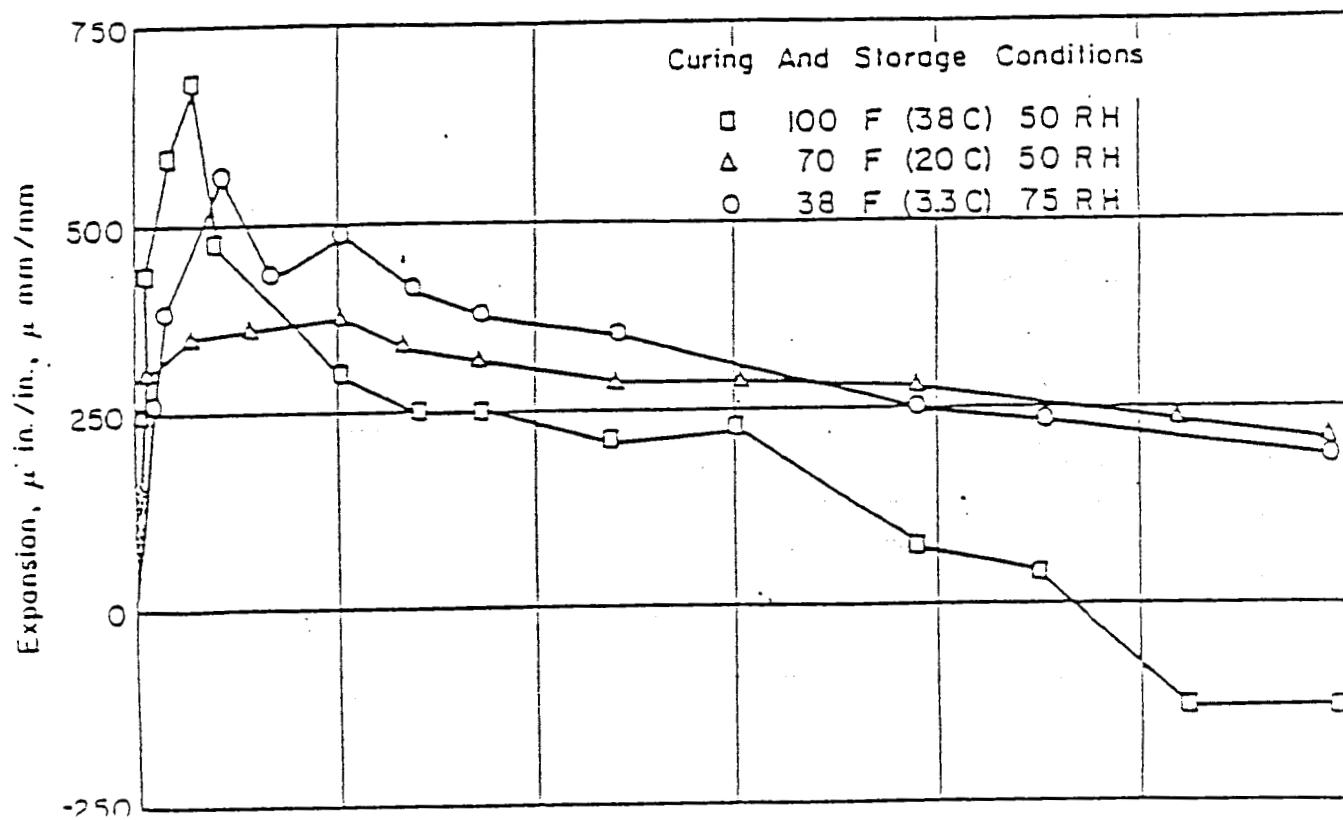


Fig. 3-6: The Effect of Curing and Storage Conditions on Expansion and Shrinkage of Non-Composite Concrete Specimens Made with Type M Expansive Concrete (Kusick and Kesler, 1976).

preceeding section. Under the present heading some specific materials and applications are surveyed.

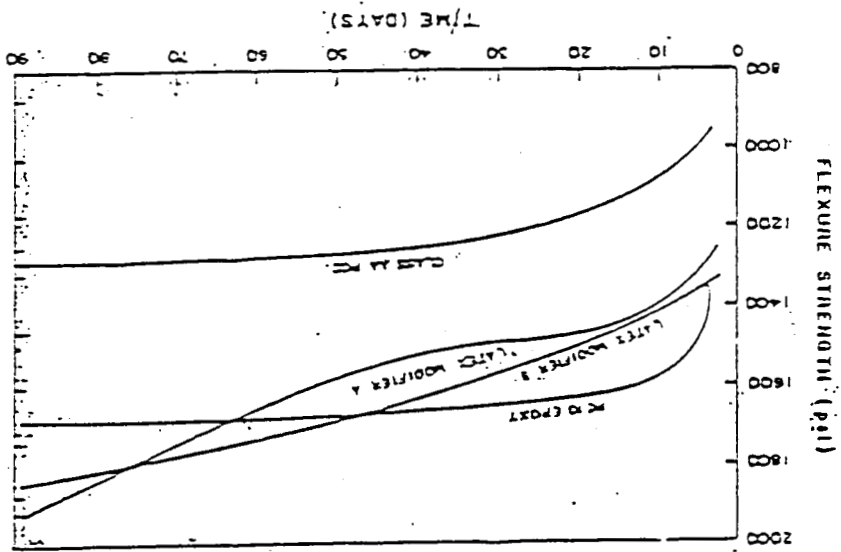
Polymer modified concrete has been used in the transportation industry primarily as overlays on concrete bridges as a protective surface due to the highly impermeable properties of this material.

Clear (1978) carried out a thorough investigation of the physical properties of five styrene/butadiene latex modified concrete mixes and the physical and chemical properties of latex emulsions. One day strengths ranged from 1360 to 2370 psi (at room temperature). Slant shear bond tests indicate bond strength (to concrete) of 50% to 70% of the compressive strength. Freeze thaw durability in terms of reduction of dynamic modulus showed high variability and sensitivity to curing conditions. Entrained air improves markedly freeze-thaw durability.

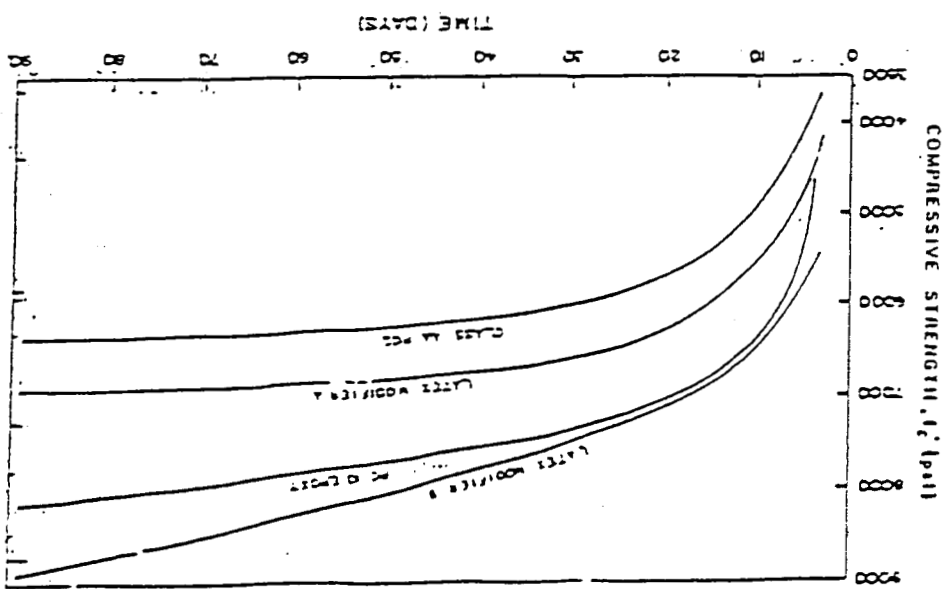
Rahal (1974) carried out compression, flexure, and freeze-thaw durability tests on three latex modifiers: Dow Modifier A, Dow Modifier B, and DuPont Latex and on one epoxy resin modifier EPI-TOP PC 10 (the last was also tested by Popovics). Dow Modifier A is a styrene butadiene latex and Modifier B is 75% saran and 25% styrene butadiene. The DuPont Latex is a neoprene (polychloroprene). Dow Modifier B gave the highest compressive strength throughout (see Fig. 3.7), all materials showed freeze-thaw durability comparable to that of ordinary Portland cement concrete (Class AA PCC) with the epoxy concrete showing the smallest reduction in dynamic modulus (Fig. 3.8). No information is given on early stages and on low temperature behavior. Initial sets indicated are 20-30 minutes for the epoxy, 40-45 minutes for Modifier B, and 45-55 minutes for Modifier A. All modifiers showed low permeability compared to PCC. No information is given on shrinkage and thermal coefficients which

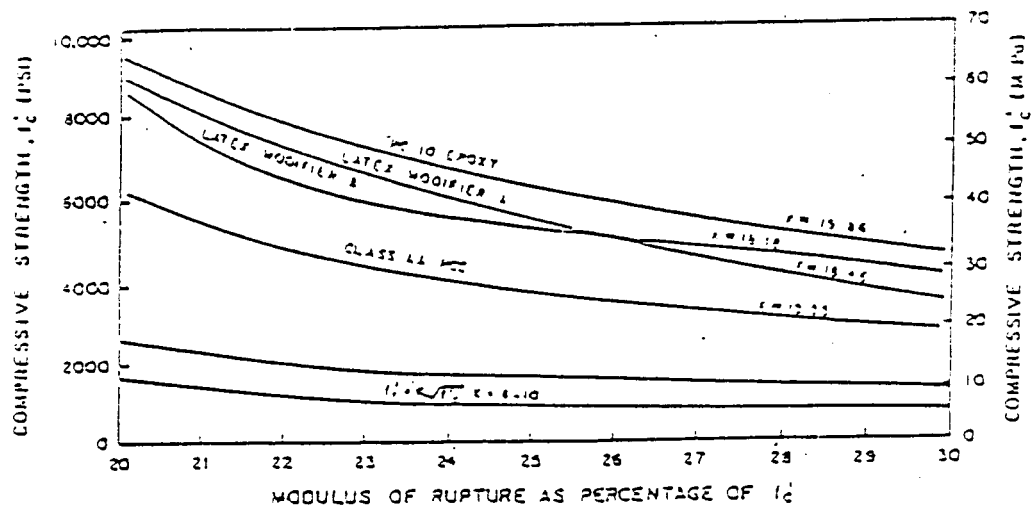
Fig. 3-7: Concrete Strength vs. Time (Rahl, 1974)

(b) Flexure Strength Versus Time for All Mixtures

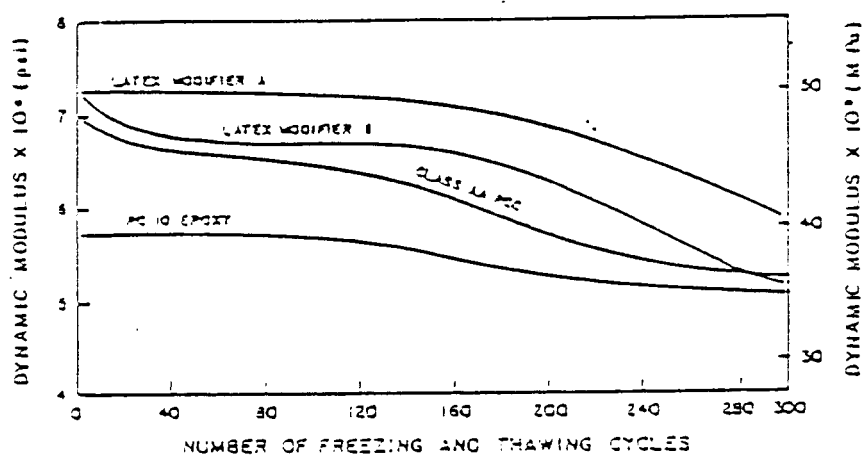


(a) Compressive Strength Versus Time for All Mixtures





(a) Relationship between Compressive Strength and Modulus of Rupture for All Mixtures.



(b) Average Dynamic Modulus of Elasticity Versus Time (Number of Cycles of Freezing and Thawing).

Fig. 3-8: Concrete Strength vs. Dynamic Modulus (Rahl, 1974)

are relevant to patching applications. Water cement ratios was .245 for all mixes.

Kuhlman (1980) surveys performance of 15 latex modified concrete overlays in terms of chloride penetration, half-cell potential, debonding, cracking and skid resistance. The latex modifiers used were Dow Modifier A and B. All overlays behaved satisfactorily overall and the report suggests a minimum life expectancy of such overlays of 20 years.

A number of experiments have been performed on epoxy modified concrete not related to bridge overlays or repairs. Nawy et al. (1975,77) tested concrete cylinders for compressive and tensile splitting strength for a number of varying cement, epoxy and water ratios. They found that significant strength increases are achieved primarily through reduction in the water/cement ratio made possible by the inclusion of the epoxy. The effect on tensile strength was particularly marked.

Compressive strength displays the usual dependency on water/cement (W/C) ratio with W/C ratios as low as 0.2 made possible by inclusion of 60% polymer by weight of cement (P/C = 0.6). Compressive and tensile splitting tests indicate an optimum of P/C ratio of approximately 0.4 for mixes with W/C ratios of less than 0.6.

The investigators also carried out tests on the elastic modulus, modulus of resilience and modulus of toughness of polymer modified concrete. These also depend primarily on W/C ratios which in turn are affected by polymer content. For a given liquid content (prescribed by workability) P/C and W/C ratios can be jointly expressed as % water replacement by polymer. All three material moduli are greatly enhanced by increasing water replacement percentage (from 0% to 93%). The Nawy group (Ukadike, 1978) also conducted freeze-thaw durability tests on polymer modified concrete (pmc) specimens. Polymer

modification showed distinct improved freeze flow durability with an optimum content around 0.3 to 0.4 by weight of cement.

Pike and Hay (1972) tested extensively two epoxy modifiers for concrete and mortar - Epoxon and Tufchem. Their tests included compressive strength, tensile splitting strength, alkali resistance, resistance to sulfuric acid and de-icing salts, bonding to concrete and to steel, linear shrinkage, creep, modulus of elasticity, coefficient of thermal expansion and others. Epoxon proved to have good overall properties, except bonding to steel, with optimum epoxy content of approximately 20% by weight of cement, however it is slow setting and thus unsuitable for patching purposes or for application in cold temperatures. Tufchem performance is reported in less detail than Epoxon but it also appears to perform satisfactorily and the coefficient of thermal expansion is compatible with that of Portland cement concrete. No setting time data is given for Tufchem but the authors do not recommend either of the products as rapid setting materials.

From the above survey it appears that polymer modified concrete could be suitable for patching purposes provided it could be demonstrated that shrinkage and thermal movement do not cause deleterious effects on the patch. Cold temperature behavior has not been investigated. It appears likely that some heating would be required. With fast setting materials this could be economically achieved.

3.3 Polymer Concrete

In polymer concrete, the cement is replaced with a polymer as the binding material. Potentially, this can eliminate the problem of freezing of the water but the requirement is that the polymer can cure in sub-freezing temperature or, alternatively, that it can cure very rapidly so that only short term heating

may be required. Ideally, the polymer should bind to wet concrete (and aggregate) to eliminate the need to dry all bonded surfaces. All these requirements restrict the range of suitable materials.

In this section some general sources on polymer concrete will be reviewed first. This is followed by review of epoxy concretes and miscellaneous materials. Finally Methyl Methacrylate (MMA) based materials are covered separately due to the prominence of this material in concrete repair work both in research and in practice.

Manson (1982) provides a useful reference source for polymer concrete technology, including overview of topics such as polymer impregnated concrete, polymer-Portland cement concrete (polymer modified concrete) and polymer concrete.

Meyer et al. (1981) provide some technical details of concrete deck repair with polymer materials at normal (mild) conditions but the paper is of limited usefulness.

Rechner (1968) reviewed a number of conference papers on polymer concrete. The paper is not very recent but gives an overall idea of materials investigated and problems encountered. Among the polymer materials covered are epoxy resins, polyester resins, polyurethane resins, furanic resin, phenolic resin and aminoplastic resins. The effect of temperature on mature specimens is widely covered. The thermal expansion coefficient of these materials, which is of particular interest in the context of patching, was found to be highly variable and dependent on temperature and density. In general the coefficient is lower the denser the material composition (density is increased by lowering the polymer/aggregate ratio). Some typical values are approximately $100 \times 10^{-6} \text{C}^{-1}$ for density of - 1.8 to $35 \times 10^{-6} \text{C}^{-1}$ for density of - 2.3. This is an order of

magnitude higher than for Portland cement concrete. Curing shrinkage is also a potential problem.

Tremper (1960) reports laboratory and field tests of repairs with epoxy concrete, carried out at the California Division of Highways. Epoxy was used either as filler in small patches or as bonding agent in larger patches of Portland cement concrete. Bonding surfaces may be damp but must not have free water. Thorough cleaning of surfaces is required. In cold weather heating is required to cure the epoxy but the heating period is short (typical setting time ~ 20 minutes, 70°F). Blow torches were used for heating.

Kemphues (1972) tested 3 epoxy resins for shrinkage and thermal expansion. Epoxy mortars of aggregate/epoxy ratios between 4:1 and 10:1 and one epoxy concrete was also tested. It should be noted that all three epoxies are relatively slow curing with a minimum of 24 hours initial setting time. Figure 3.9 presents the results for coefficients of thermal expansion. Linear expansion coefficients range from 7×10^{-4} in/in (for P9 4:1 ratio) to 5×10^{-5} in/in (P13 10:1 ratio). Although these epoxies are too slow to use as patching materials the results give an indication of the magnitude of dimensional changes which can be expected.

Johnson (1980) investigated a number of polymers and two water cured commercial compounds for suitability to cold weather application. All materials are fast setting and exothermic in their hardening process (Fig. 3.10).

The polymer materials included a urethane resin system, epoxy resin and polyester resin system. The urethane system performed particularly well with good workability and a 24 hour compressive strength of 2700 psi at -10°C (14°F) and 2200 psi at -10°C (-14°F), when mixed with sand (1.5 sand to 1 resin). In addition it showed no volume change due to shrinkage. The epoxy system tested (Epotuf) did not perform well in the cold. The polyester resins tested performed

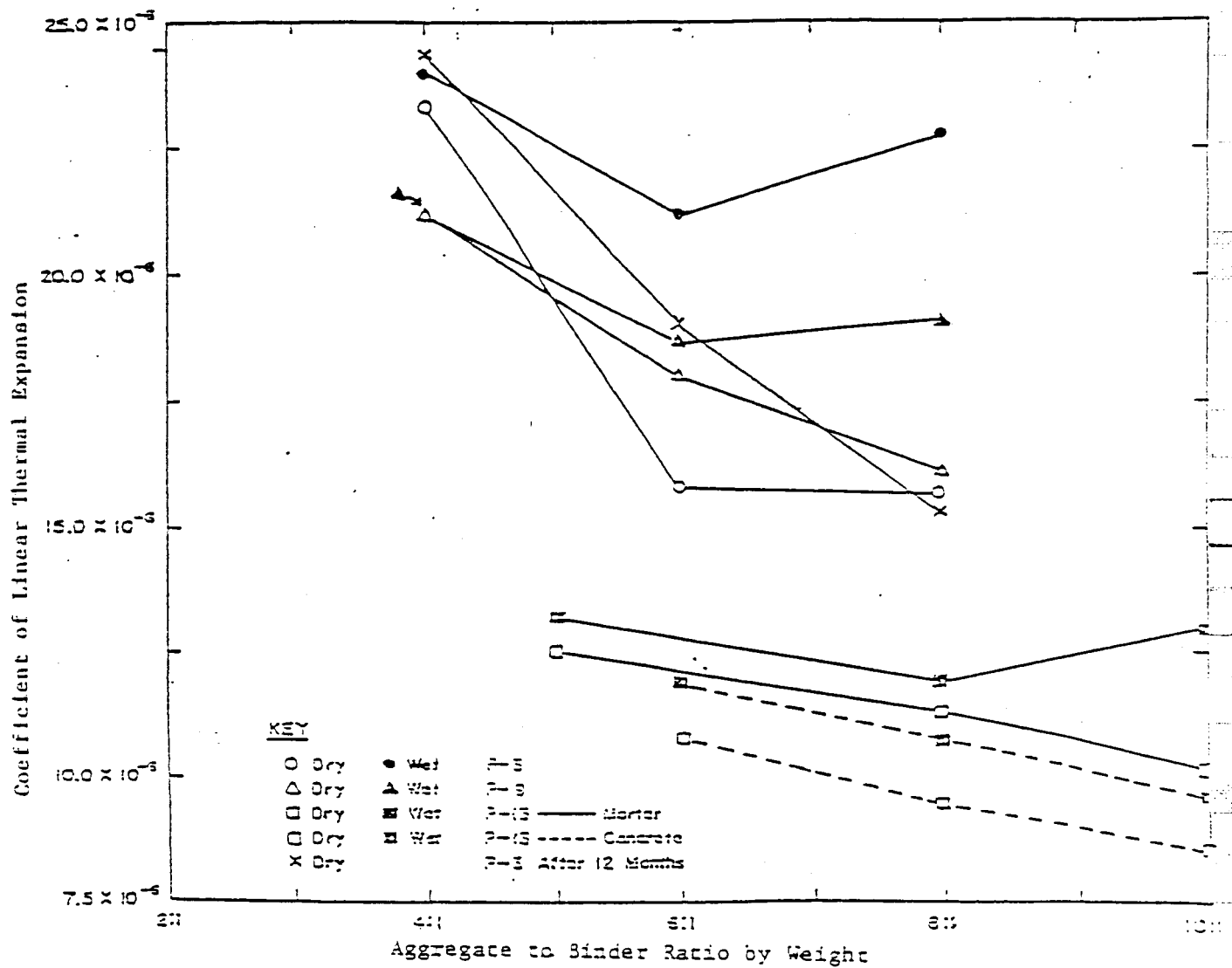


Fig. 3-9: Coefficients of Thermal Expansion of Three Epoxy Systems (Kemphues, 1972).

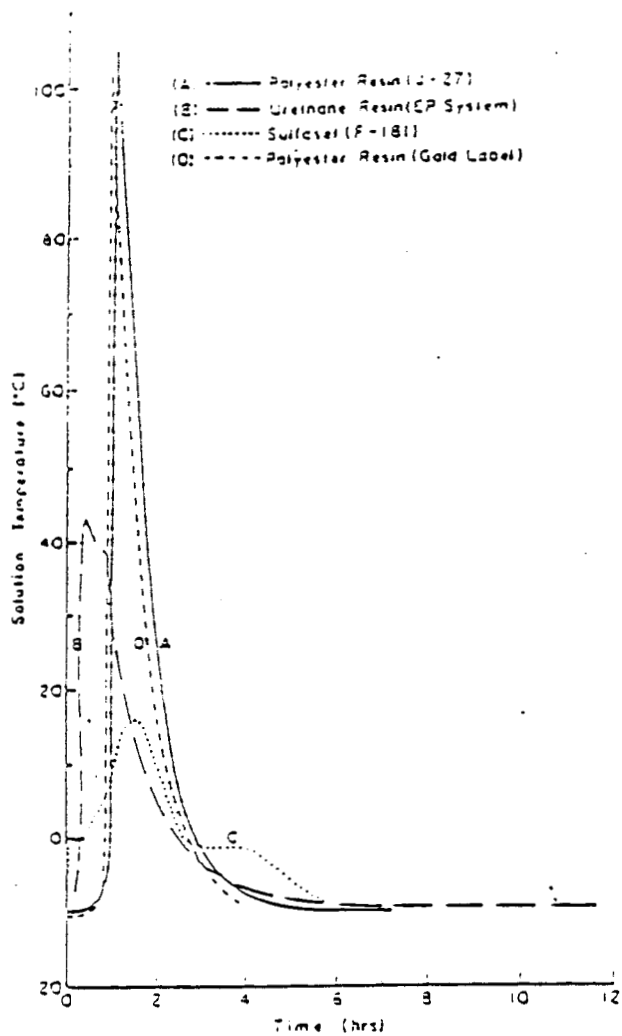


Fig. 3-10: Set Test Results of Heat Mixes at -10°C (Johnson, 1980)

reasonably well at -10°C (14°F) with mortar. Compressive strength of 770 psi at 24 hours for J-27 polyester and 1019 psi for "Gold Label". No shrinkage information is available but results with neat mixes indicate high shrinkage and shrinkage cracking. Of the two water cured compounds, F-181 anchoring compound performed well at -10°C giving 4700 psi compressive strength at 24 hours for the neat slurry. No sand mix is reported and no shrinkage information given.

McNerney (1981) reviews potential methods used to patch runways in adverse weather conditions, including low temperatures. This is a very general review of requirements and possible methods. Methyl methacrylate and "silikal" are mentioned as potentially suitable all weather materials for polymer concrete.

Methyl Methacrylate Based Materials

Haddad et al. (1983) investigated the effect of addition of initiator (Benzoyl peroxide -BzP) and promoter (N,N-dymethyl-paratoluidine-DMPT) to a monomer mixture of 95% methyl methacrylate (MMA) and 5% trimethylol propane trimethacrylate (TMPTMA), at different temperatures. The amounts of initiator and promoter were designed to maximize modulus of rupture. Results for neat polymer cast at 30°F (the lowest temperature tested) are given in Table 31. It was shown that promoter and initiator content can be adjusted to control the setting time at any given temperature. The investigation included also effect of aggregate inclusion on physical properties and bond characteristics to Portland Cement concrete. It is interesting to note that the bond strength in flexure is higher at lower casting temperature, and at 30°F it is comparable to the control monolythic Portland cement concrete beam. No information is given on shrinkage and thermal expansion.

At Brookhaven National Laboratory, use of Methyl methacrylate and related materials, and some other polymers have been studied. Although most

Table 31 Properties of MMA Based Polymer
(Hadad et al., 1983)

Bzp %	DMT %	Work Time min	Set Time min	Average Modulus of rupture (psi) 24 hrs.
4	2	9	47	2029
3.5	1.75	11.5	52	2224
3	1.5	19	60	2444
2.5	1.25	21	70	2376

of that work was focused on polymer impregnation of both sound and deteriorated concrete, substantial work was also performed on polymer-concrete, as a patching material. The four publications are reviewed chronologically in what follows.

The report edited by DeRay and Kukacka (1973) is a comprehensive compilation covering review of polymer materials, polymerization and impregnation and fabrication techniques, test results for polymer impregnated concrete and various applications. The report is primarily concerned with polymer impregnated concrete, with high strengths and with elevated temperatures and is, thus of marginal relevance to the current topic.

The reports by Kukacka et al. (1974,1975a,b) are directed to bridge deck repair but deals with impregnation of deteriorated concrete with the polymer. The main technical obstacle is the need to thoroughly dry the concrete since MMA based materials will not bind to wet or moist surfaces. The two reports do, however, give some data on the field applications of polymer concrete using 95% MMA and 5% TMPTMA in some medium sized patches on the Major Deegan Expressway in New York. The lane was open to traffic 2 hours after completion of the patching. 19 months later, no deterioration of the patch (case at 50°F) was observed.

Fontana et al. (1978) designed two mixes for application at temperatures of 35°F - 70°F and at 70°F - 90°F, respectively. The mixes differ in the amounts of promoter and initiator. They report a number of field applications of polymer concrete patches using this mix design (including the one described above). Details of patching operations are given. Preplaced aggregate with the monomer-initiator-promoter mixture poured on top was the method used for small patches (up to 15 sq. ft.). For larger patches, a concrete mixer was used to mix all the ingredients.

The paper by Webster et al. (1978) is essentially the same as the preceding one but gives more details on the properties of the two mixes used.

Romano and Butrick present the implementation of polymer concrete patching program at the Massachusetts Department of Public Works. The authors give details of patching operations at a number of locations. Four types of patches, namely: full depth, partial depth, shallow and thin patches were performed. They used kerosene heaters and infra-red heaters to dry the surrounding concrete. This also serves to raise the temperature under cold conditions (and thus promote curing). One of the patches they repaired was carried out at ambient temperatures of 17°F but this patch failed. Problems were observed with shrinkage leading to debonding and cracking of the patch. Based on their experience, the authors proposed a procedure for patching and mixing operation and for patching mix composition.

Dinitz (1983) also gives technical details for various operations employing pre-packed MMA based polymer concrete.

In a three volume report by the University of Oklahoma group, Ismalia et al. (1980) and Root et al. (1980) give details of various applications of polymer concrete and its properties. The monomer is primarily MMA + TMPTMA but other monomer systems are also described. Applications include polymer impregnated concrete, polymer concrete overlays and polymer concrete patching. Volume II of the report deals specifically with bridge deck patching. The group investigated a 95 MMA + 5% TMPTMA monomer with Lauroyl Peroxide (LP) as initiator and DMPT as promoter. Cure time as a function of initiator content and temperature is given in Fig. 3.11 for LP and in Fig. 3.12 for BP (Benzoyl Peroxide). The authors give some details on field tests including bridge deck patching. Overall results are satisfactory but little long-term performance is reported. All patches were carried out at moderate and high

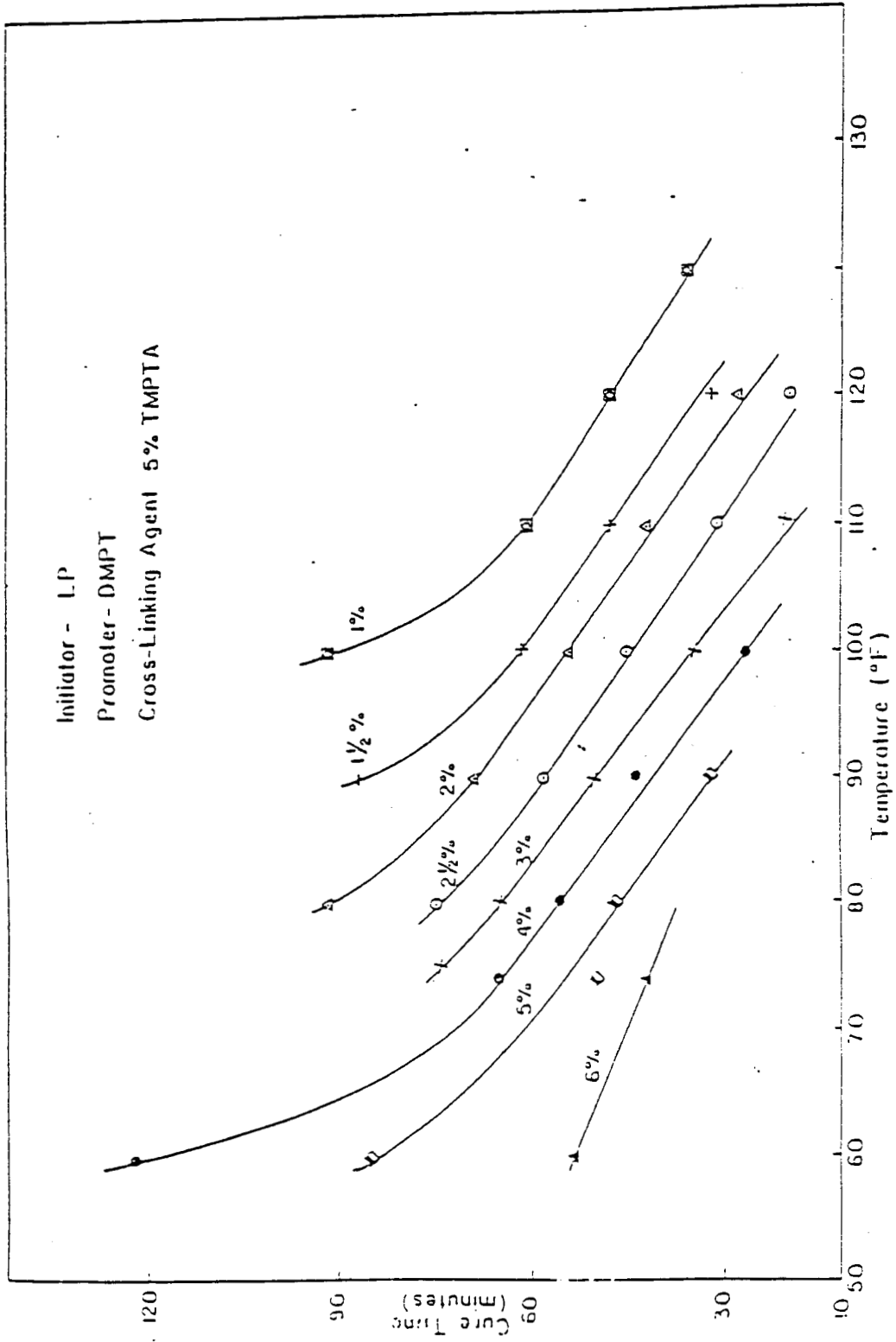


Fig. 3-11: Cure Time vs. Temperature (Root et al, 1980)

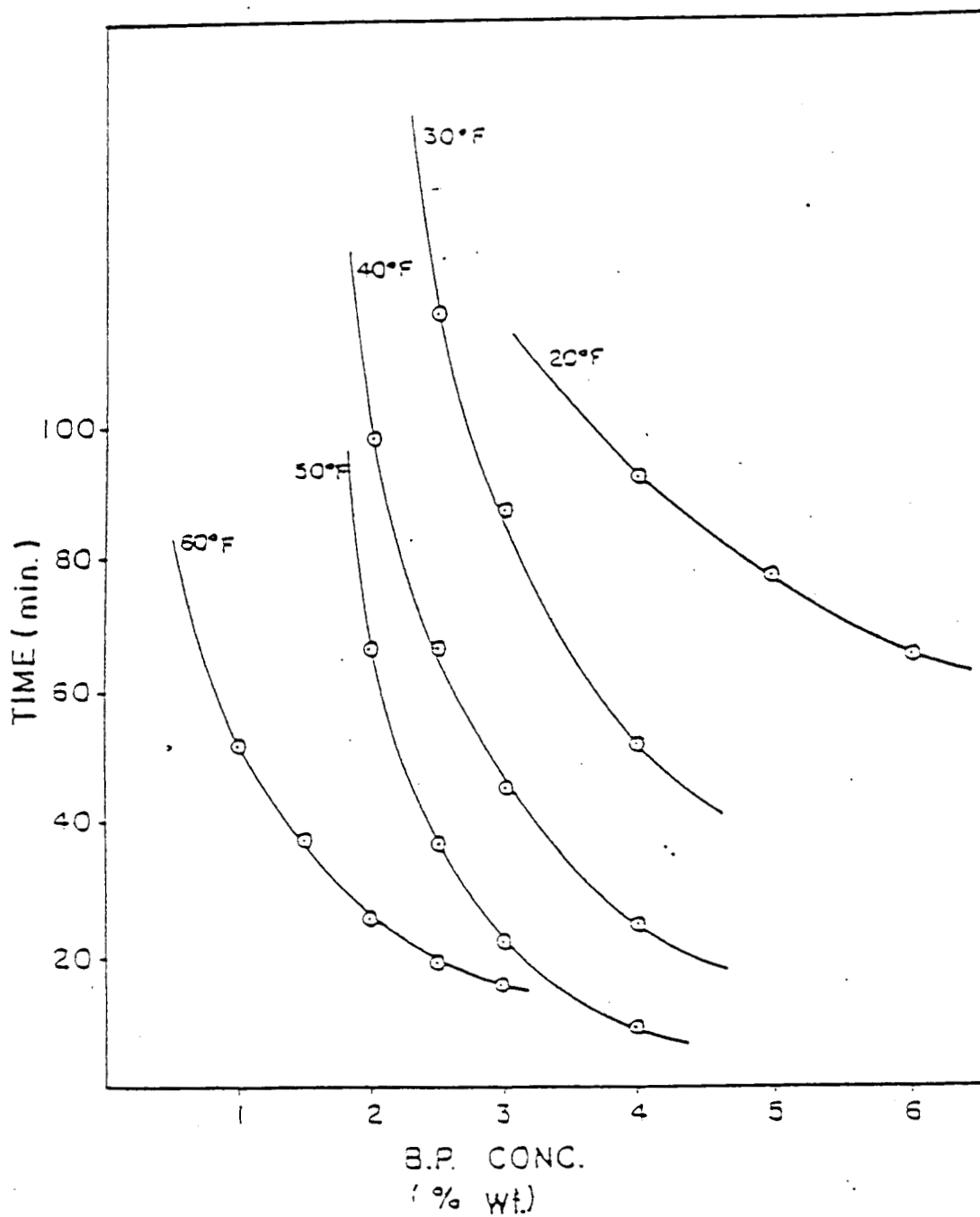


Fig. 3-12: Cure Time vs. BP Concentration (Root et al., 1980)

temperatures. Volume III of the report is a user's manual for patching operations based on the investigators experience. It is interesting to note that although dry aggregate is required for the PC mix, the authors do not require dry patch surface, but allow damp though not wet surfaces. This is an important point which needs further investigation.

It can be concluded that the use of polymer concrete, and, in particular methyl methacrylate based polymers, is a potential method for all weather patching. Performance at low temperatures needs further investigation (no successful patching at low temperatures has been reported). The requirement for dry conditions of aggregate and patch surfaces is a serious handicap. The claim by the University of Oklahoma group that damp surfaces can be accommodated needs investigating. Other polymers - in particular urethane based materials also merit investigation. There may also be health hazards associated with the handling of some of these materials which may restrict their use.

3.4 Miscellaneous Materials

This section contains various non-Portland cement materials which do not fall under preceding categories and various proprietary materials.

The report by Hartvigas (1979) was mentioned in the General section. Of the 15 commercial products reviewed by Hartvigas, three are magnesium phosphate based (Acmaset, Darex 240, Set 45). Two of four other compounds rated for winter patching (Minute Patch 1-2-5, Speed-crete) are of undisclosed composition, one (set Instant) is silica based on one (Texas mix) consists of Portland cement and gypsum. The remaining mixes were tested in summer conditions only. Of the above mentioned materials the Set Instant patch lasted 15 months, the remaining failed within 12 months. Only three of the compounds

were placed at sub-freezing temperatures: Set Instant (14°F), Minute Patch (26°F, snow), and Speed-Crete (26°F, snow). Lanes were opened to traffic 1 1/2 - 3 hours after patching.

The report by Ross (1975) was mentioned under the Portland Cement section. As mentioned there, the four recommended patching compounds are non-Portland cement based, but they were tested only at normal temperatures. The four compounds are: a calcium aluminate based material, a regulated set cement based material, a gypsum containing material (other ingredients not specified) and a premixed packaged material (System M) of undisclosed composition. The regulated set cement material had low durability factor in laboratory tests. The calcium aluminate material had a set time of over 4 hours, all four had relatively high shrinkage (from .028 to .089 in/in at 16 weeks).

Fast setting materials for bridge patching have been investigated at University of Texas, Austin (1984). Beer et al. (1984) and Ballou et al. (1984) investigated four packaged products: Duracal, which is a modified Portland cement based material, Set 45 which is a magnesium phosphate based mortar, Neco-Crete which is magnesium polyphosphate based and Gilco Patch which is a modified Portland cement material. The control was Type III Portland cement concrete. Tests included compressive strength, modulus of elasticity, flexural strength, flexural shear bond, flexural bond, and sand blast abrasion. All experiments were performed at normal (mild) temperatures on mortar and concrete specimens. All materials except Duracal reached sufficient strength within 1 hour (above 1500 psi) and Duracal reached it within 3 hours. Some results are presented in Fig. 3.13. Figure 3.14 presents curing exotherm for three materials and suggests that Set 45 and Neco-Crete may be suitable for low temperature applications. Shrinkage, thermal expansion and durability tests are yet to be reported.

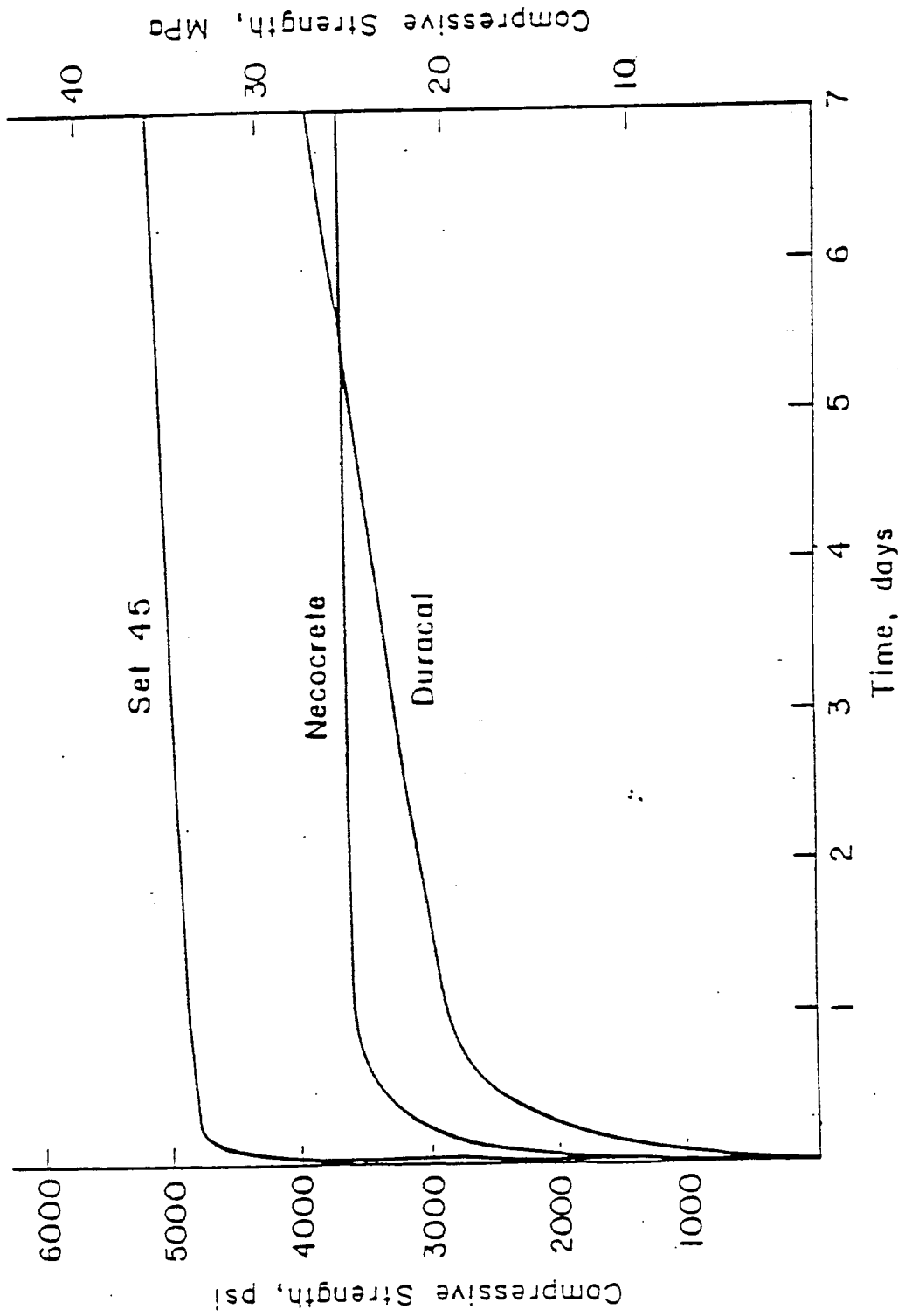


Fig. 3-13: Compressive Strength of 3 in. x 6 in. Cylinders (Beer et al, 1984)

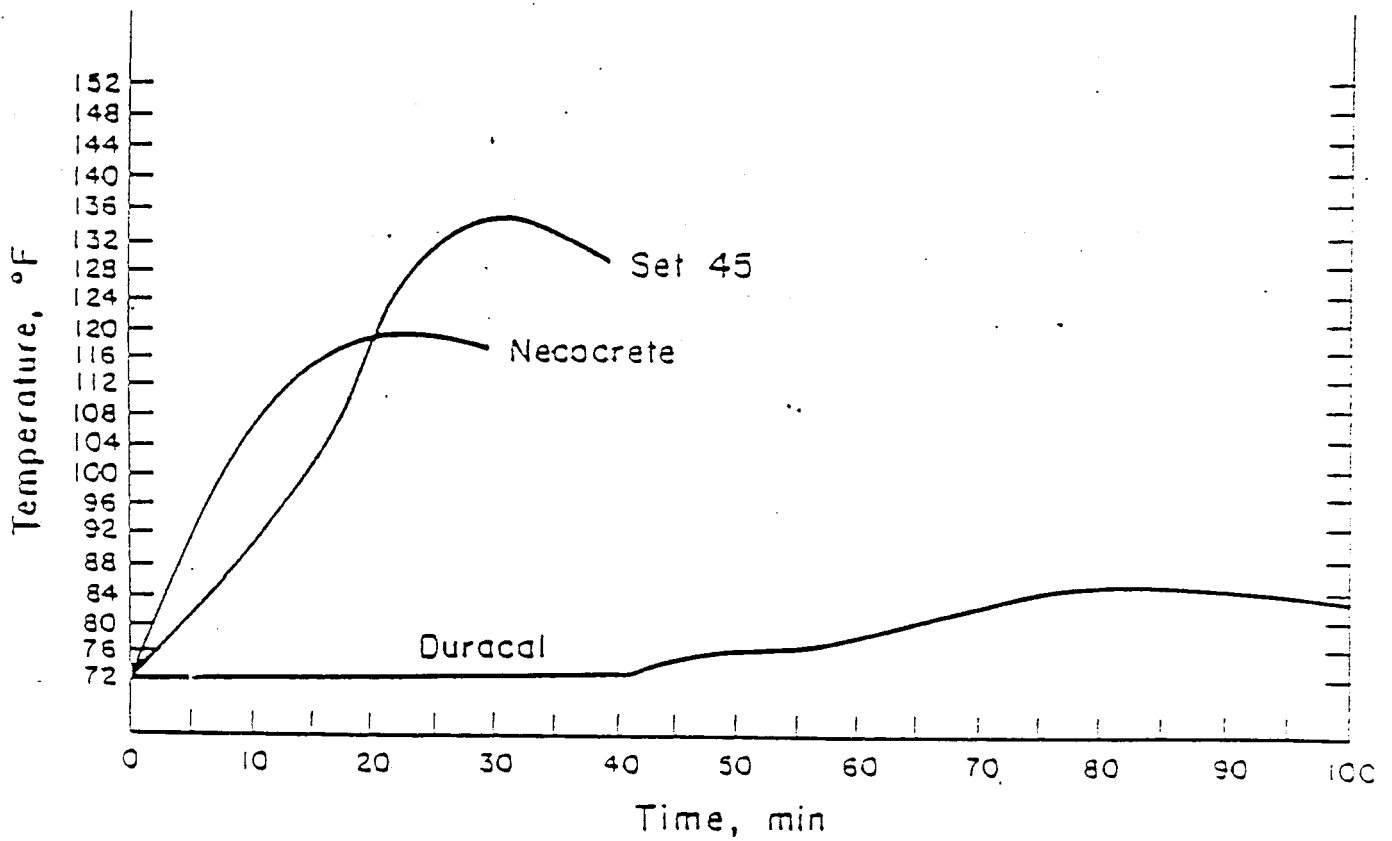


Fig. 3-14: Time vs. Exothermic Temperature Relationships (Beer et al., 1984)

Smith (1974) reports the use of Pre-Krete which is supposed to be fast-setting, "non-shrinking, non-cracking" patching material. However, Hartvigas (1979) who tested this calcium aluminate based material in summer conditions reports only qualified success: four "feathered" patches out of six cracked within 12 months but two "squared" patches were sound at 30 months. The material may warrant investigation at low temperatures.

El Jazairi (1982) reports on the properties of a magnesium phosphate based compound - FEBSET-45 used in the U.K., which is probably a derivative of the U.S. compound SET-45 (produced by Set Products, Inc.) and tested under normal conditions by Hartvigas (1979) and by Beer et al. both reporting good performance. El Jazairi reports also some low temperature behavior. A patch was placed in a cold store floor at temperature of -18°F (0°F) although the mixing was done outside the store and the floor was infrared heated prior to placing (to melt any present ice).

Janowiecki and Semler (1970) and Semler (1974) investigated a quick setting silico-phosphate cement. The material is based on Wollastonite mineral which contains 51% of silica and 47% of lime with traces of other minerals. To the ground mineral is added a buffered phosphoric acid solution with given specifications. The resulting cured material is porous and white in appearance. The authors report very high compressive strengths (3200-4500 psi) reached within 4 hours and with set time of 15 to 180 minutes.

The material behaves well at elevated temperatures but no low temperature results are reported. Bonding to Portland cement concrete appears to be poor and bonding agents are required. Freeze thaw durability appears to be good and thermal coefficient of expansion is compatible with concrete (mean $4.6 \times 10^{-6} \text{F}^{-1}$). The curing process is exothermic which may imply suitability for

cold weather applications. The porosity of the material, however may require coating or other measures to reduce permeability to water and de-icing salts.

3.5 Methods

As mentioned in Chapter 2, two special methods are considered for the specimen tests - steel fiber reinforcement and heating. For large scale applications, shotcreting, use of precast patch panels and bonding agents may also be considered. Some sources dealing with these methods are reviewed below.

Fiber Reinforcement, Heating, Shotcrete

Fiber reinforced concrete has a rich literature on its own. Here only sources directly related to bridge patching or heating will be reviewed. As mentioned in Chapter 2, the main objective of fiber reinforcement in the current project is to provide a simple heating method. Improved bond and crack control may be additional benefits.

Pailleri and Sarrano used fiber reinforced concrete as a means of adjusting resistance for electric conduction heating. Fiber content between 0.5% to 2% by volume, a voltage of 30V (AC) and current of 2A (i.e., a power supply of 60W) was used for heating.

Other short term heating methods have been mentioned in conjunction with other repair techniques and materials, e.g., blow torches, kerosene heaters, infrared heaters.

Fowler (1979) and Pand et al. (1975) characterize properties of fiber reinforced shotcrete. Fowler investigated the effect of different types of steel fiber on the mechanical properties. Pand found that fibers improve tensile and flexural properties of shotcrete but reduce somewhat compressive strength (probably due to reduced compaction).

A short article in *Better Roads* (in "Sub-Freezing Weather Bridge Deck Repaired with Quick-Set Gunned Concrete", 1975) describes the use of shotcreting for winter repair. The magnesium phosphate based material (probably Acmaset - see report by Hartvigas, 1979) set in 20 minutes and reached 2500-3000 psi in 3 hours at 20°F. This rapid patching method could be a good solution for winter repair operations. The mixing of components is performed in the nozzle and thus overcomes problems of short workability times. Control on mix proportions may be a problem though.

Precast Panels and Bonding Agents

Precast panels can be used to repair large areas. Two problems arise - maintaining continuity of the reinforcement and bonding of the panels to existing concrete.

Elkins and McCullough describe a repair system which maintains reinforcement continuity through lap joints filled with cast in-place accelerated set or polymer concrete. To shorten required splice length, "positive" connection of reinforcement can be achieved by welding or clamping.

Meyer and McCullough (1983) give more details on the procedure described in the preceding paper, including illustration of actual implementation (on IH-30 near Mt. Pleasant, Texas). Welding on some patches and U bolts on others were used to connect the reinforcement and MMA based polymer concrete was used for bonding. Performance is reported good 3 years later.

Creech (1975) performed laboratory and field tests for partial penetration precast panel patching. The problem associated with partial depth patching is cutting a constant depth smooth patch and bonding to the horizontal surface. The experiments demonstrated the feasibility of cutting a satisfactory patch. Epoxy was used for bonding and performed satisfactorily but cured too slowly. A fast curing epoxy is required. Due to the additional difficulties involved,

careful preparations and more experience is required with this technique. Cold temperatures present special problems, especially with respect to the bonding agent.

Huggenschmidt (1980) reports tests of three epoxy adhesives (normal temperatures) for bonding new to old concrete. The author claims that similar formulations can be used to bond precast concrete panels and even reinforcing steels. The tests at Ciba Geigy, Switzerland included fatigue and creep tests. Two of the adhesives are claimed to be curing at low temperatures. No data are given for set time, however.

Dixon and Sunley (1983) give a brief report on tests on a styrene-butadiene resin modified cement grout as a bonding agent. Diagonal split prism tests indicated bond strength lower than the control of concrete to concrete bond.

The problem of cold weather bonding of fresh concrete to old appears unresolved. If bonding agents become necessary (as may be indicated by results of the current program) this subject will require further investigation.

4. SUMMARY OF MATERIAL PROPERTIES

Table 4.1 presents a summary of reported properties of materials reviewed in Chapter 3, which are relevant to cold weather patching of concrete bridge decks. Also included are some brand names not covered by the literature survey for which the manufacturers' supplied data were used.

From the table, which is only a partial list of available materials, it can be seen that potentially suitable materials are available for winter patching. Experience with actual performance, however, is very scant, and to the extent that it exists, has been disappointing.

An extensive testing and assessment program is called for to evaluate performance of available materials and to develop a reliable and economic system for winter patching. This is the objective of the experimental portion of the current project, presented in subsequent sections of the report.

Table 4.1 - Summary of Material Properties

Material	Set time hrs:mins	Cure time, temperature strength	Ease of handling & application	Applicability in Wet Conditions	Comments
I. <u>Portland Cement Based</u>					
I(a). <u>Accelerators, Anti-freezing</u>					
PC Type III + CaCl ₂ < 2 %	~ 1 hr	3 days @ 50°F	Easy	Yes	Too slow, heating required
CaCl ₂ (+NaCl) < 20 %	~ 1 hr	3-7 days @ 0°F - 14°F	Easy	Yes	Too slow, may be ok with some heating. Effect on durability not known.

"Hydra Set" (CaCl ₂)	Initial: 1:50-3 hrs Final: -2:15-4 hrs	24 hrs @ 40°F 1660 psi			Reported by Macadam et al. (1984)
"Daraset" (Ca(NO ₂) ₂) + Ca(NO ₂) ₂	Initial: -2 Final: - 2:30	8 hrs @ 75°F - 2000-2500 psi	Easy	Yes	Daraset not suitable for low temperatures. Darex has best all around properties. Hydraset also satisfactory
"LA-40" (NaSCN)	Initial: 2-8 Final: 4-12	3 days @ 40°F 3250 psi			No sub-freezing performance reported
"Acceleguard 80" (Ca(NO ₃) ₂)	Initial: 2:40-4:50 Final: 3:15-7:30	3 days @ 40°F 2060 psi			Heating may be required

Table 4.1 - Summary of Material Properties

Material	Set time hrs:mins	Cure time, temperature strength	Ease of handling & application	Applicability in Wet Conditions	Comments
I(b). <u>Regulated Set Cement</u>	1-2 hrs	a) 1000 psi in 3 days @ 15°F b) 3100-4100 psi in 1 day @ 68°F	Easy	Yes	High variability sources report different strength developments. Relatively high drying shrinkage
I(c). <u>Shrinkage Compensating Cement</u>	NA	NA	Easy	Yes	To be used with accelerators and possibly heating
I(d). <u>Polymer Modified Concrete</u>					
Styrene-Butadiene Modifiers	10-90 mins	1 days @ ~70°F 1360-2370 psi	Easy	Yes	To be used with accelerators, possibly heating. Shrinkage may be problem
Epoxy Modifiers	varies 20-30 mins PC10 6 hrs Epxon	varies depending on epoxy ~4000 psi at 4 days, room temperatures, PC10 epoxy 3000 psi @ 3 days (normal temps.) - Epxon	Relatively Easy	Yes	Heating may be required. No cold weather applications required.

Table 4.1 - Summary of Material Properties

Material	Set time hrs:mins	Cure time, temperature strength	Ease of handling & application	Applicability in Wet Conditions	Comments
II. Polymer Concrete					
Epoxy	varies with type, e.g. 20 mins @ 70°F	varies with type. Few will cure at sub-freezing temps	Thorough cleaning mixing plant	Some Epoxies do	No cold weather applications reported. Curing may be problem, heating may be required.
Polyester	1-2 hrs @ 14°F	24 hrs @ 14°F 700-1000 psi	Mixing plant cleaning solutions	Probably dry conditions required	
Urethane	20-40 mins (39°F)	24 hrs @ 14°F 4700 psi	Mixing, cleaning	Dry	Looks promising shrinkage and performance data not available
MMA & IMP/MA	Adjustable e.g., 40 min to 70 mins @ 30°F	24 hrs cast 30°F Tested 70°F 2000 psi (Typ)	Mixing, cleaning	Dry	One source allows moist patch surface. No cold temperature performance required.

III. Miscellaneous

Sulfaset F-181 Anchor bolt compound	1 hr	24 hrs @ 14°F 4000 psi	Probably easy (water mixed)	Probably	Check shrinkage, suitability for patching.
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Table 4.1 - Summary of Material Properties

Material	Set time hrs:mins	Cure time, temperature strength	Ease of handling & application	Applicability in Wet Conditions	Comments
<u>Magnesium Phosphate</u>					
Set-45	:15 min @ 20°C	6 hrs @ 0°F 2000 psi	Easy	Yes	Promising. Needs investigation in cold.
Darex 240	-	-	Special activator	Probably	Not enough information. Doubtful performance in cold. See "Darex" as accelerator. Both claimed suitable for cold.
Acmaset			Special solvent	Probably	
Necocrete	~10 mins @ ~70°F	1 hr @ 70°F 1780 psi	Easy	Yes	
Bostick 276	~160 mins @ 32°F	1 hr @ 72°F 2000 psi	Easy	Yes	
Silico-Phosphate Cement	Adjustable :15 min-2:30 at ~70°F	4 hrs @ ~70°F 3200-4500 psi	complex preparation no pre- packaged package	-	Poor bond to hardened concrete. Porous, permeable.
<u>Calcium Aluminate</u>					
Pre-crete	:16 mins @ room temp	3 hrs @ room temp. 2200 psi	Easy	Yes	No cold temp performance reported. Appears to require smooth boundaries.

Table 4.1 - Summary of Material Properties

Material	Set time hrs:mins	Cure time, temperature strength	Ease of handling & application	Applicability in Wet Conditions	Comments
<u>Commercial Packages</u>					
Speed-crete	:3-5 mins @ room temp	24 hrs @ room temp, 2200 psi	Easy	Yes	Some experiences in winter, doubtful. Seems better without gravel.
Texas mix (Portland cement & gypsum)	-	more than 4 hrs in winter	Easy	Yes	Good experience in summer. Doubtful in winter.
Minute Patch 1-2-5	-	2 hrs in winter	Easy	Yes	Low wear performance.
Set Instant (Silica)	-	90 mins, winter heating	Easy	Probably	Doubtful performance, possible high shrinkage.
Anti hydro	-	24 hrs, 500 psi (room temp.)	Easy	Yes	Doubtful performance in winter (not reported).
Concresive 1001-regulator	5 hrs @ 75°F	3 days @ 75°F	thin liquid	-	too slow
1001-LPL	4 hrs @ 40°F	4 hrs @ 75°F	viscous liquid		
1419	-	48 hrs @ 16°F 3600 psi	reasonably easy		working temp. 25-50°F (some heating may be required).
Concresive 1422 Epoxy bonding agent	-	24 hrs @ 25°F			

Table 4.1 - Summary of Material Properties

Material	Set time hrs:mins	Cure time, temperature strength	Ease of handling & application	Applicability in Wet Conditions	Comments
Concresive 2020 Acrylic polymer concrete (MMA)	~45 mins @ 40°F	1-3 hrs @ 20°F	-	-	see MMA. Probably similar.
Transpo Polymer Concrete (MMA)	pot life 10-15 mins	32°F: 105 mins 14°F: 120 mins		See MMA	

PART II: EXPERIMENTAL PROGRAMS

5. INTRODUCTION

Part I of the report surveyed the relevant literature and identified a large number of materials and methods, potentially suitable for cold weather application. Part II covers the second phase of the project, involving an extensive testing program aimed at evaluating the performance of some of those materials, at the specimen level.

The large number of materials identified in the literature search necessitated splitting this second part of the project into two main phases. The first phase comprised screening tests of a large number of commercially available products. The tests involved the determination of early strength development. Those materials which performed well in these screening tests were subjected to a more extensive and rigorous testing program which involved various types of strength and durability tests. A supplementary phase, involving slab specimens was implemented to assess two-dimensional effects.

The report presents experimental procedures and results of the three series of tests, namely the cylinder screening tests, the prism tests and the slab tests. Conclusions are drawn and recommendations made concerning the performance of the tested materials and the need for further investigations. Table 5.1 lists in categories the extensive testing program conducted.

Table 51 Testing Program Listing

<u>Cylinders</u>	
Preliminary Tests: Materials	51
Strength	21
Slant Shear (Dry Patch)	21
Slant Shear (Moist Patch)	21
Trial Mix - Parent Concrete	60
Control Cylinders for prism tests	90
Control Cylinders for slab tests	46
	<hr/>
	<u>310*</u>
<u>Prisms</u>	
Static Tests (Dry Patch)	30
Static Tests (Moist Patch)	30
Cyclic Tests (Dry Patch)	15
Cyclic Tests (Moist Patch)	15
Freeze-Thaw Tests	18
	<hr/>
	<u>108</u>
<u>Slabs</u>	
Long Patch (Smooth Surface)	3
Long Patch (Rough Surface)	3
Wide Patch (Smooth Surface)	3
Wide Patch (Rough Surface)	3
Control	2
	<hr/>
	<u>14</u>

6. SCREENING TESTS

6.1 Materials

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

6.1.1 Portland Cement Based Materials

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

Modified Portland cements include high early strength cement (type III), Regulated set cement (§3.2.2) and shrinkage compensating cement (§3.2.3). The relevance of the latter in patching concrete may be for improving bond to existing concrete.

Admixtures may include, in addition to air entraining and water reducing agents, accelerating and/or antifreezing and other early strength promoting materials (e.g., silica fume). Of the accelerating/antifreezing agents, the most commonly used is calcium chloride (CaCl_2). The effect of this agent on corrosion is still controversial. In the United States its content is generally limited to 2% or less. For calcium chloride to be effective on its own, without heating, substantially higher contents are required. Most of the experience with high calcium chloride contents comes from the Soviet Union with supporting

evidence from the U.S. (§3.2.1). Other antifreezing agents were used by the Soviet group, particularly sodium nitrite (NaNO_2). The latter, however, does not have an accelerating effect.

Various proprietary admixtures are available for cold weather application which contain various active ingredients but actual experience and test data at sub-freezing temperatures are very scarce.

Some polymer modifiers are accompanied by exothermic reactions which could have a freeze retarding in addition to water reducing effect (§3.2.4). Polymerization, however, is usually retarded at low temperatures.

6.12 Polymer Concrete

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

The most widely used and tested polymer concrete is methyl methacrylate (MMA) based (§3.3) but only one source (Romano and Butrick, 1981) reports a sub-freezing application, which was successful. Other polymers for use as binders in polymer concrete, include polyester, epoxies and polyurethane. Some tests at low temperatures were carried out on these polymers (Johnson, 1980) with encouraging results reported for polyester and polyurethane, but epoxies do not set well at sub-freezing temperatures.

6.13 Non-Portland Cement

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

6.2 Test Procedure and Results

Seventeen materials were obtained from manufacturers and tested under the screening tests program. The materials are listed generically (with results and comments) in Table 6.1, under their respective groups. Some fast setting materials, particularly water based, may require short-term heating to accelerate setting and/or prevent premature freezing. A heating method was developed to accommodate such options (Pailleri and Serrano, 1977), employing 0.75% to 1% steel fiber reinforcement and a low voltage power source. The fibers act as conductor/resistor for the electric current which can be adjusted to provide the required amount of heating (Fig. 6.1).

All specimens were 4x8 inch cylinders cast and maintained at ambient temperatures of 15°F to 20°F. The cylinders were tested for compressive strength at 24 hours after casting. Ordinary Portland cement mixes were based on a standard mix (see specimen tests for details). Commercial products were prepared in accordance with manufacturers' instructions.

Results of the screening tests are presented in Table 6.1 for both heated and non-heated specimens. It can be observed that none of the Portland cement based mixes produced adequate strength at 24 hours. Of the polymer concretes, methyl methacrylate and polyurethane based materials performed well. The polyester based material, although possessing adequate strength, performed poorly by other criteria, having very poor workability, high shrinkage and strong odors. The material was, therefore, omitted from the second phase. In the non-Portland cement materials group, the magnesium phosphate based products performed very well.

Table 6.1: Screening Test Results

Product	Manufacturer	24 hrs. Compressive Strength (psi)		Comments
		Non-Heated	Heated	
<u>Portland Cement Admixtures</u>				
1. CaCl ₂ (1-4%)	Dow Chemicals	Did not set	N.A.	
2. Antihydro	Antihydro	"	Did not set	
3. Plastocrete 161HE (accelerator)	SIKA	"	"	
4. Plastocrete 161F (accelerator)	SIKA	"	"	
5. Sikament/c	SIKA	"	"	
6. Regulated set cement	National Gypsum	"	450	
<u>Polymer Concrete</u>				
7. Gold label (polyester based)	Preco Indust.	2000	N.A.	Strong odor, low workability
8. Transpo T17 (MMA)	Transpo Indust.	3900*	N.A.	
9. Concesive 2020 (MMA)	Adhesive Eng.	3600*	N.A.	Strong odor, good workability
10. Percol S-100 (polyurethane)	ARNCO	1760*	N.A.	very fast set low elastic modulus, disposable utensils required
<u>Non-Portland Cements</u>				
11. Set 45 Magnesium phosphate (water based)	Master Builders	3000*	N.A.	good workability
12. Bostik 276 Magnesium Phosphate (non-water based)	UPCO Products	1600* Bostik Const.	3800	mild odor good workability
13. PreKrete (calcium aluminate)	Patterson-Kelley	760	1000	
14. Sonopatch	Rexnord			
15. Sonogrout	Chemical	Did not sell		Did not sell
16. Sonoset	Products			
17. Speed Crete	TAMMS Indust.	Did not sell	517	High shrinkage

N.A. = not applied

* = selected for further investigation

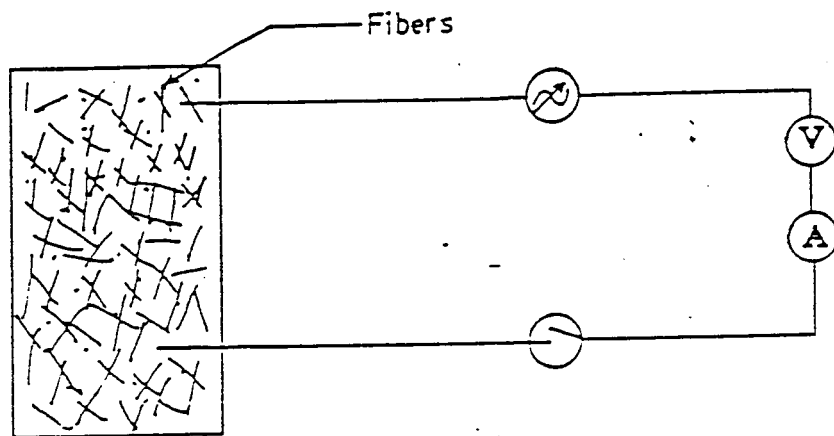


Fig. 6-1:

Heating Method

7. SPECIMEN TESTS

7.1 Materials

Based on results of the preliminary screening tests, five products representing four generically distinct materials, were selected for further investigation at the specimen level. These materials are designated as follows:

- M₁ Transpo - Methyl methacrylate based polymer concrete
(No. 8 in Table 61)
- M₂ Coneresive - Methyl methacrylate based polymer concrete
(No. 9 in Table 61)
- P₁ Set 45 - Water based magnesium phosphate
(No. 11 in Table 61)
- P₂ Bostik 276 - Non-water based magnesium phosphate
(No. 12 in Table 61)
- U Percol S-100 - Polyurethane polymer concrete
(No. 10 in Table 61).

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

7.2 Design of the Experiments

An experimental investigation normally consists of assessing the effects of a number of controlled parameters (factors) on a number of measured response variables. The main objective of the present investigation is the evaluation of the performance of the selected patching materials. In order to provide as many evaluation criteria as possible, a large number of response

variables (i.e., experiments) was adopted. Experiments fall under two general categories: strength and durability.

Strength tests involve testing of the strength of the patching material, on one hand, and the bond of the patching material to existing or "parent" concrete, on the other. The measurement of strength depends on the mode of loading - compression, tension, shear and flexure strengths, for instance, are distinct types of strength. In addition, in the context of structures subjected to dynamic loads, both static and cyclic loading are of interest.

Durability of concrete in highway structures is affected by two major processes: freeze-thaw cycling and corrosion of reinforcement due to de-icing salt chloride attack. It has been established that the cause of corrosion is not so much the presence of chloride and other cations, but of ion gradients which cause ion movements in which steel in areas of high cation concentrations acts as the anode. Since patch material does not normally contain chloride ions, ion gradients are established across the patch boundary between the patch and the surrounding concrete, which may promote active corrosion.

The above considerations led to a testing program which consists of six experiments as follows:

Strength Tests:

Cylinder Tests:

1. Compression of neat patch material
2. Slant shear of patched specimens (Fig. 7.1)

Flexure Tests:

3. Static loading of patched prism specimens (Figs. 7.2, 7.3)
4. Fatigue loading of patched prism specimens (Figs. 7.2, 7.3)

Durability Tests:

5. Freeze-thaw durability of patched specimens (Figs. 7.2, 7.4, 7.5)
6. Change in half cell corrosion potential across patch boundary during freeze-thaw cycling (Fig. 7.6).

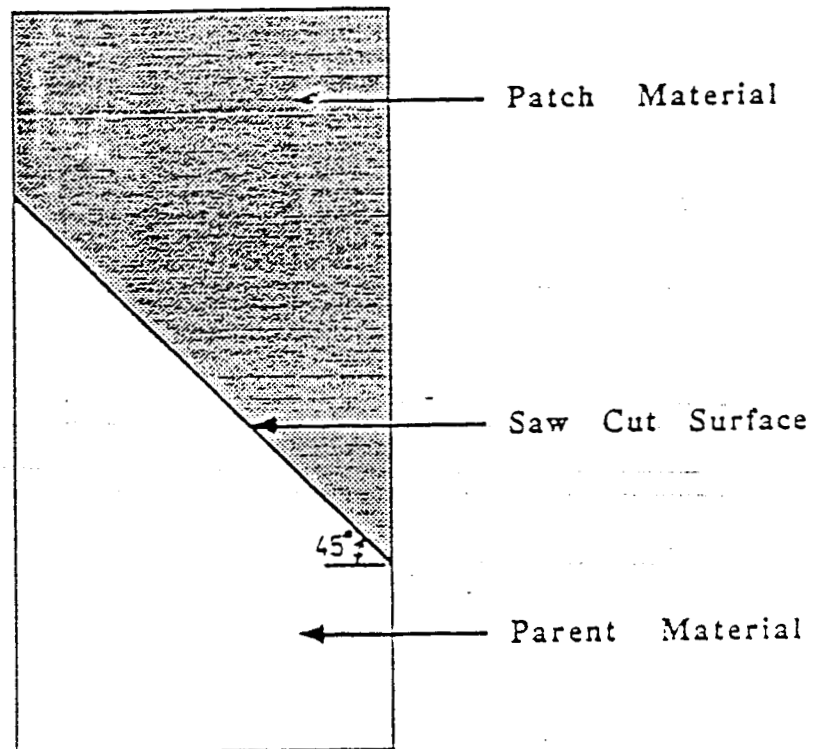


Fig. 7-1:

Slant Shear Specimen

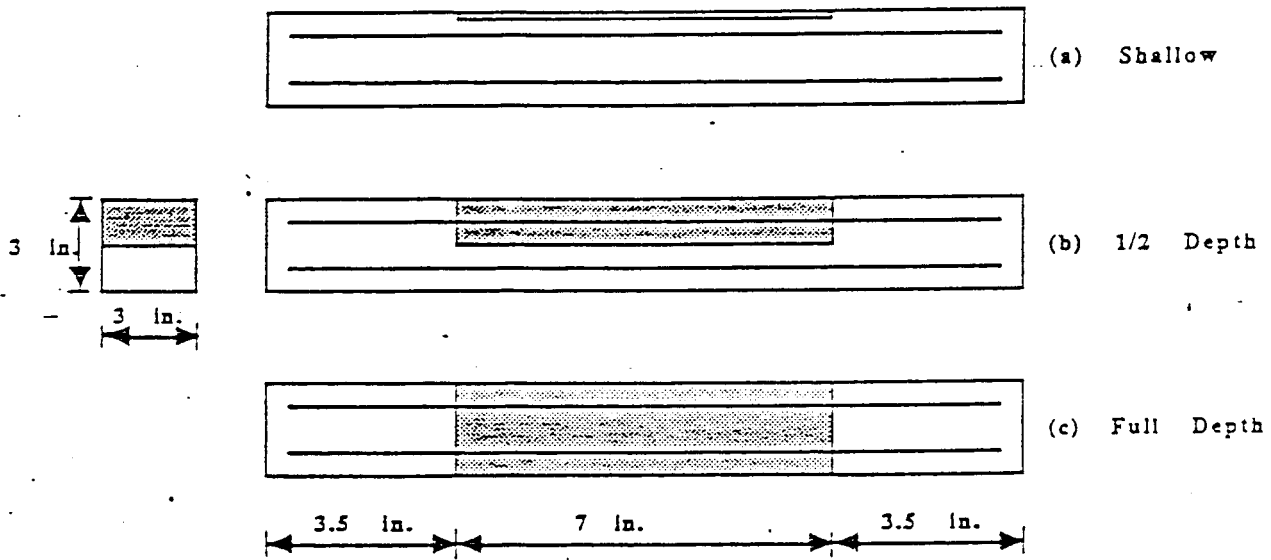


Fig. 7-2: Flexure Specimens

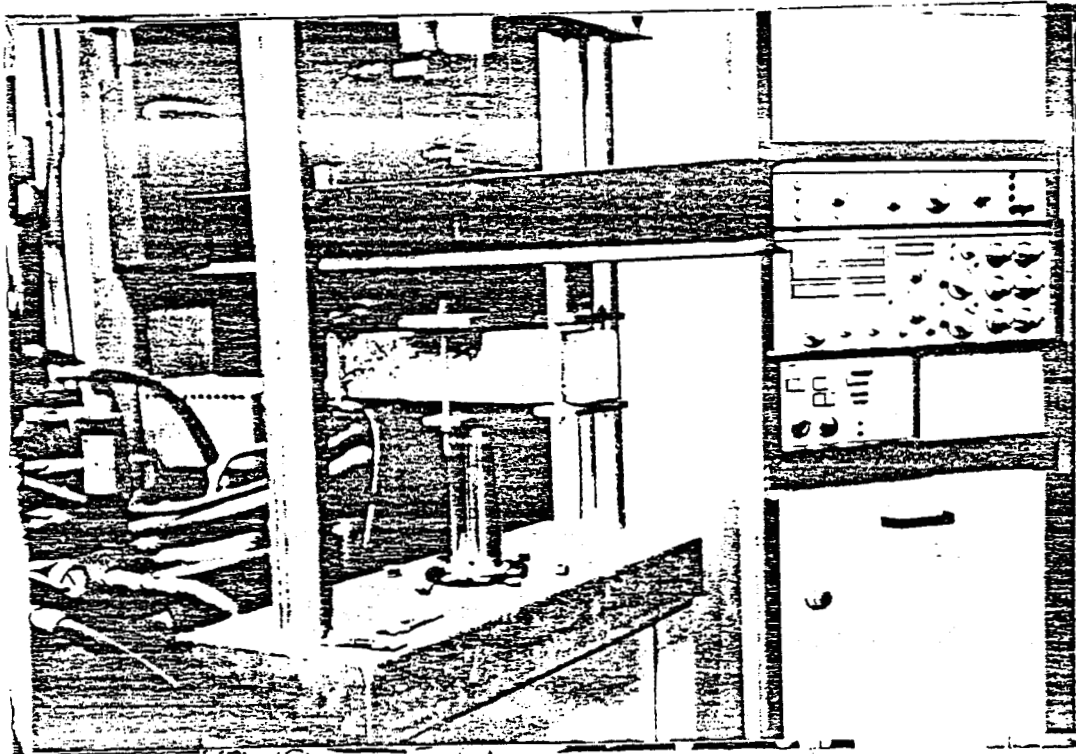


Fig. 7-3: Flexure Test Set-up

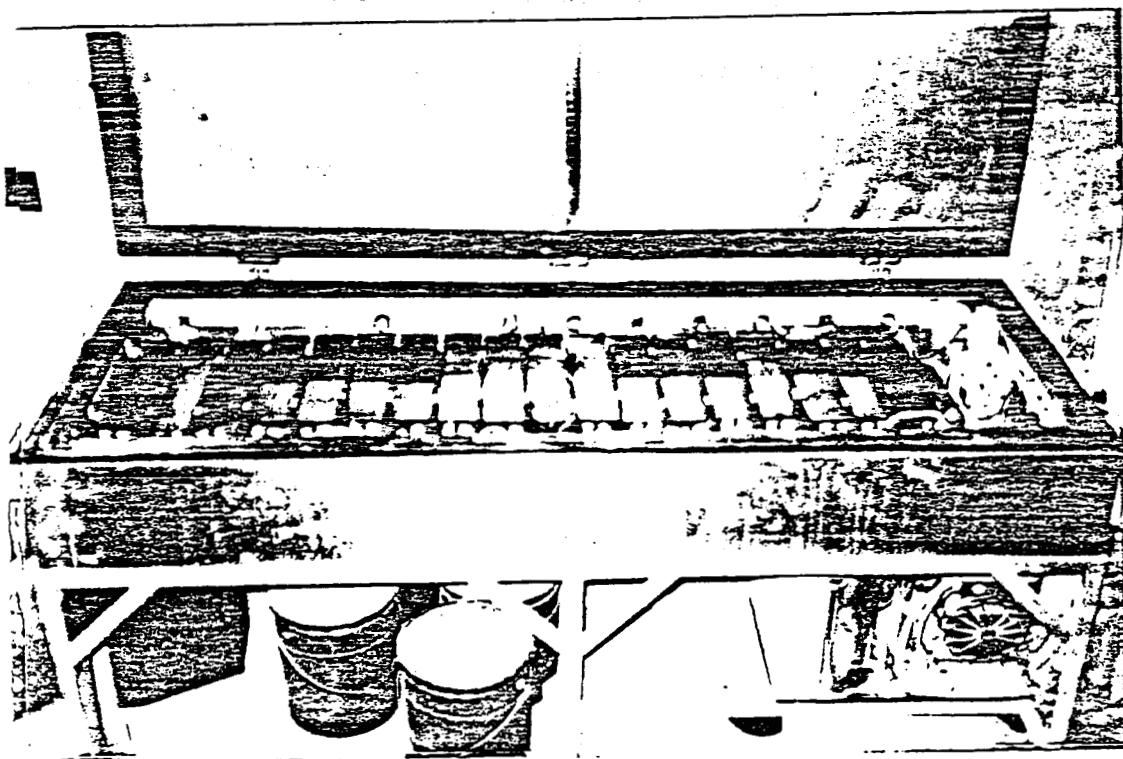


Fig. 7-4: Freeze-Thaw Chamber Layout

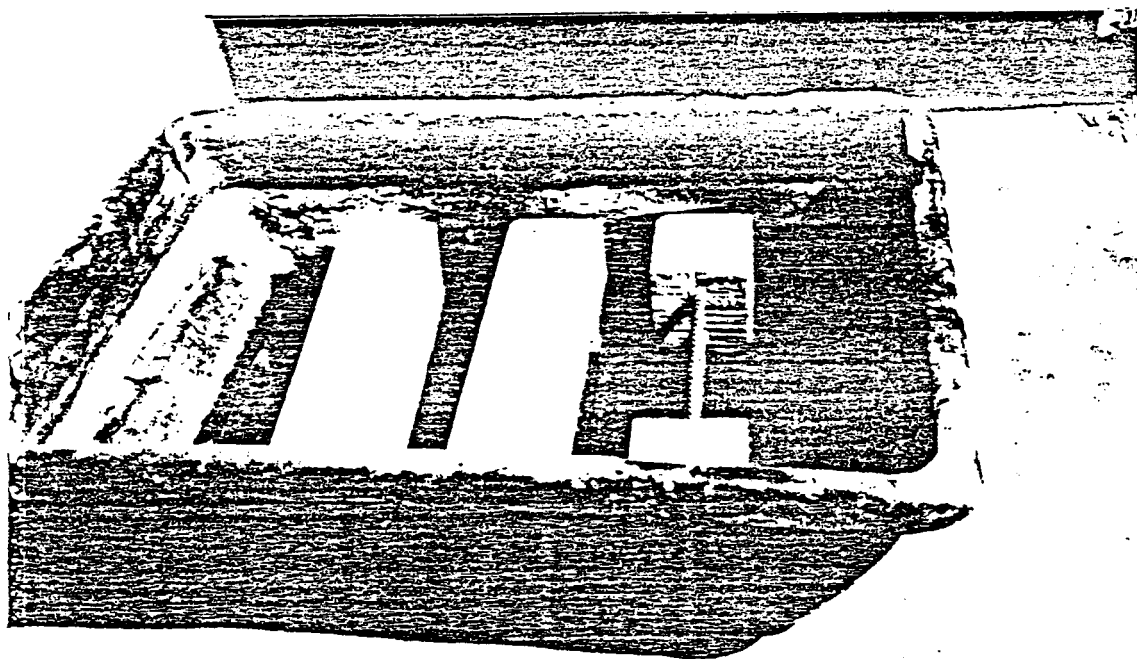


Fig. 7-5: Freeze-Thaw Specimens in Salt Bath Prior to Testing

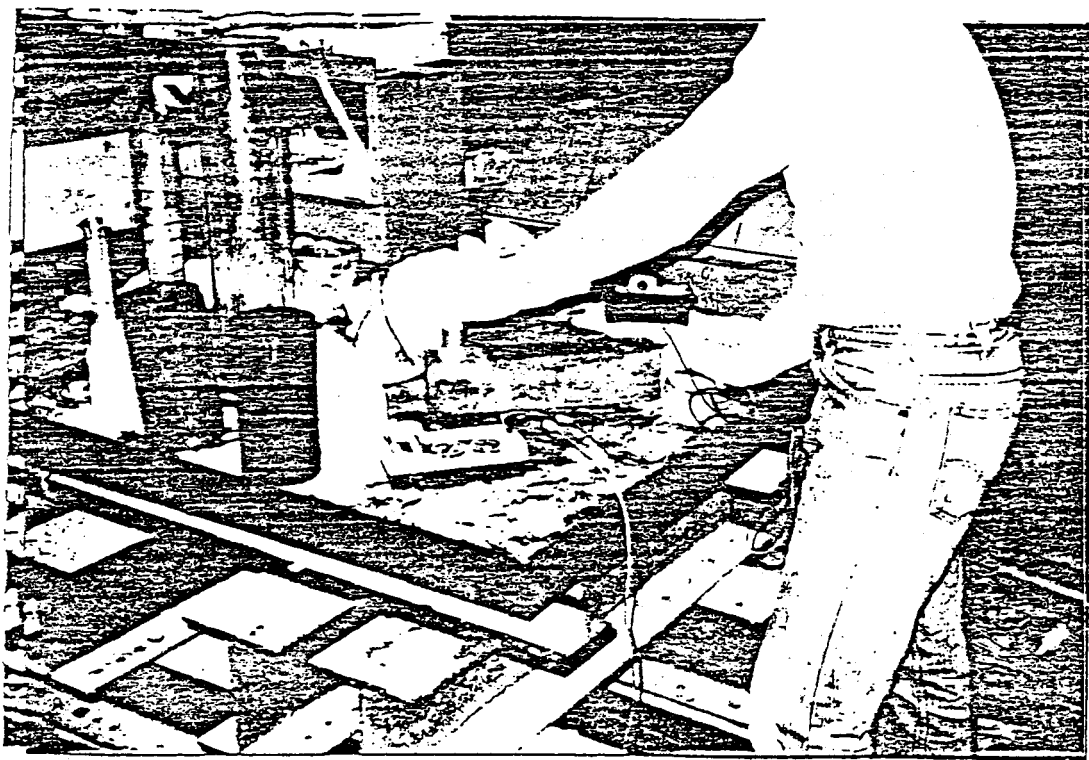


Fig. 7-6 : Half Cell Corrosion Potential Measurement

Having designed the experiments in terms of measured responses, what is left is to determine what parameter effects need to be considered. Many factors may affect the behavior of patches in concrete. Naturally the major parameter is the patching material itself. Additional factors may include patch geometry, patch surface conditions, ambient conditions (temperature, humidity) and others. In view of the large number of responses selected, only one factor was initially included in the investigation in addition to material type, in order to limit the size of the experiment. This additional factor was patch depth, which is related to patch geometry (see Fig. 7.2). Three patch depths were involved: a shallow depth (approximately 10th of the full specimen depth), half depth and full depth. This factor applies, naturally, only to prism specimens. A third factor - age - was applied to cylindrical specimens (strength tests) only. Cylinders were tested at ages of 7 and 24 days (see procedures below).

The experimental design can be summarized as follows: each of the four experiments involving prism specimens can be considered as a factorial experiment involving two factors (material and patch depth) at five levels (materials) and three levels (patch depths) respectively. Cylinder tests are factorial experiments with two factors (material and age) at five levels and two levels respectively. Since methyl methacrylate materials occur in two configurations - with and without gravel - these experiments were modified to seven levels for the materials and two levels for age.

Following completion of the test series, experiments 2 through 5 were repeated under conditions of moist contact surface between patch material and parent concrete. The objective of this supplemental test series was to assess the effect of humid patching environment on patch performance since avoiding the need to dry the patched surfaces prior to testing can be highly beneficial.

Although the sequential nature of the procedure, dictated by time schedule constraints, may introduce some systematic errors, it was thought that such error could not amount to a highly significant effect. This supplementary test series introduced an additional factor - moisture - at two levels (dry and moist).

7.3 Procedure

7.3.1 Specimen Preparation

Specimens were cast of the standard mix over a period of six months. Specimens consisted of 4x8 in. cylinders and 3x3x14 in. prisms, with the patch of 7 in. long by the appropriate depth blocked out. Some full prisms were cast as controls. Prism specimens were reinforced with two #3 bars (Fig. 7.2). Specimens were cured for seven days under plastic cover and then stored in air in the laboratory for a minimum of 3 months prior to patching and testing operations. This procedure ensured mature concrete with time and maturity effects expected to be negligible. Cylinders were taken from some batches for 28 days moist curing and testing to determine compressive strength.

7.3.2 Cylinder Tests

Cylinder specimens for slant shear tests were diamond cut at 45° to their axis, as shown in Figs. 7.1 and 7.7, each cylinder producing two half cylinders for parent material. In all, twelve 4x8 in. cylinders were cast of each patching material - six full cylinders and six half cylinders cast over the diamond cut surface of the parent concrete (Fig. 7.1)

All cylinders were cast in a temperature controlled room at temperatures of 15°F to 20°F . Patch mixes were prepared in accordance with manufacturers' instructions, where applicable. Magnesium phosphate materials were prepackaged and cast as received. Methyl methacrylate may be cast with or without coarse pea gravel added to the sand containing prepackaged material.

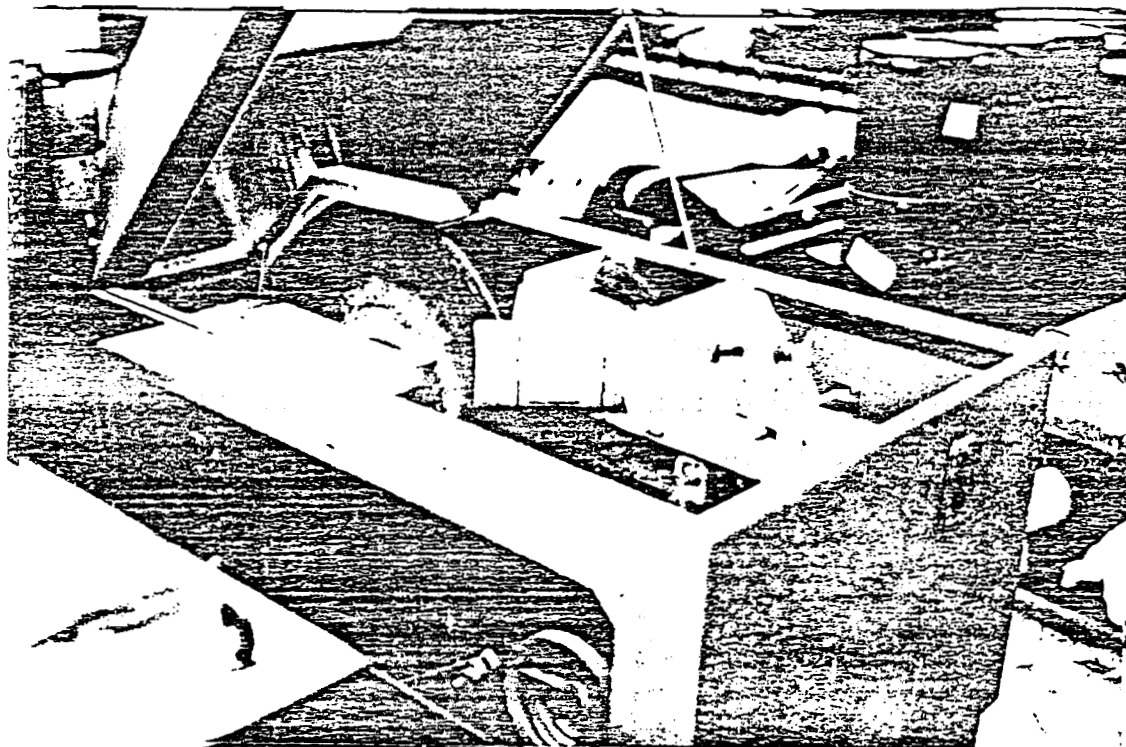


Fig. 7-7: Diamond Saw Cutting of Slant Shear Specimen

depending on patch depth. Accordingly, two sets of cylinders were cast of each of the two MMA based materials - one with and one without 3/8" pea gravel, thus augmenting the number of materials tested by two. The gravel containing mixes are denoted M1(G) and M2(G) to distinguish them from the non-gravel containing mixes of M1 and M2, respectively. The polyurethane binder is a low viscosity liquid which is poured over the preplaced aggregate (3/8" pea gravel).

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

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

7.3.3 Flexure Tests

Casting procedure for flexure specimens was similar to that of cylinders. Patches were cast in the cold room and stored there for seven days. Shallow patches of MMA materials contained only sand. Half and full depth patches also contained 3/8 in. pea gravel. Shallow, polyurethane patches contained no aggregate while half and full depth patches contained 3/8 in. pea gravel.

Static tests consisted of loading the specimen at a constant rate of deflection (stroke controlled) to failure. The full load-displacement curve and the failure mode were recorded (see Fig. 7.3 for the test set-up). Fatigue tests were carried out in the same test frame. Load was cycled between 250 lbs. and 1,750 lbs. (approximately 0.06 to 0.5 of the ultimate load) at 10 cycles/second. Ultrasonic pulse velocity readings were taken prior to testing and after 30,000

cycles to assess the extent of cracking (see Fig. 7.9). Cycling was then continued to failure or to 1 million cycles, whichever occurred first.

7.3.4 Durability Tests

Durability tests were carried out on prism specimens similar to those used in flexure. In order to initiate a corrosion cell, specimens were placed in a saturated salt solution for seven days prior to patching (Fig. 7.5). Half cell potential readings were taken prior to patching and confirmed the existence of potentially active corrosion cell. Patching operations followed the same procedure as for flexure specimens. After seven days of cold storage, specimens were put in the freeze-thaw chamber (Fig. 7.4) and subjected to 300 freeze-thaw cycles in accordance with ASTM Standard C666 Procedure A. Half cell potential, ultrasonic pulse velocity and weight measurements were taken prior to cycling and at intervals not exceeding 36 cycles of exposure to the freezing-and-thawing cycles.

7.3.5 Moist Surface Tests

Moisture is regarded as a qualitative factor in these experiments. Patched surfaces were moistened with a wet rag outside the cold chamber prior to patching in the cold chamber. This procedure has the effect of converting surface moisture to surface ice at the time of patching. However the moderate amount of moisture was insufficient to produce an ice film.

7.4 Test Results

7.4.1 Cylinder Tests

Table 7.1 presents results of compressive strengths and slant shear bond strengths for the seven patching materials in dry conditions. Failure modes of slant shear tests are also indicated. The three failure modes - bond failure, material failure (parent or patching) and the combined mode - are illustrated in

Table 71 Cylinder Test Results (Dry)

Material	Compressive			Slant Shear Strength (psi) and Failure Mode (F.M.)*			
	Patch Material 1 day	Parent 7 days	Parent 28 days ^{**}	1 day	F.M.	7 days	F.M.
M1	9788	7918	3541	4138	PC	3661	PC
	9828	8475	±261	4019	PC	3820	PC
	9828	8037		4536	PC	3700	PC
M1(G)	6605	7003	4806	4456	PC+B	5252	PC
	6486	8117	±981	6511	PC	5133	PC
		7878		4456	PC+B	5889	PC+B
M2	6923	6287	3385	4218	PC	3700	B
	7525	6326	±224	5650	B	3899	B
	7043	6366		3571	B	3661	B
M2(G)	4775	5610	4070	4297	PC	5133	PC
	4934	5531	±524	4536	PC+PM	5411	PC+PM
	4775	5570		4457	PC	5093	PC
P1	6923	7639	3578	2984	B	4934	B
	6724	7242	±250	2149	B	5262	B
	6366	7162				4257	PC
P2	4615	4775	3501	3820	PC+B	4576	PC
	4536	5769	±236	2467	PC+B	3979	PC+PM
	4775	5411		3342	PC+B	3479	PC+B
U	1671	2984	4505	2109	B	2546	PC+PM
	1870	2865	±648	2149	B	2905	B
	1751	2865		2069	B	2825	B

* PM = patch material, PC = parent concrete, B = bond.

** Mean + Standard Deviation of six sets of 3 cylinders taken from parent concrete batches used in slant shear tests

Fig. 7.8. The results are presented graphically in Fig. 7.9. The error bars shown in Fig. 7.9 are the standard deviation and indicate the variability of the results.

It can be observed that all materials possess adequate strength. Slant shear strengths are generally lower than compressive strengths, with gravel containing MMA based material having somewhat higher strength than the magnesium phosphates. The behavior of MMA based materials is noteworthy:

Mixes with gravel have higher slant shear strength but lower compressive strength than the plain mixes.

While generally there is an increase in strength with age, plain MMA mixes appear to shed strength with age.

There is considerable difference between the two MMA compounds with M1 being clearly superior to M2.

These aspects are further commented on in the discussion that follows.

Results for slant shear of moist patch cylinders are presented in Table 7.2 and Figure 7.9c.

7.4.2 Flexure Tests

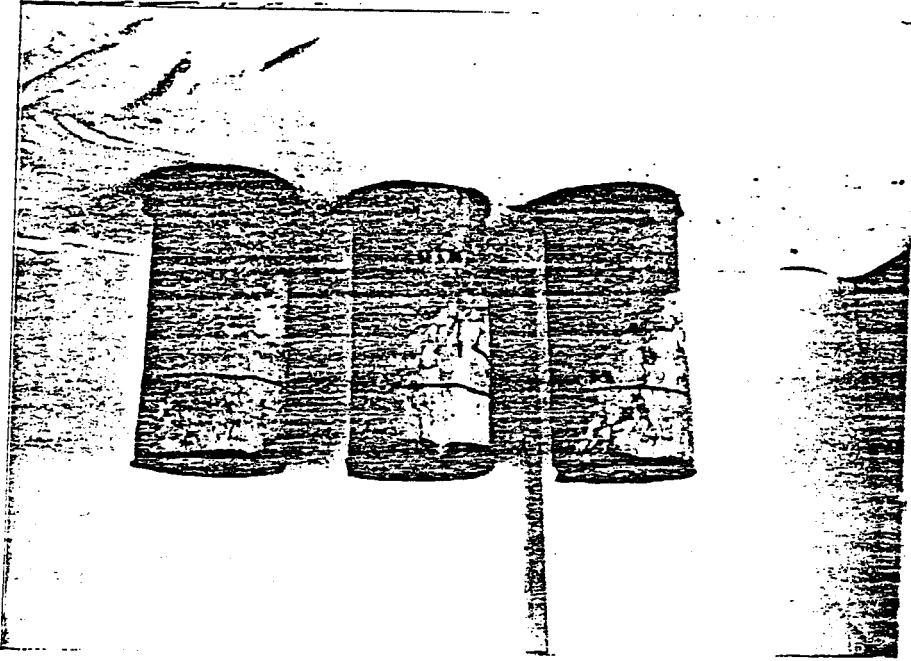
Figure 7.10 displays a typical load deflection curve of a statically loaded and of a cyclic loaded specimen. Additional curves are reproduced in Appendix A.

Figure 7.11 shows typical failure modes of the three patch geometries. Failure is often initiated by tensile bond failure at the patch-parent boundary, followed by a shear failure. No delamination of patches (particularly shallow patches) was observed for dry specimens. Some moist path specimens showed limited delamination under cyclic and static loads, particularly Percol (U).

Results of the two replicates of static tests are presented in Tables 7.3a and 7.3b and in Fig. 7.12. The cyclic tests are presented in Tables 7.4a and 7.4b

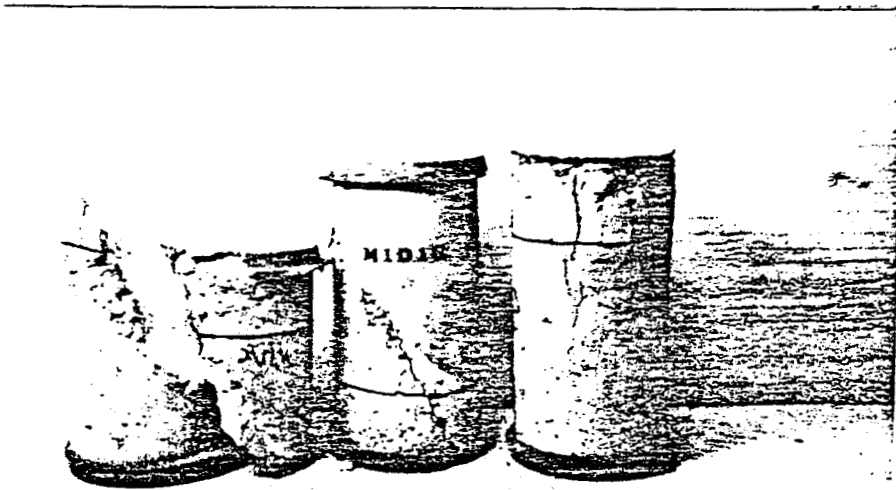
Fig. 7-8: Slant Shear Failure

(b) M1 - 7 days

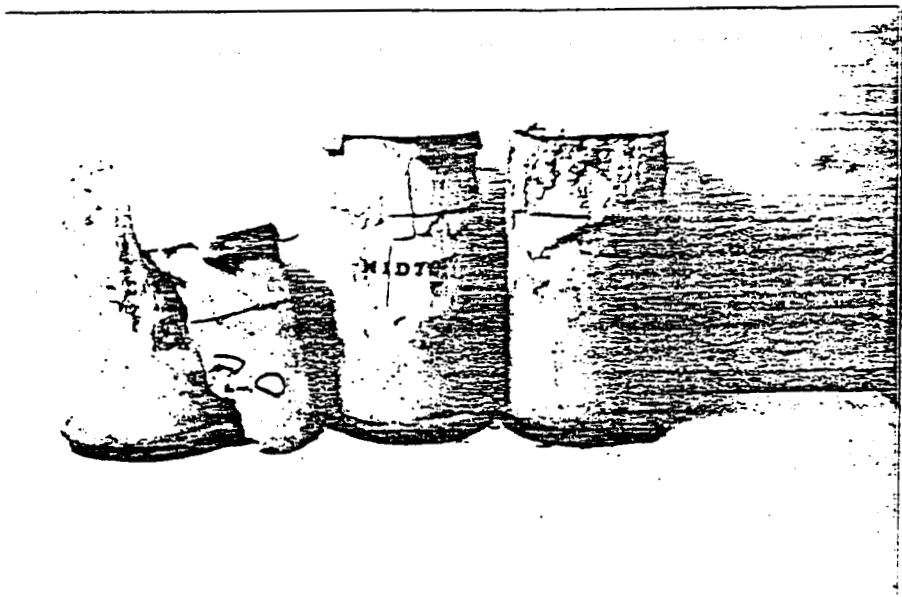


(a) M1 - 1 day



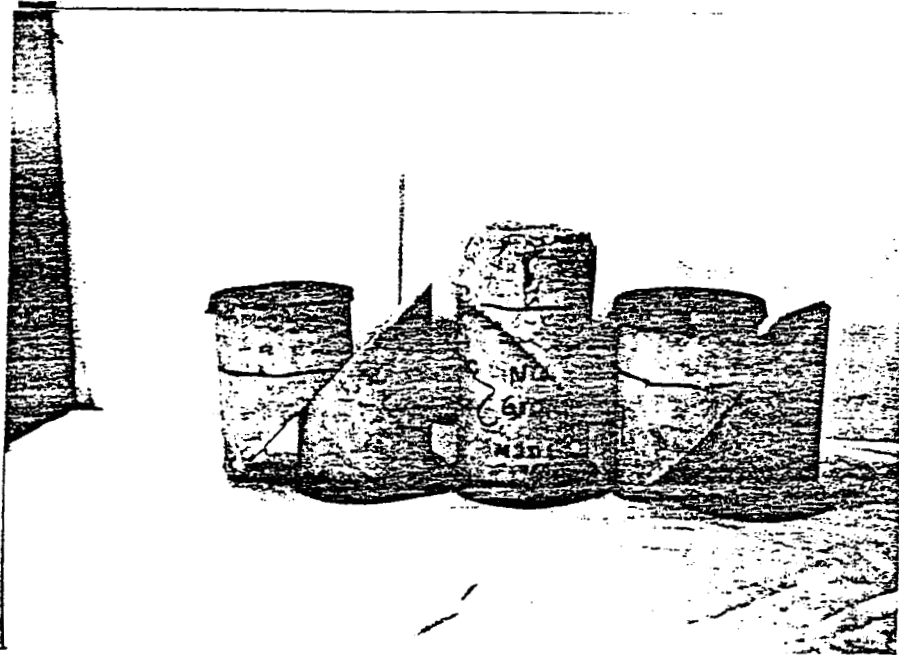


(c) M1(G) - 1 day

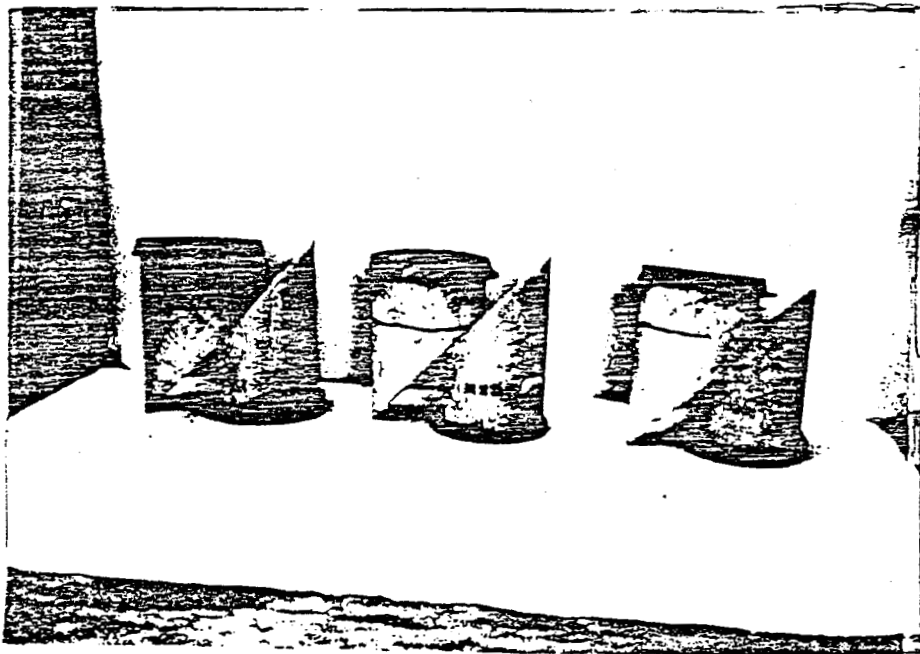


(d) M1(G) - 7 days

Fig. 7-8: Slant Shear Failure (continued)

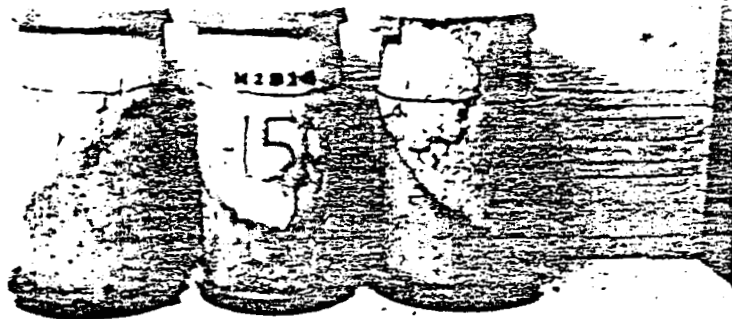


(e) M2 - 1 day

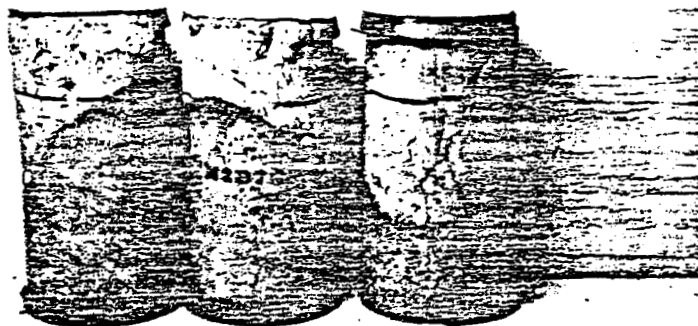


(f) M2 - 7 days

Fig. 7-8: Slant Shear Failure (continued)

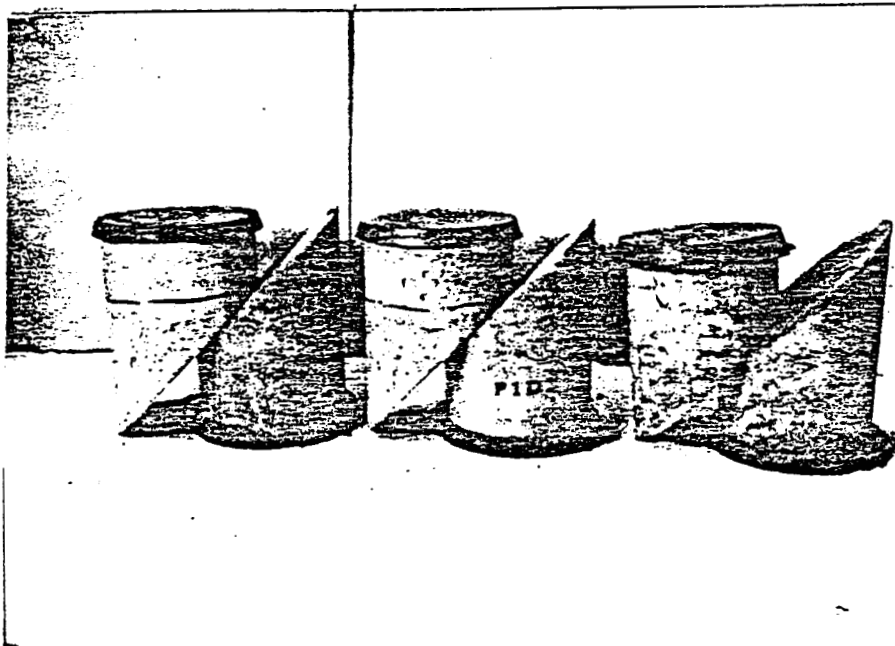


(g) M2(G) - 1 day

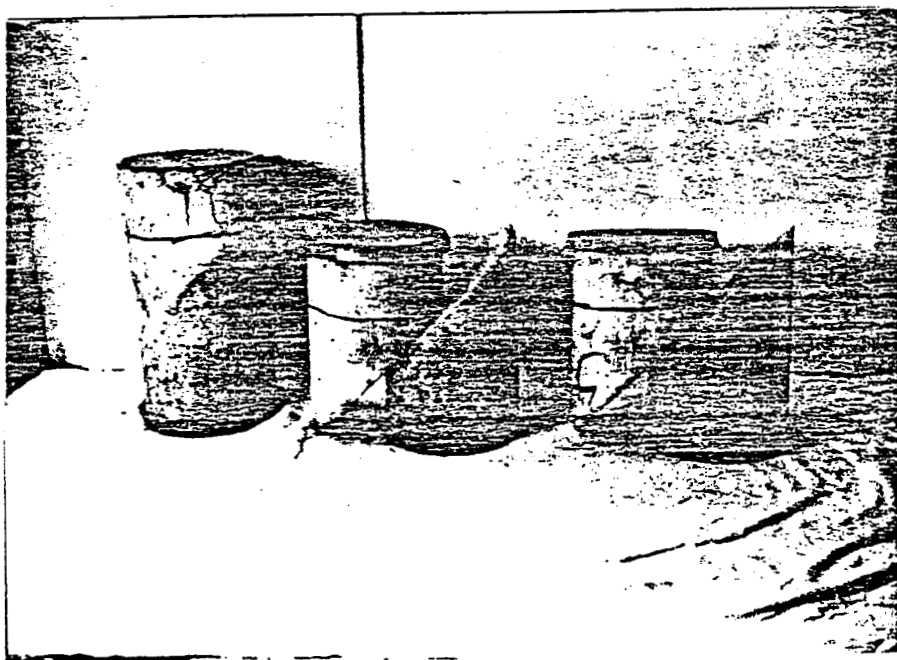


(h) M2(G) - 7 days

Fig. 7-8: Slant Shear Failure (continued)

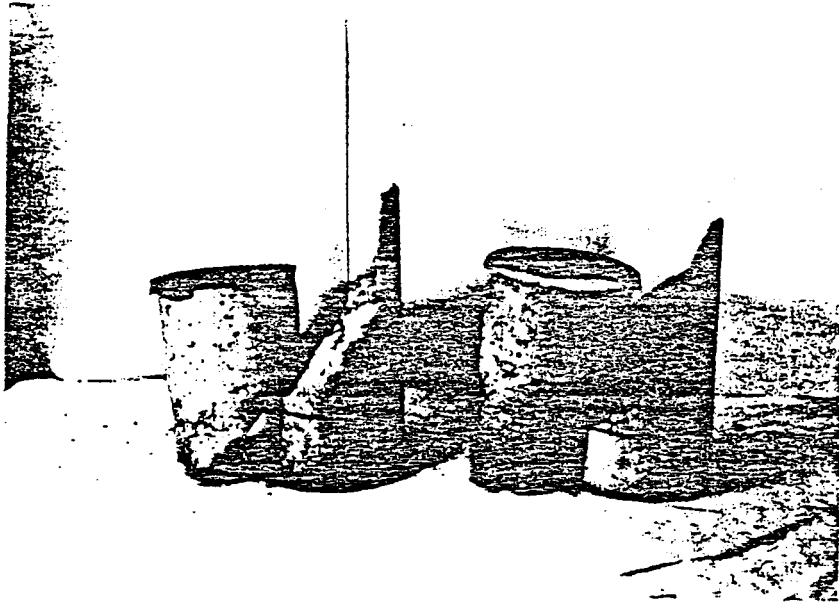


(i) P1 - 1 day



(j) P1 - 7 days

Fig. 7-8: Slant Shear Failure (continued)

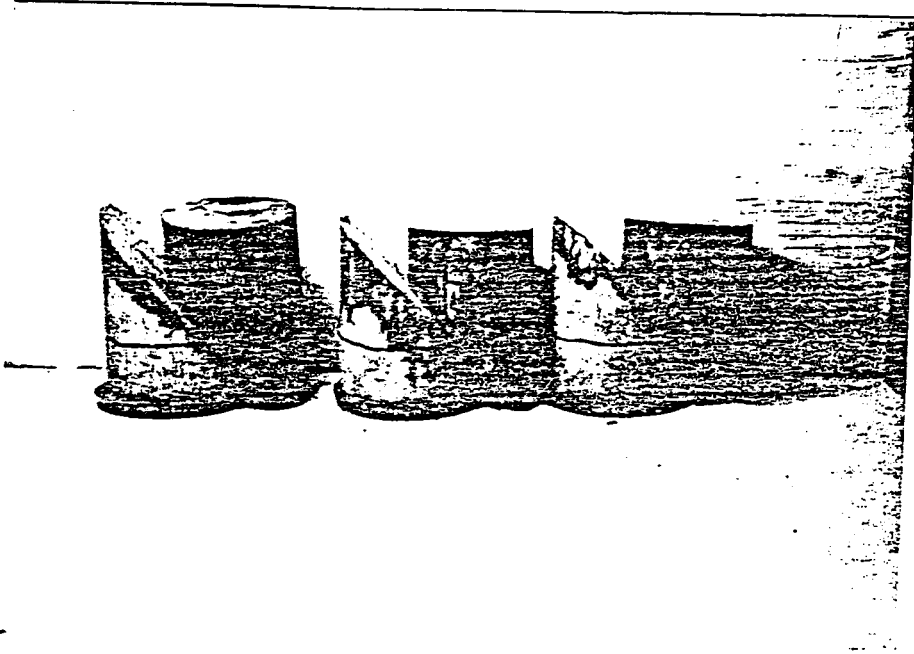


(k) F2 - 1 day

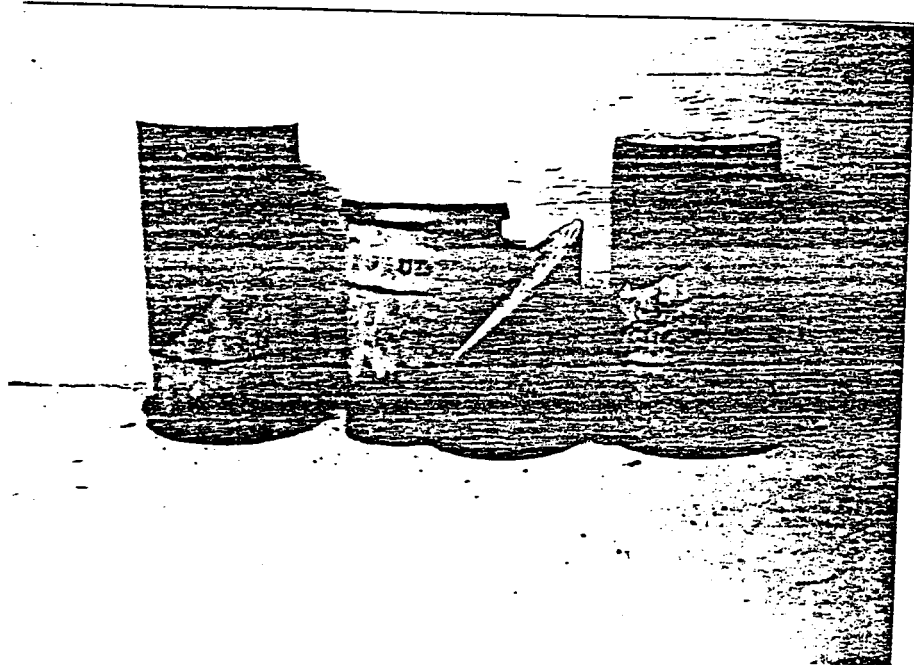


(l) F2 - 7 days

Fig. 7-8: Slant Shear Failure (continued)

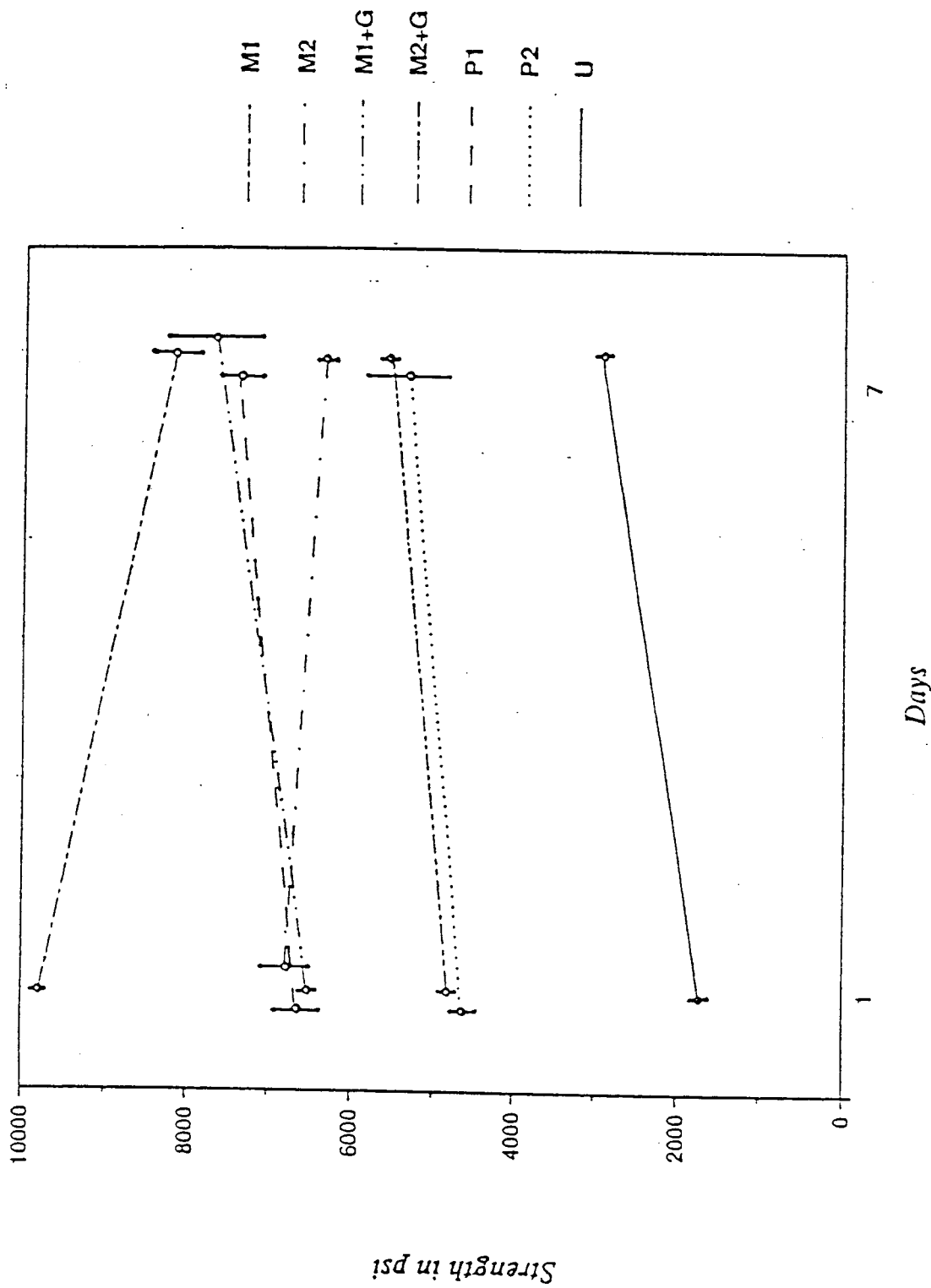


(m) \bar{U} - 1 day



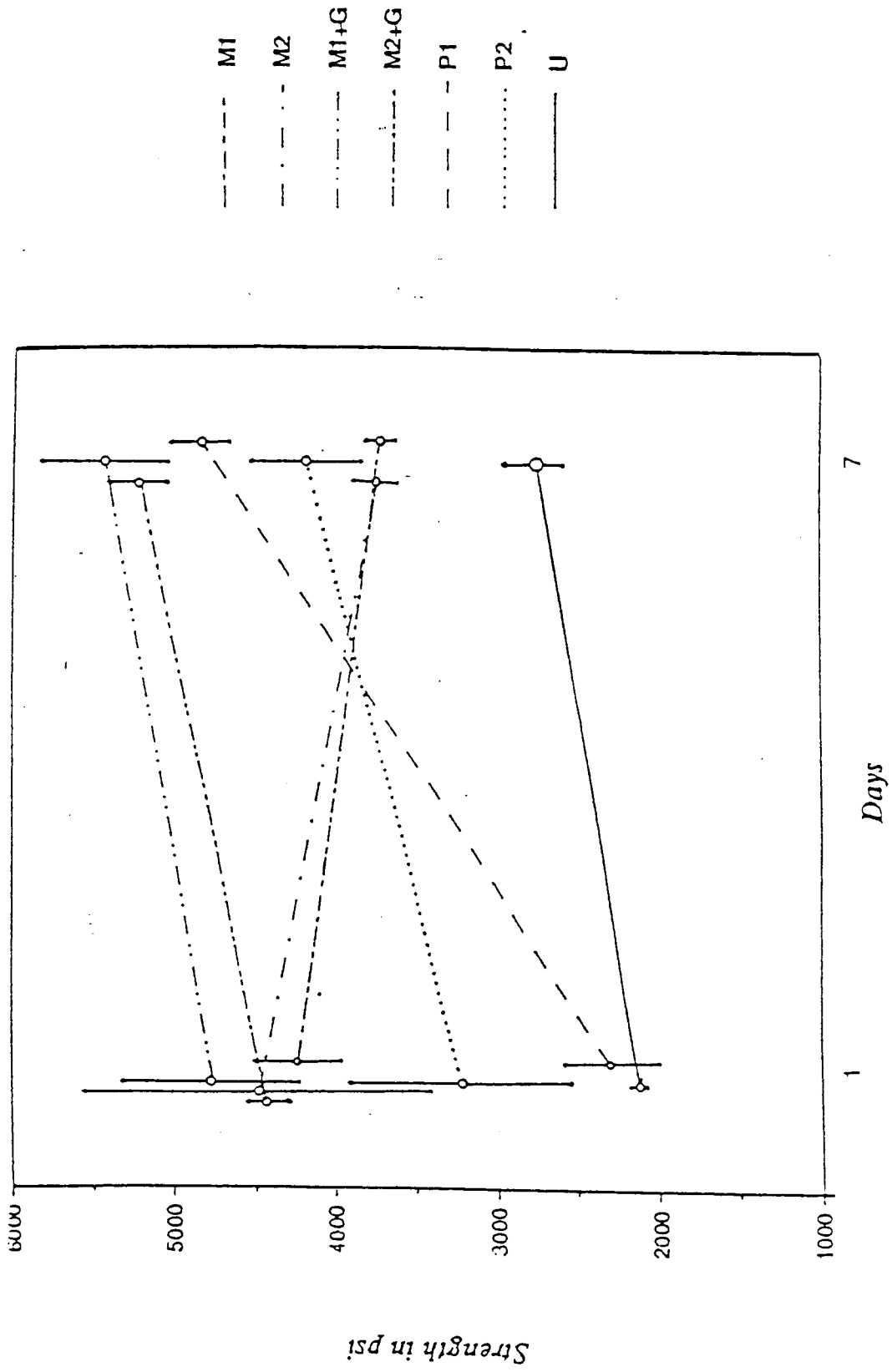
(n) \bar{U} - 7 days

Fig. 7-8: Slant Shear Failure (continued)



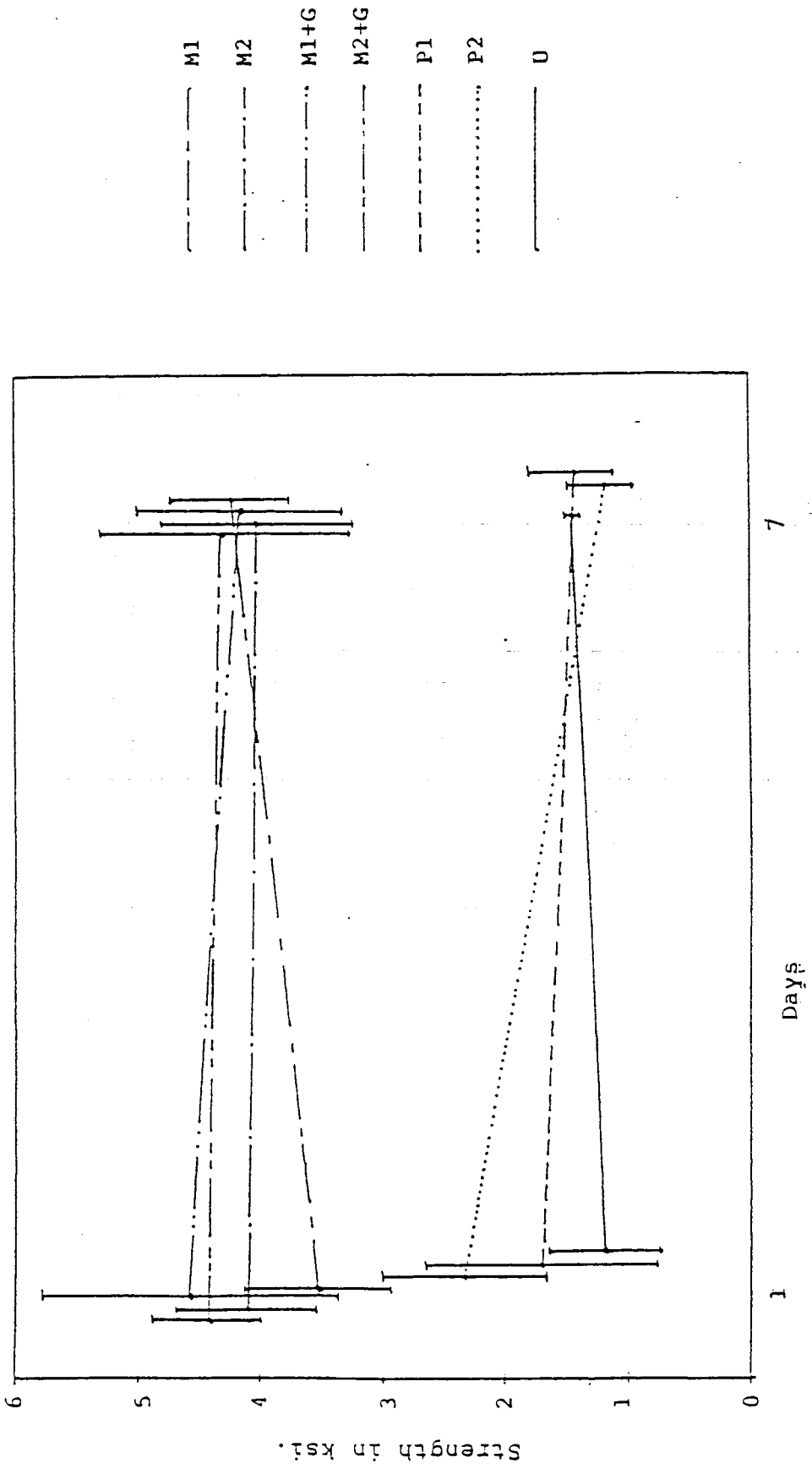
(a) Compressive Strength

Fig. 7-9: Cylinder Test Results



(b) Slant Shear - Dry Specimens

Fig. 7-9: Cylinder Test Results (continued)



(c) Slant Shear - Moist Specimens
Fig. 7-9: Cylinder Test Results (continued)

Table 72 Slant Shear Strength - Moist Specimens

Material	1 day	F.M.	7 days	F.M.
M1	4058	PC	3661	PC
	3661	PC+B	4337	PC
	2875	PC+B	4655	PC
M4(G)	4775	B	3104	PC
	3899	PC+B	4615	PC+B
	3661	B	4337	PC
M2	4775	B	3104	PC
	3899	PC+B	4615	PC+B
	3661	B	4337	PC
M2(G)	4058	PC	4058	PC+B
	4934	B	3342	PC
	4297	PC	5371	B
P1	2507	B	1035	B
	1552	B	1472	B
	2865	B	955	B
P2	1592	B	1790	B
	796	B	1074	B
	2706	B	1432	B
U	477	B	1472	B
	1472	B	1432	B
	1592	B	1432	B

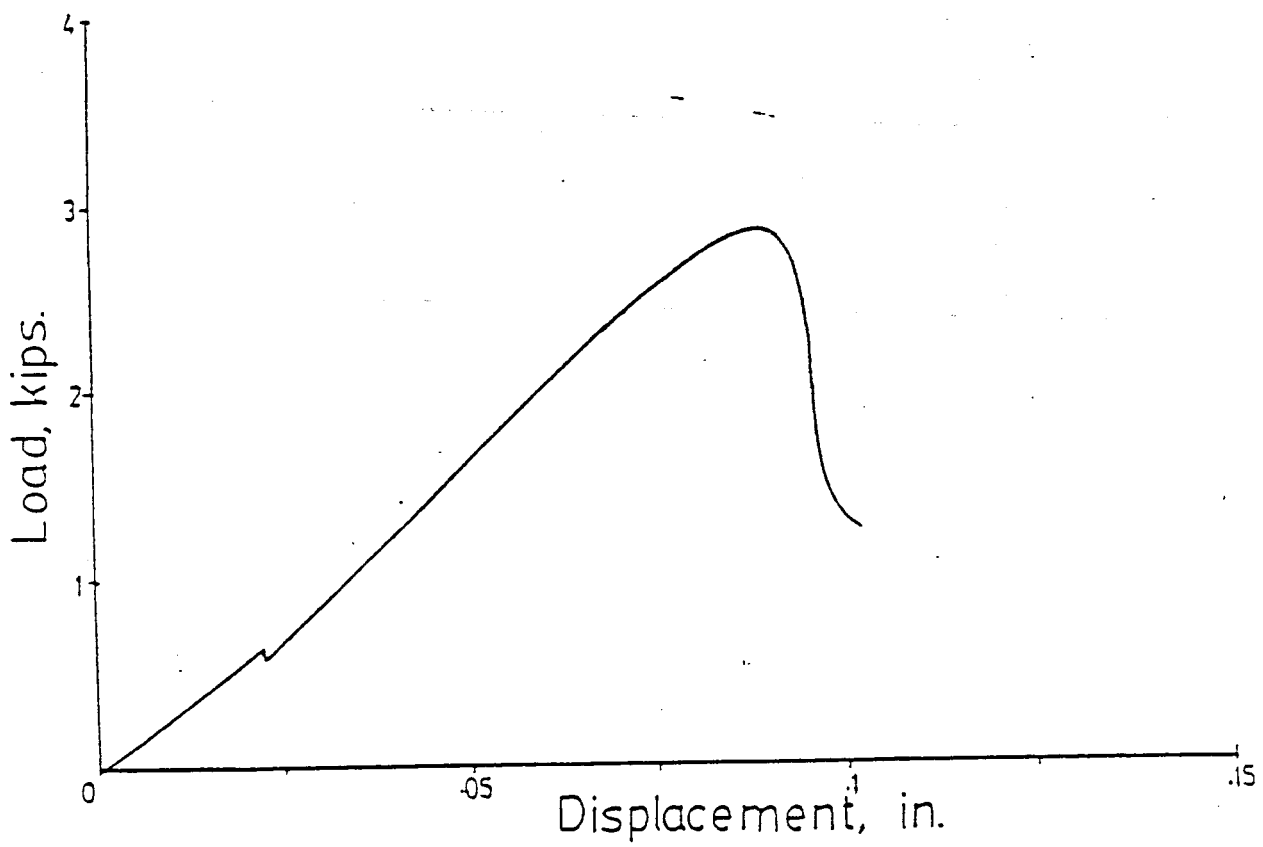
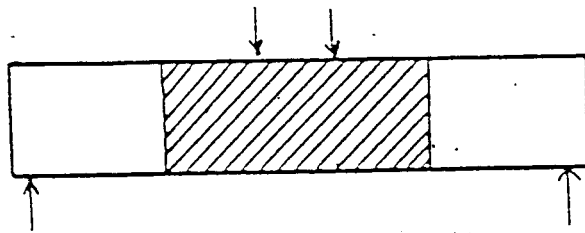
Flexure Test(Static)

Fig. 7-10: (a) Static Load
Typical Flexure Load-Displacement Curves

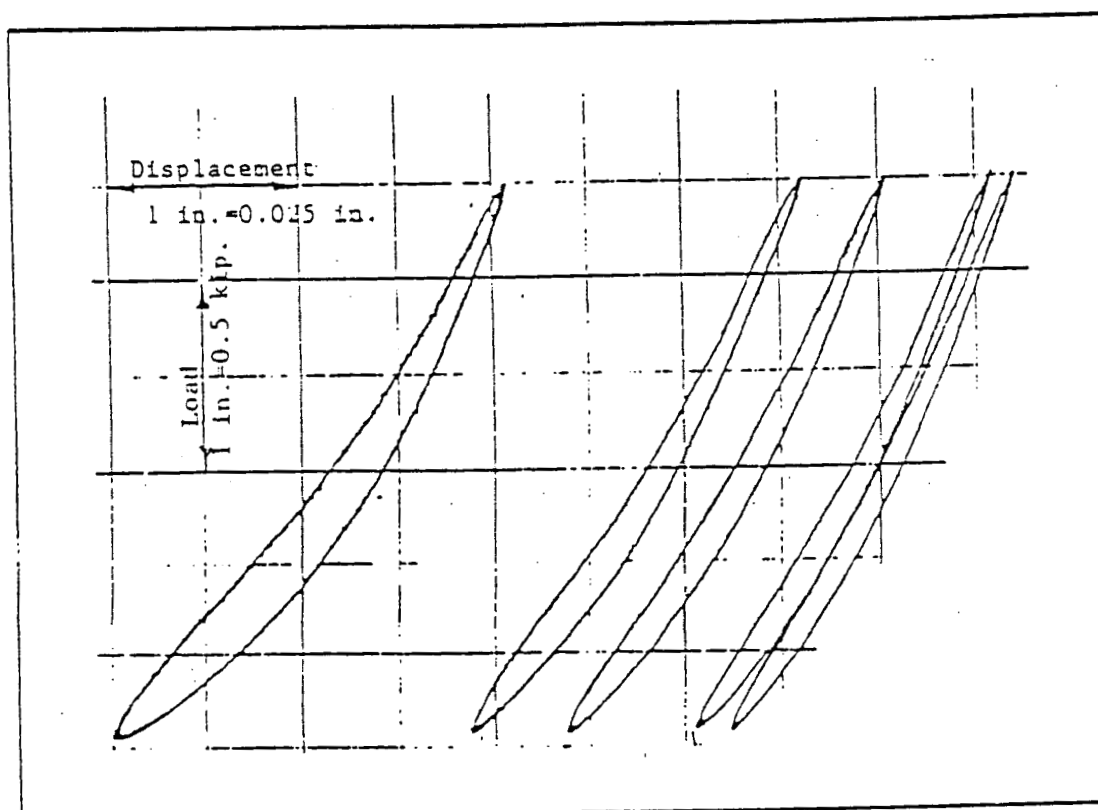
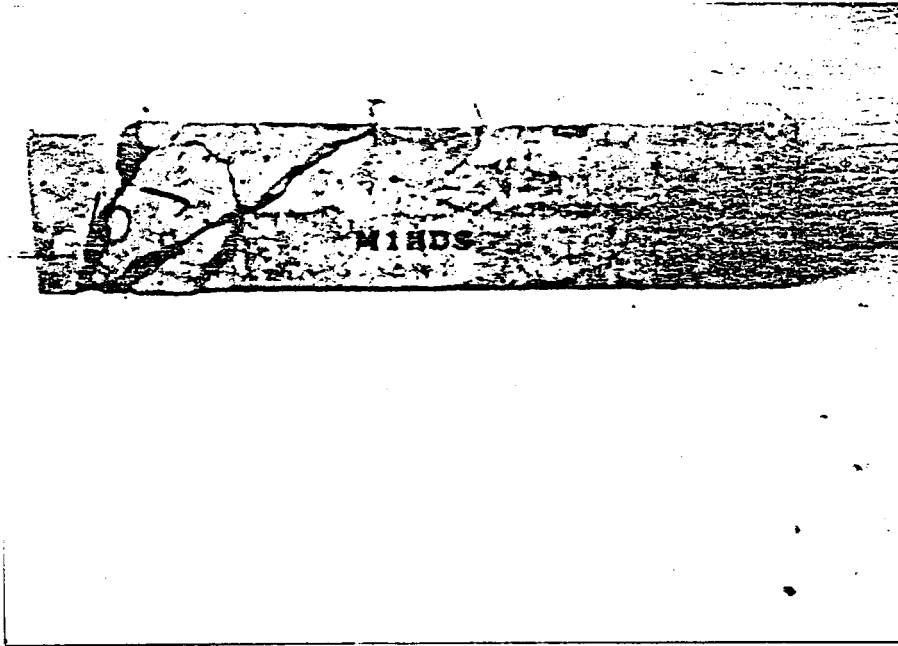


Fig. 7-10: (b) Cyclic Load
Typical Flexure Load-Displacement Curves (continued)

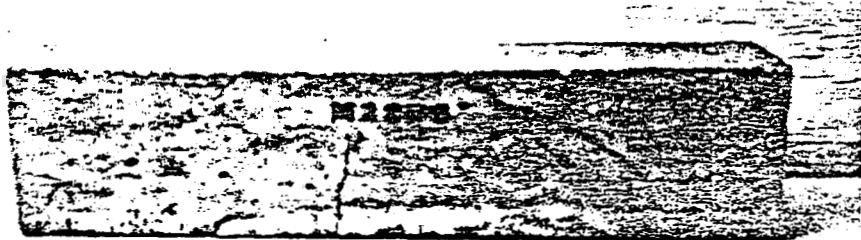


(a) Shear



(b) Bond and Shear

Fig.7-11: Typical Failure Modes of Flexure Specimens



(c) Flexural and Shear



(d) Bond

Fig. 7-11: Typical Failure Modes of Flexure Specimens (continued)

Table 73a Static Flexure Test Results - Dry Patch

Material	Depth*	Pu(K)	f_c' (psi)**	Failure Mode***
M1	S	2.6, 2.5	6700, 6050	B+S, B+S
	H	4.4, 3.9	5900, 6400	B+S, B+S
	F	4.2, 3.5	6450(+), 6300	B, B
M2	S	3.3, 3.25	5700, 6300	F+S, B+S
	H	3.1, 3.8	5700, 6300	B+S, B+S
	F	3.9, 3.75	6800, 6400	B+S, B+S
P1	S	3.6, 3.7	5500, 6300	S, +
	H	4.1, 4.0	5900, 6300	F+S, S
	F	3.9, 3.4	6960, 6600	B+S, B+S
P2	S	3.45, 4.0	5900, 5600	F+S, F
	H	2.7, 4.0	5500, 6400	B+S, F+B+S
	F	2.7, 3.0	6300, 6400	B, F+B+S
U	S	3.4, 4.1	4650, 6300	B+S, B+S
	H	3.5, 3.7	5700, 6300	B+F, B+S
	F	2.7, 3.2	5050, 6400	B, B
Control		4.0	5100(+)	F+S
		4.3	6100	F+S
		3.9	7200(+)	F+S

* Patch depth: S = Shallow, H = half depth, F = full depth

** Cylinder strength of parent concrete cured with specimen

*** B = tensile bond, D = delamination (shear bond),
F = flexure, S = diagonal shear. The letters in combined
modes appear in sequence of occurrence.

(+) = 28 days moist cured cylinder

Table 73b Static Flexure Test Results - Moist Patch

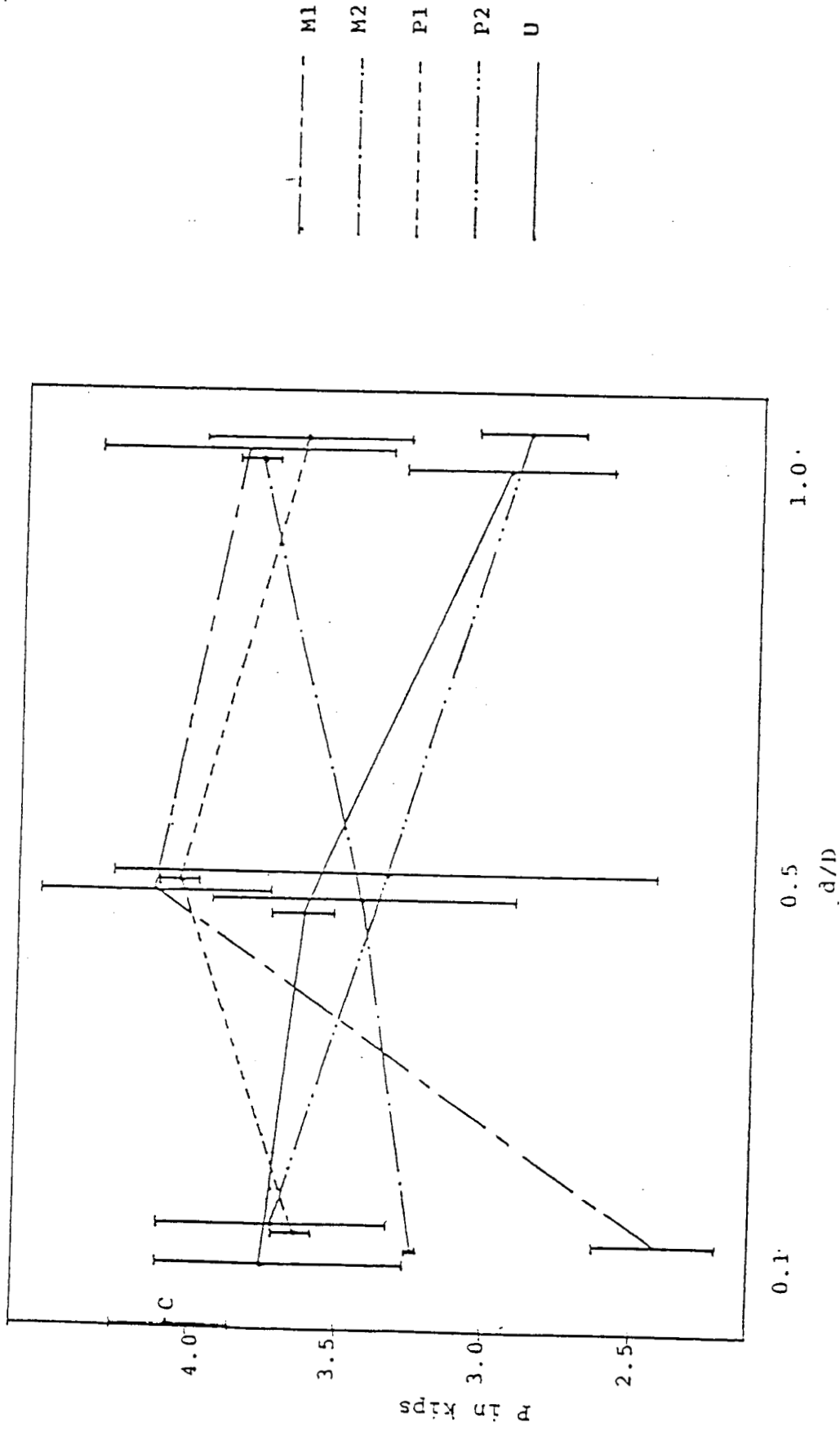
Material	Depth*	Pu(k)	f_c' (psi)**	Failure Mode***
M1	S	2.8, 3.15	6400, 6300	B+S, B+S
	H	3.9, 3.35	6050, 6400	B+S, B+D+S
	F	2.6, 2.9	6500, 5600	B, B
M2	S	6.2, 3.6	6500, 6400	B+D+S, B+D+S
	H	2.9, 3.1	5600, 5500	B+S, B+D+S
	F	3.2, 3.5	5500, 6000	B, B
P1	S	3.8, 3.8	6000, 5600	F+B+D, F
	H	3.5, 3.75	5700, 6400	B+S, B+D+S
	F	2.3, 3.0	6200, 5600	B, B+S
P2	S	2.85, 4.0	5700, 5600	B+S, F+S
	H	3.15, 3.3	6200, 5600	B+S, B+S
	F	3.0, 2.5	5700, 5600	B+S, B+S
U	S	3.1, 3.7	5500, 7050	B+D+S, B+D+S
	H	3.1, 3.1	5500, 3600(+)	B+D+S, B+D+S
	F	2.5, 3.3	- , 7100(+)	B , B

* Patch depth: S = Shallow, H = half depth, F = full depth

** Cylinder strength of parent concrete cured with specimen

*** B = tensile bond, D = delamination (shear bond),
F = flexure, S = diagonal shear. The letters in combined
modes appear in sequence of occurrence.

(+) = 28 days moist cured cylinder



(a) Dry Patch Static Flexure Test Results

Fig. 7-12:

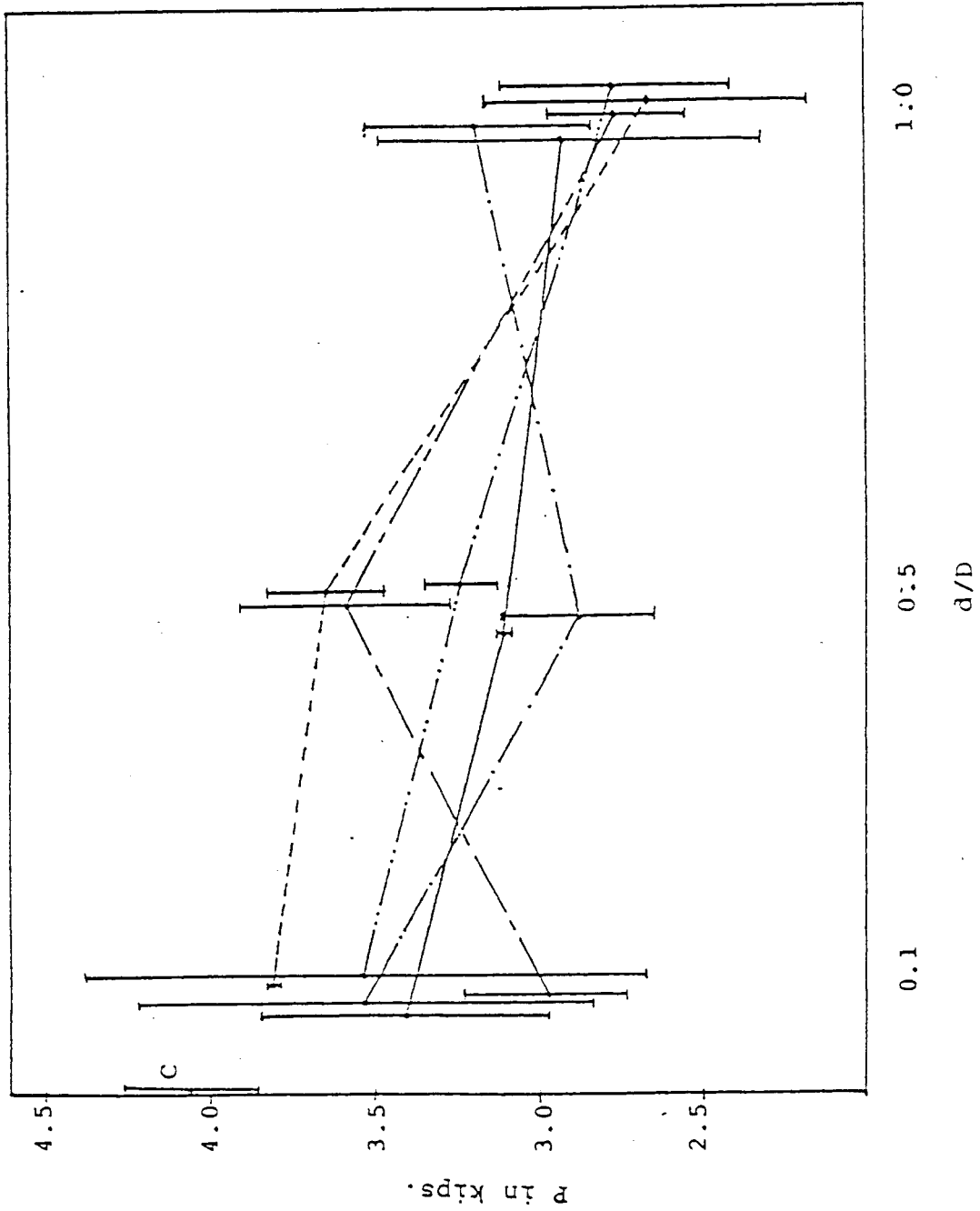


Fig. 7-12: (b) Moist Patch Static Flexure Test Results (continued)

Table 7.4a Cyclic Flexure Test Results - Dry Specimens

Material	Depth *	$(\Delta E_d/E_d)_{\max} \%$	Maximum No. of Cycles	Comments
		30,000 cycles ***		
M1	S	15	10^6	Bond, flexure cracks
	H	9	10^6	No cracks
	F	28	10^6	No cracks
M2	S	100	11.4×10^3	Bond-shear failure Bond failure
	H	100	20.5×10^3	
	F	81.5	108.5×10^3	
P1	S	37	330×10^3	Bond-shear failure
	H	18.5	10^6	No cracks
	F	24	10^6	No cracks
P2	S	10	10^6	Bond, flexure cracks
	H	45	10^6	No cracks
	F	24	42.8×10^3	Bond failure
U	S	52	10^6	Flexure cracks
	H	33.2	10^6	No cracks
	F	13.8	204.6×10^3	Bond failure
Control		17.5	10^6	Flexure cracks
		13.9	10^6	Flexure cracks
		23.9	10^6	Flexure cracks

* S = shallow, H = half depth, F = full length

*** Maximum change in dynamic modulus:

$$(\Delta E_d/E_d)_{\max} = \max\{[(upv)_{\text{initial}}]^2 - (upv)_{\text{final}}^2\} / (upv)_{\text{initial}}^2$$

upv = ultrasonic pulse velocity

Table 7.4b Cyclic Flexure Test Results - Moist Patch Specimens

Material	Depth*	$(\Delta E_d/E_d)_{\max}$		Comments
		30,000 cycles		
M1	S	52		Flexure cracks
	H	6		No cracks
	F	14		No cracks
M2	S	38		Flexure cracks
	H	17		No cracks
	F	42.5		Bond cracks
P1	S	12		Bond, shear, flexible cracks
	H	24		No cracks
	F	Readings not taken		No cracks
P2	S	46		Bond, shear crack
	H	18		No cracks
	F	10		No cracks
U	S			Delaminated
	H			Debonded
	F			Debonded

Note all species tested to 1 million cycles

*S = shallow, H = half depth, F = full length

**Maximum change in dynamic modulus:

$$(\Delta E_d/E_d)_{\max} = \max\left[\frac{(upv)_{\text{initial}}^2 - (upv)_{\text{final}}^2}{(upv)_{\text{initial}}^2}\right]$$

upv = ultrasonic pulse velocity

and in Figures 7.13 and 7.14. Figure 7.13 presents the results in terms of number of cycles to failure. Figure 7.14 presents the results in terms of the change in dynamic modulus, as measured by ultrasonic pulse velocity after 30,000 cycles as compared to the value prior to testing. Figure 7.15 shows the positions of the electrodes for measuring pulse velocity. The maximum change in dynamic modulus which is proportional to the square of the pulse velocity, is given in Tables 7.4a and 7.4b and in Fig. 7.14. The maximum change in velocity is the best indicator of a major crack, but it should be noted that the presence of reinforcing bars makes the detection of cracks difficult. In Fig. 7.14, results for the three patch geometries of each material were combined, since patch geometry would not affect patch-parent cracking significantly and no such effect was observed in the results. This allows for error estimate as shown by the error bars in Fig. 7.14. All moist patched specimens sustained 1 million cycles without failure.

7.4.3 Durability Tests

Results of the various measurements of freeze-thaw durability and of change in half cell corrosion potential across patch boundary, are presented in Table 7.5 together with visual observations on the conditions of specimens after 300 cycles of freeze-thaw. Photographs of the specimens are presented in Fig. 7.16 and 7.17.

All materials, with the exception of the water-based magnesium phosphate (P1), exhibited good durability and had better durability than the parent concrete. Weight loss results are not very meaningful and are given for the sake of completeness only. The results do not discriminate between weight loss of patch and of parent material. In addition, since specimens were not saturated initially, initial weight increased due to adsorption of water. The

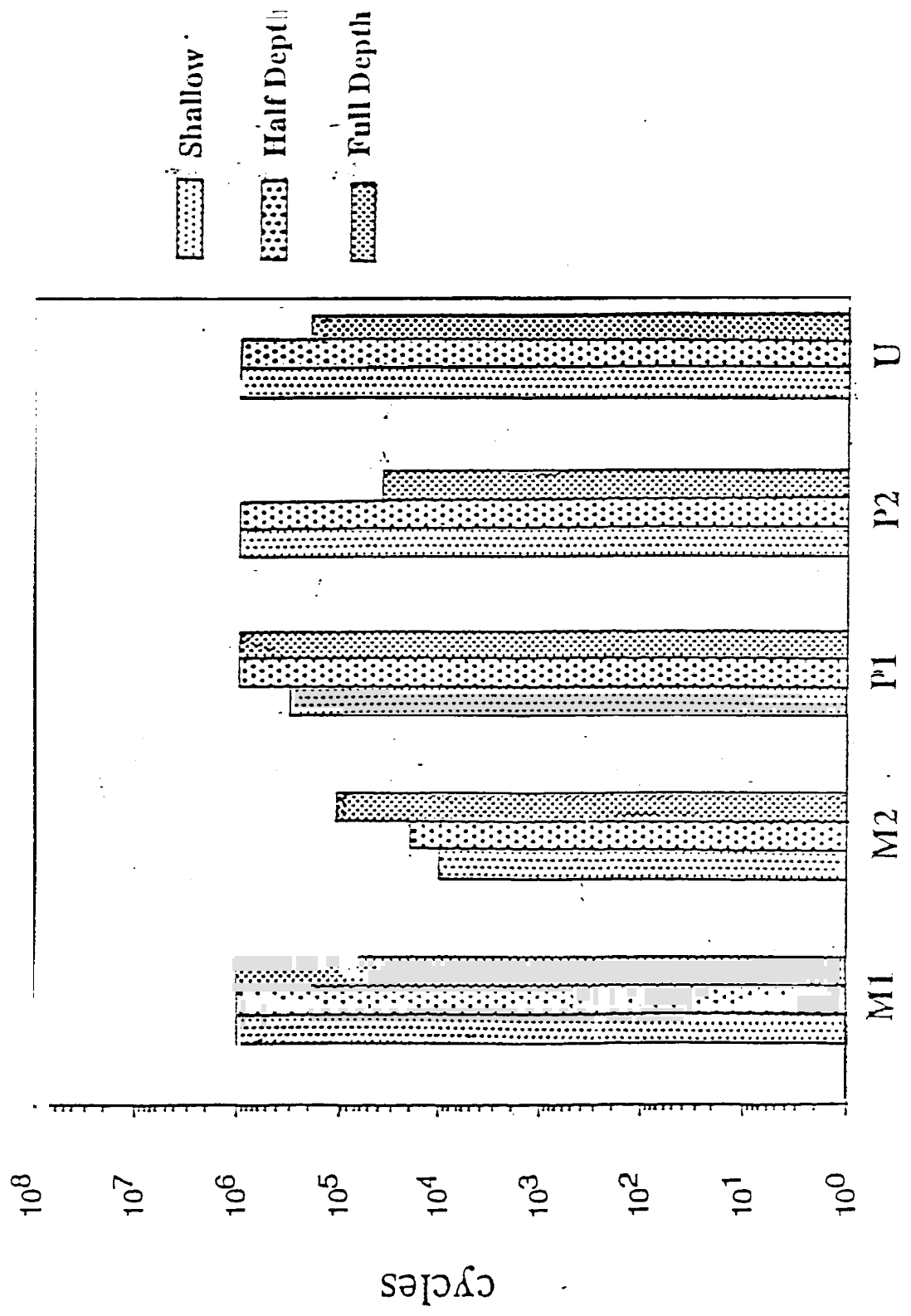


Fig. 7-13: Fatigue Test Results

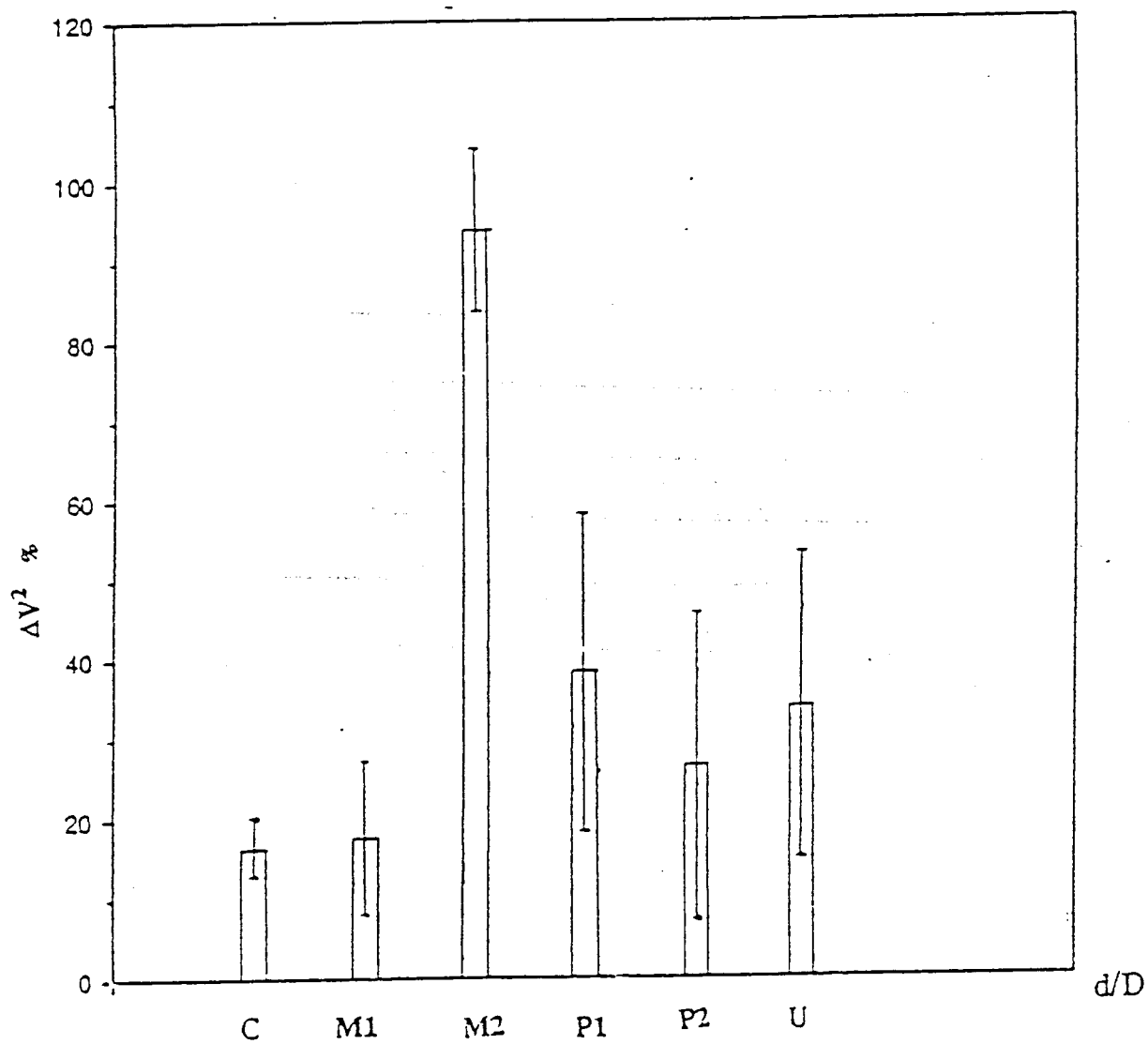


Fig. 7-14: Drop in Dynamic Modulus of Cyclic Flexure Specimens (Dry Patch)

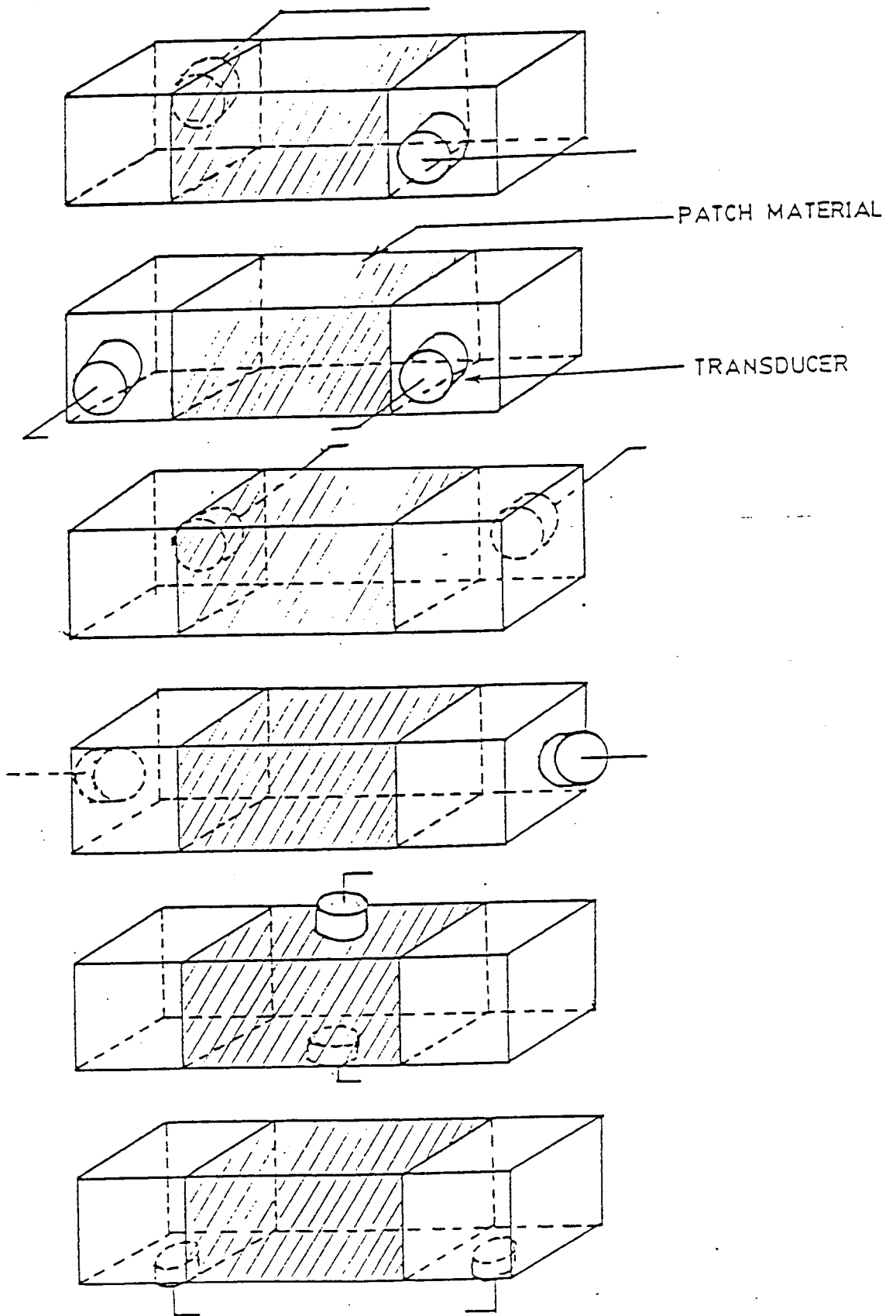
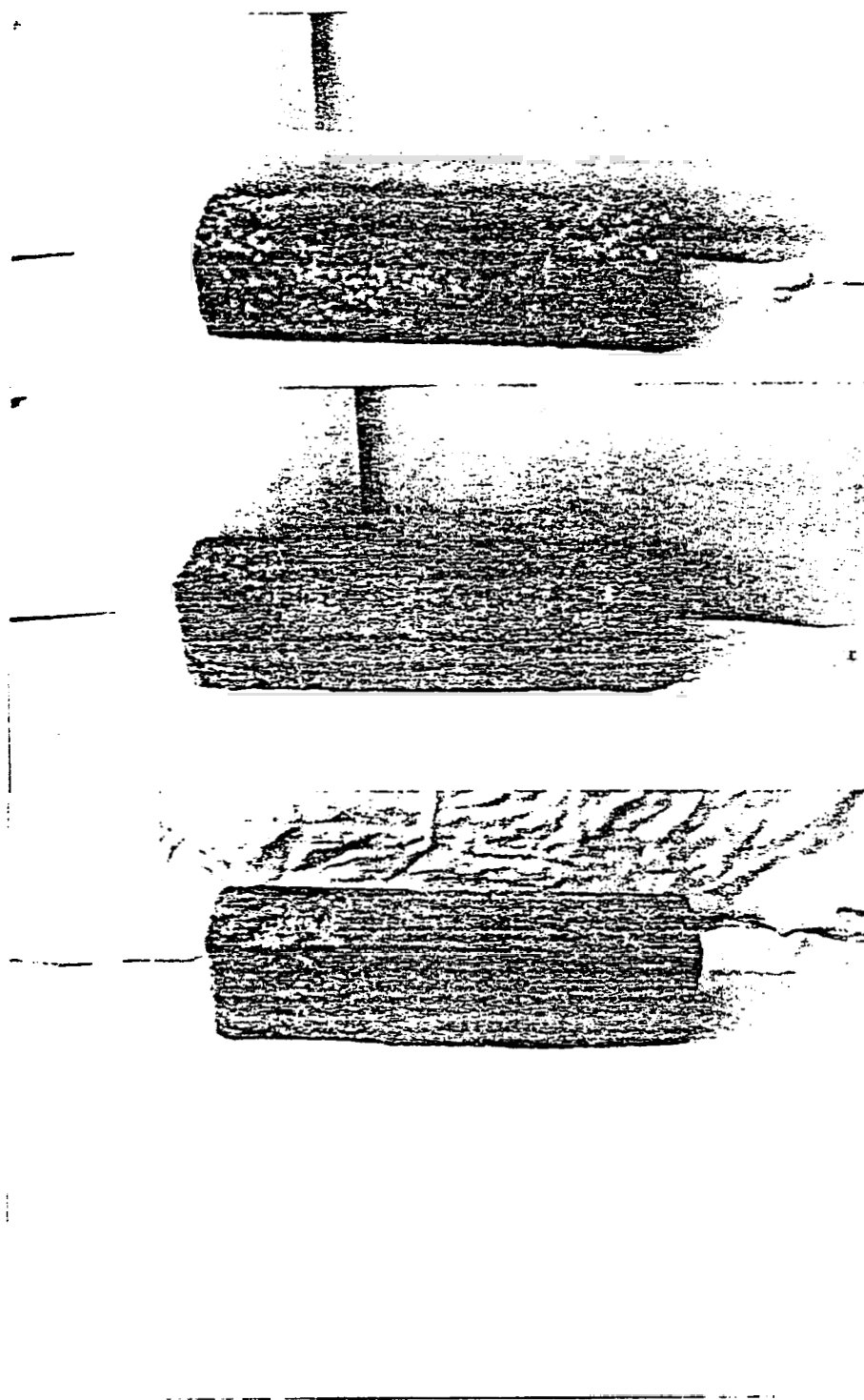


Fig. 7-15: Ultrasonic Pulse Velocity Measurement Positions

Table 7.5 Durability Test Results

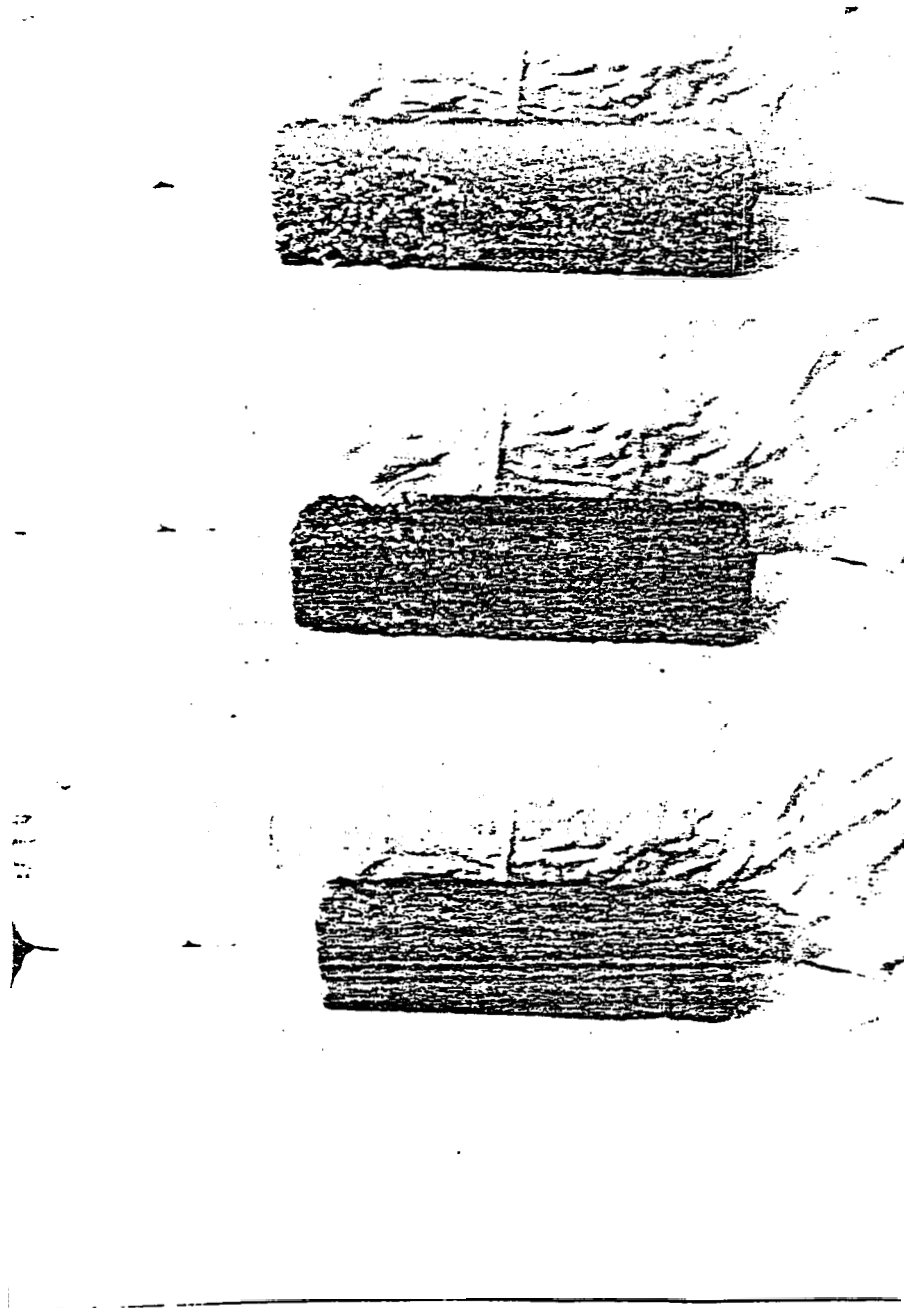
Material	Weight Loss (%)	Dynamic Modulus Drop (%)*	1/2 Cell Potential Change	Visual Observations
a) <u>Dry Patch Specimens</u>				
M1	1	33±17	Equalized in 90 cycles	Some scaling of concrete
M2	6	22±12	Equalized in 200 cycles	Extensive scaling of parent concrete
P1	2	29±13	No change	Considerable scaling of patch material
P2	2	22±20	No change	Slight scaling of patch but less than parent concrete
U	5	35±25	Equalized in 250 cycles	Extensive scaling of parent concrete
Controls	3.5	33±25	-	Extensive scaling
b) <u>Moist Patch Specimens</u>				
M1	1.5	-	Equalized in 30 cycles	Shallow patch delaminated
M2	1.8	-	Equalized in 30 cycles	
P1	12.6	-	-	Extensive deterioration of patch material. Reinforcement exposed in full depth specimens, see figure.
P2	1.1	-	-	
U	8.7	-	Equalized in 230 cycles	Total delamination of shallow patch, debonding of other patches

*Mean ± Standard Deviation.



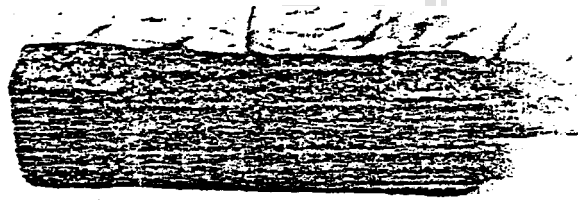
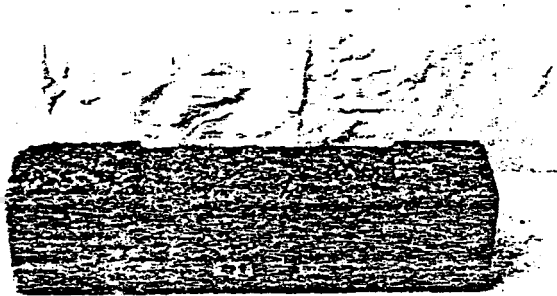
(a) M1

Fig. 7-16: Freeze-Thaw Specimens after 300 Cycles (Dry Patches)



(b) M2

Fig. 7-16: Freeze-Thaw Specimens after 300 Cycles (continued)



(c) P1

Fig. 7-16: Freeze-Thaw Specimens after 300 Cycles (continued)

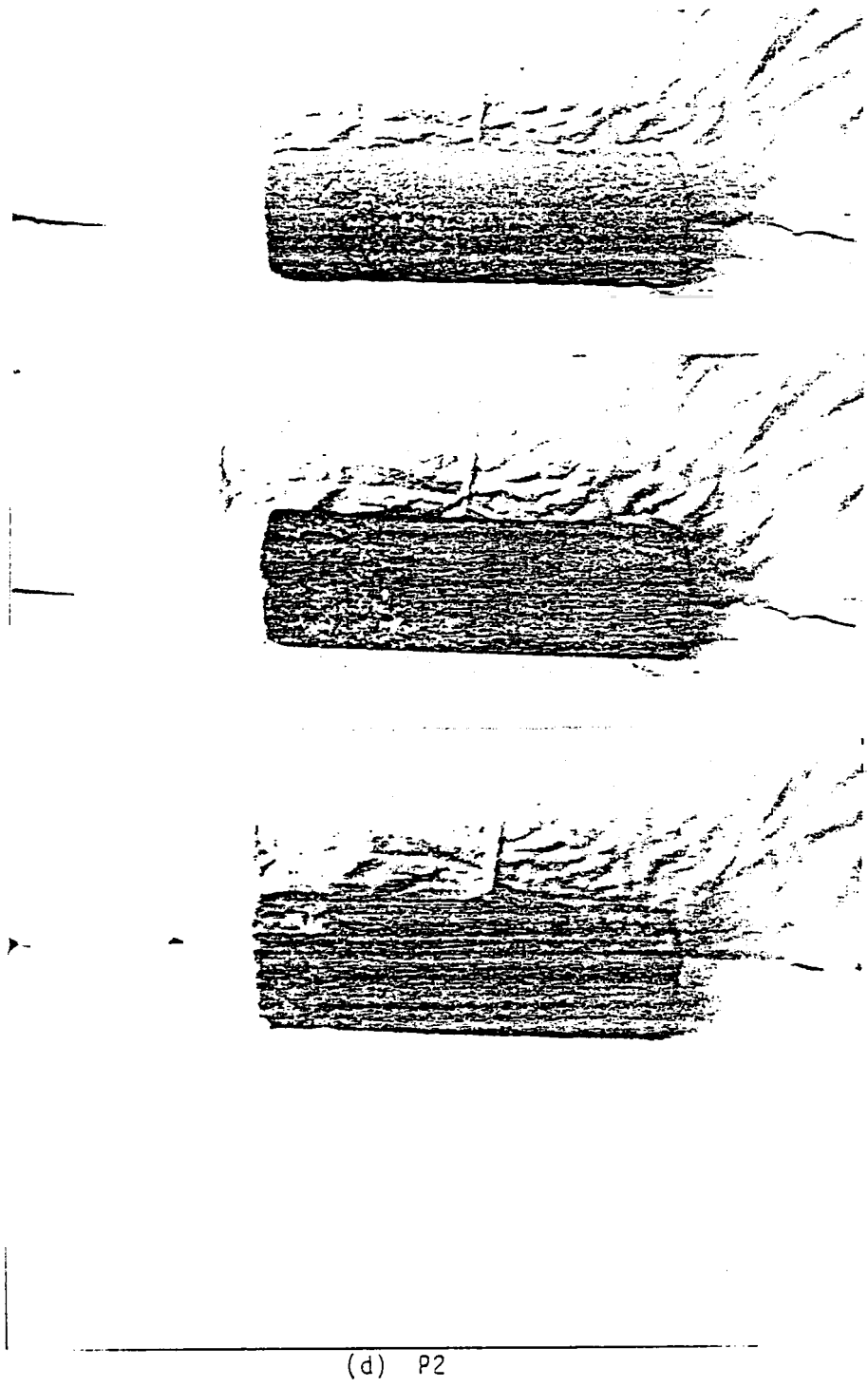
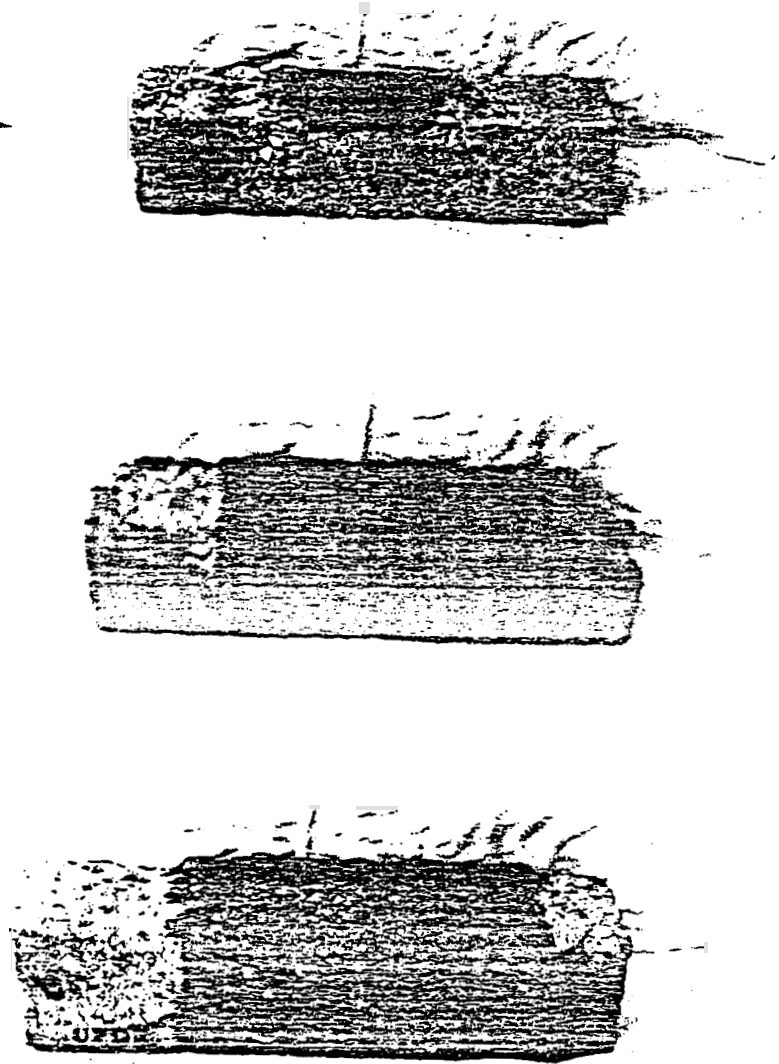


Fig. 7-16: Freeze-Thaw Specimens after 300 Cycles (continued)



(e) U

Fig. 7-16: Freeze-Thaw Specimens after 300 Cycles (continued)

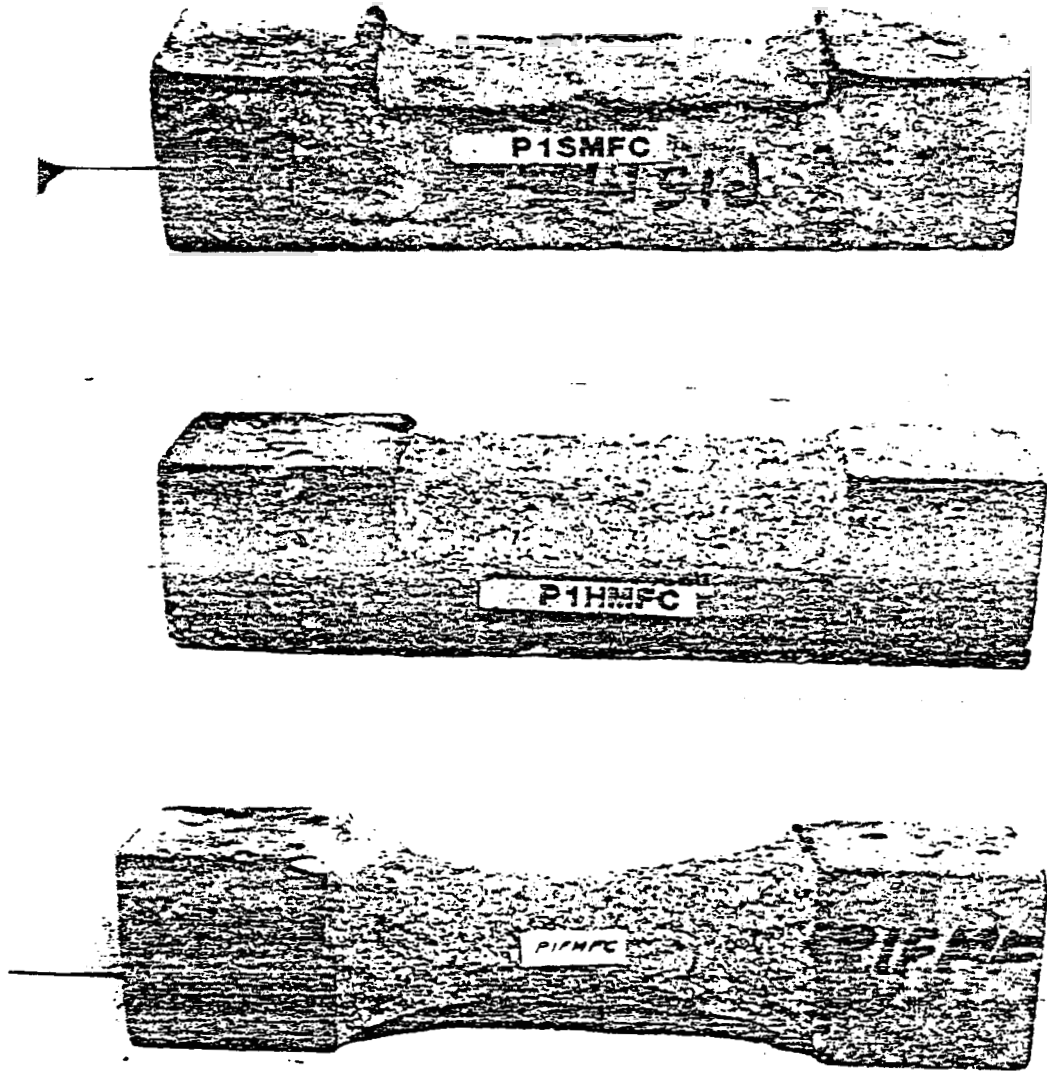


Fig. 7-17: Moist Patch Specimens P1 after 300 Freeze-Thaw Cycles

figures give the weight loss (in percent) from the condition of maximum weight measured.

The values of dynamic modulus reduction suggest substantial internal cracking. The results for dynamic modulus drop are presented graphically in Fig. 7.18. The values are changes in the square of the ultrasonic pulse velocity measured, which is proportional to the dynamic modulus. The actual values of the pulse velocity and the dynamic modulus are of no interest since they are affected by the reinforcing bars. Readings of pulse velocity fluctuated a lot during the cycling, possibly due to the presence of ice in the specimen. The values given are averaged over all reading positions and all patch depths and are indicative only. Patch depth is not expected to have significant effects on any of the parameters measured, and no trend was observed in the results.

Half cell potential results give the number of cycles after which potential readings in the patch equalized those in the parent material, indicating ion movement across the patch. Magnesium phosphate specimens gave approximately equal readings from the start, probably due to the presence of phosphate ions.

Specimens subjected to freeze-thaw cycling were subsequently subjected to cyclic flexural load to assess the effect of freeze-thaw cycles on fatigue strength. Results are presented in Table 7.6a and 7.6b and in Fig. 7.19. Finally, freeze-thaw specimens were broken up to expose the reinforcement in order to observe any corrosion, particularly at patch boundary (half depth and full depth specimens). Results of this visual inspection are presented in Table 7.7. The observations are combined for dry and moist patches. Corrosion categories are ranked mild, moderate, substantial and intense. The top surface is the surface initially immersed in salt solution. Observations on half depth patches relate to the top reinforcement bar which passes through the patch, observations on full

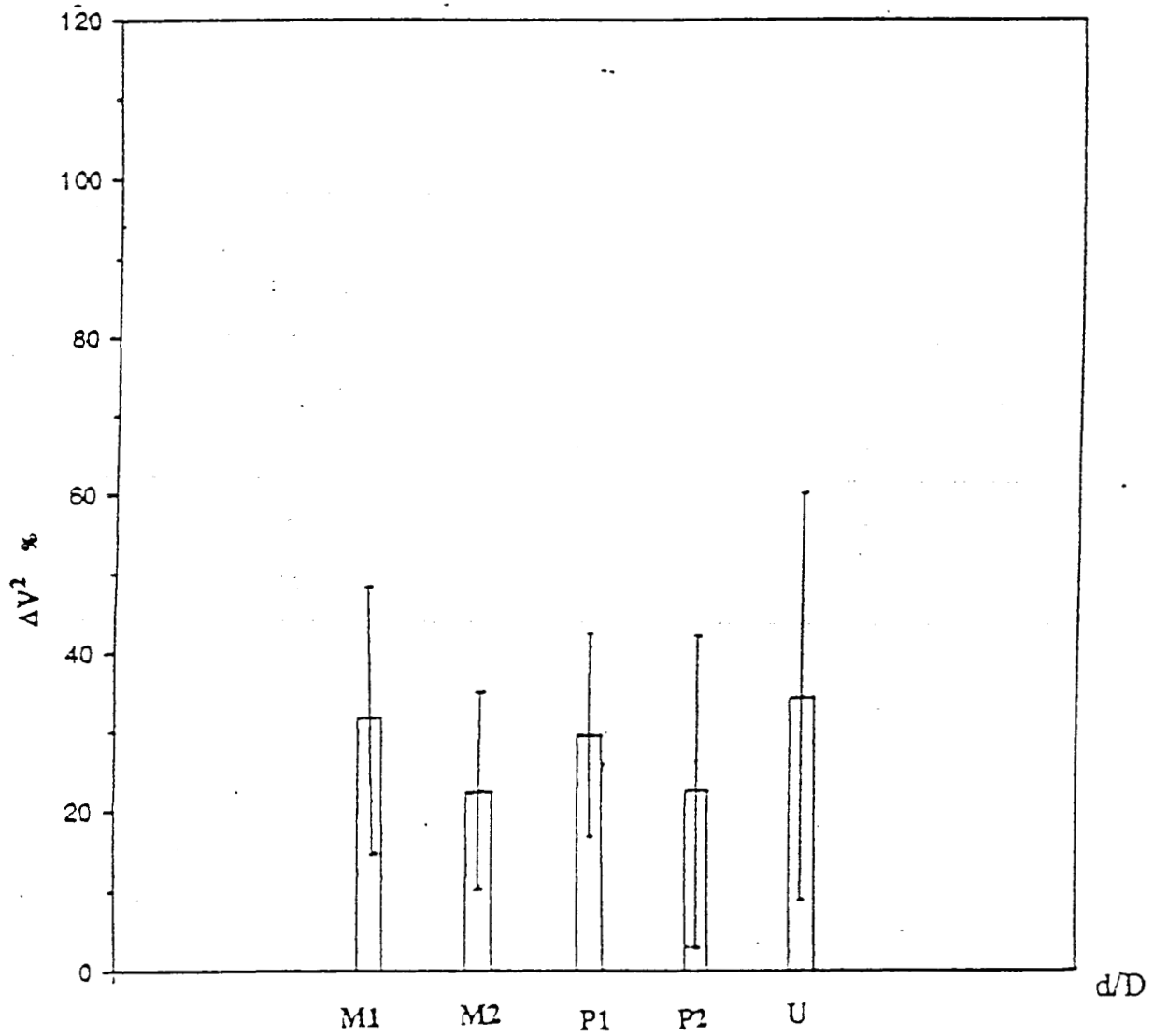


Fig. 7-18: Reduction in Dynamic Modulus of Freeze-Thaw Specimens (Dry Patch)

Table 7.6a Results of Cyclic Loading of Freeze-Thaw Specimens - Dry

Material	Depth	No. of Cycles	Observations
M1	S	110	Bond-shear failure
	H	1770	Shear failure
	F	10 ⁶	No cracks
M2	S	570	Shear failure
	H	22,350	Shear in parent
	F	177,700	Shear in parent
P1	S	630	Bond-shear failure
	H	820	Bond-shear failure
	F	Not tested due to excessive wear	
P2	S	4160	Shear failure
	H	160	Bond failure
	F	10 ⁶	Bond failure
U	S	10	Shear in parent
	H	-	Shear in parent
	F	10	Bond, shear failure
Control		10 ⁶	Flexural cracks

Table 7.6b Results of Cyclic Loading of Freeze-Thaw Specimens - Moist

Material	Depth	No. of Cycles	Observations
M1	S H F	Delaminated - not tested 10^6 10^6	No cracks No cracks
M2	S H F	10^6 10^6 10^6	Limited debonding No cracks Limited debonding
P1	S H F	Not tested due to excessive deterioration of patch material	
P2	S H F	10^6 10^6 10^6	No cracks No cracks No cracks
U	S H F	Delaminated - not tested 10^6 10^6	Debonded but not cracked Debonded. Failed by steel bond failure

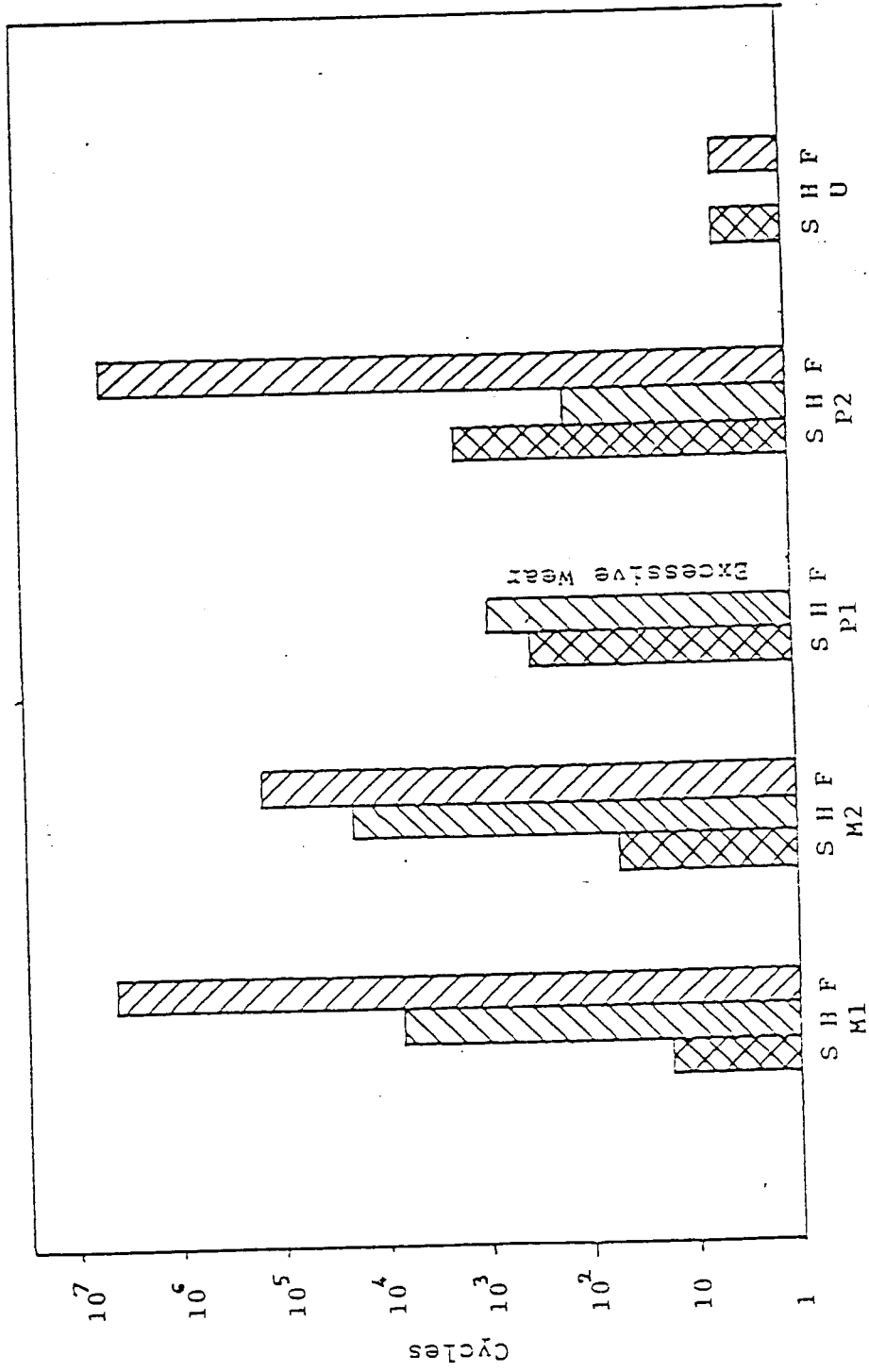
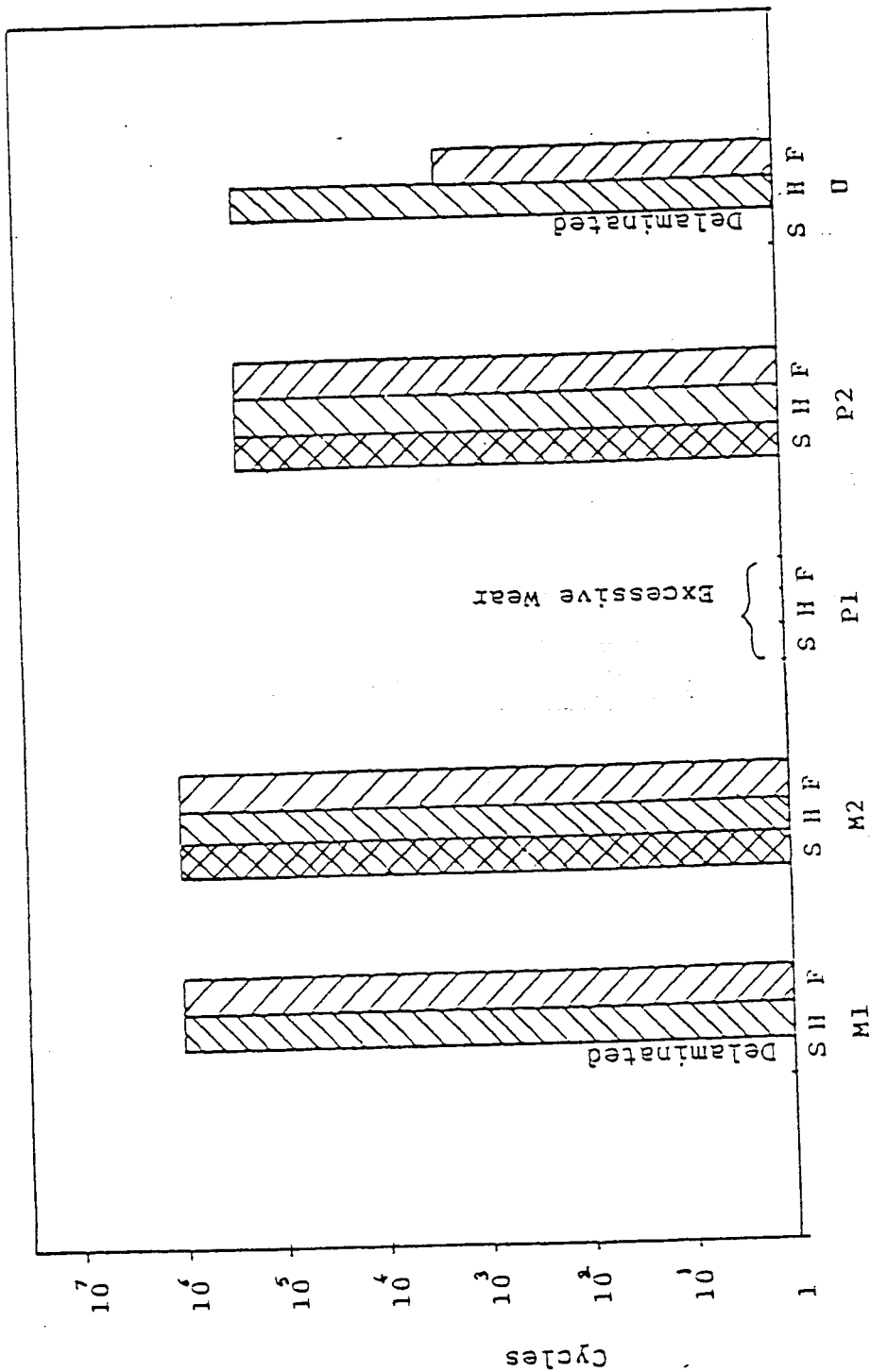


Fig. 7-19: (a) Dry Patch Fatigue Test Results of Freeze-Thaw Specimens



(b) Moist Patch Fatigue Test Results of Freeze-Thaw Specimens (continued)

Fig. 7-19:

Table 7.7 Corrosion in Freeze-Thaw Specimens

Material	Observations
M1	Intense corrosion at patch boundaries for half and full depth patches. Some localized corrosion for shallow patches
M2	Intense corrosion at patch boundaries for half depth, substantial corrosion for full depth and some localized for shallow patches
P1	Intense corrosion at patch boundaries for full and half depth patches. Some corrosion of bar adjacent to shallow patch.
P2	Moderate to substantial corrosion at patch boundaries for full and half depth patches
U	Intense corrosion at patch boundary and substantial corrosion along patch for full and half depth patches. Some localized corrosion for shallow patches
Control	Some localized mild to moderate corrosion, particularly inner surface of top bar

depth patches relate to both reinforcing bars while observations on shallow patches relate to the top bar adjacent to the patch. Table 7.7 lists the relative corrosion behavior of the various patching materials.

7.5 Analysis and Interpretation of Test Results

In this section, the results presented in the preceding section are discussed in terms of their statistical significance and implications for winter patching applications. The discussion follows the same sequence as the presentation of results. Under each experiment, results for dry patched specimens (where applicable) are discussed first followed by discussion of the effect of moist patching on the results. The reason for separating the effect of moisture from other effects (particularly of the materials) is discussed in the relevant context.

7.5.1 Cylinder Tests

The results of cylinder tests are presented in Tables 7.8 and 7.9 for the compressive strength and slant shear tests, respectively. Tables 7.8a and 7.9a present the means and standard deviations of the observations of Table 7.1 in the form of two-way tables. The row and column means indicate the effect of material and age, respectively. Tables 7.8b and 7.9b present the analysis of variance of the results. The F test of significance yields very high significance (at less than 1% level) for both age and material effect and for their interaction in both experiments. The strong interactions means that the effect of one factor (e.g., material) depends strongly on the level of the other (age). This strong interaction is due largely to the anomalous behavior of M1 and M2 without gravel, namely, the reduction in strength with age. The interaction is apparent in Fig. 7.9 by the out of parallel of curves for different materials. If the two plain methacrylates are ignored, the interaction becomes small and the row means of Tables 7.8a and 7.9a provide a good comparison of material

Table 7.8 Compressive Strength-Analysis of Results

a. Means and Standard Deviations (psi)

Material	Age		Row Mean
	1 day	7 days	
M1	9815 ± 23	8143 ± 293	8979
M1(G)	6545 ± 84	7666 ± 586	7106
M2	6830 ± 271	6326 ± 40	6578
M2(G)	4828 ± 92	5570 ± 40	5199
P1	6671 ± 282	7348 ± 255	7014
P2	4642 ± 122	5318 ± 503	4980
U	1764 ± 100	2905 ± 68.9	2334
Column Mean	5871	6138 Overall mean	6027

b. Analysis of Variance

Source of Variation	Sum of Square (x10 ⁶)	Degrees of Freedom	Mean Square (x10 ⁶)	Significance	
				F	F(0.01)
Material	159.4	6	26.57	392.8	3.56
Age	1029	1	1029	15.2	7.68
Interaction	9.598	6	1.60	23.6	3.56
Residual	1894	27	0.06764	(error)	
Total	171.96	40			

Table 7.9 Slant Shear-Analysis of Results (Dry Patch)

a. Means and Standard Deviations (psi)

Material	Age		Row Mean
	1 day	7 days	
M1	4231 ± 271	3727 ± 83	3979
M1(G)	4774 ± 551	5425 ± 407	5100
M2	4438 ± 1060	3753 ± 128	4118
M2(G)	4430 ± 122	5212 ± 173	4821
P1	2567 ± 590	4814 ± 185	3691
P2	3209 ± 686	4178 ± 345	3694
U	2109 ± 40	2759 ± 188	2419
Column Mean	3686	4263 Overall mean	3974

b. Analysis of Variance

Source of Variation	Sum of Square ($\times 10^6$)	Degrees of Freedom	Mean Square ($\times 10^6$)	Significance	
				F	F(0.01)
Material	27.49	6	4.582	19.6	3.56
Age	3.488	1	3.488	14.9	7.68
Interaction	8.802	6	1.467	6.3	3.56
Residual	5.976	27	0.234	(error)	
TOTAL	45.47	40			

performance. Ignoring the M1 and M2 behavior is justified on the grounds that the methacrylates are not used without gravel except in very shallow patches, where the material behavior is not well represented by a cylindrical specimen. Since all materials possess adequate strength, the slant shear tests are the more interesting of the two experiments for comparison of performance. Table 7.8a yields the following grading of performance in descending order: M1(G); M2(G); P2-P1; U. This grading is, roughly, in agreement with failure modes observed in Table 7.1 (ascending number of bond failures).

Table 7.10a presents the means and standard deviations of moist-patched specimens. Table 7.10b presents the analysis of variance (ANOVA) of the combined effects of the three factors - material, age, moisture. It can be seen from the ANOVA table that the effect of moisture, which is significant at the 1% level, strongly interacts with both material and age factors with the result that the age effect is obscured. Even the three factor interaction, which normally should be small is significant at the 1% level.

The strong interaction of moisture with material is to be expected, since, clearly, the effect of moisture is different for different materials. In order to avoid confusion resulting from the interaction, the effect of moisture is handled separately from material effects in the following discussion. Materials are compared on the basis of dry patched specimens and the effect of moisture is considered for each material separately.

The results of the modified ANOVA are presented in Table 7.11 for the seven materials. Here, the tests for each material are considered as an experiment with two factors (age and moisture) at two levels each. It can be seen that the effect of moisture is highly significant (at 1% level) for the magnesium phosphate and the polyurethane materials but not for the methacrylates. The interaction of moisture with age is also significant for some

Table 710 Slant Shear-Moist Patch-Analysis of Results

a. Means and Standard Deviations (psi)

Material	1 day	7 days	Row Mean
M1	3553 ± 602	4218 ± 508	3875
M1(G)	4563 ± 1220	4165 ± 850	4364
M2	4112 ± 587	4019 ± 804	4066
M2(G)	4430 ± 453	4257 ± 1030	4344
P1	2308 ± 679	1154 ± 278	1731
P2	1698 ± 959	1432 ± 358	1565
U	1180 ± 612	1445 ± 23	1313

Column Mean 3117

b. Analysis of Variance of 3 Factors

Source of Variation	Sum of Square	Degrees of Freedom	Mean Square ($\times 10^6$)	Significance	
				F	F
Material (A)		6	15.141	37.5	1%
Age (B)		1	0.635	1.58	N.S.
Moisture (C)		1	19.041	47.2	1%
Interaction (AxB)		6	0.327	0.81	N.S.
Interaction (AxC)		6	2.006	4.98	1%
Interaction (BxC)		1	2.300	5.705	5%
Interaction (AxBxC)		6	1.619	4.02	1%
Residual		56	0.403	(error)	
TOTAL		83			

Table 711 ANOVA of Age and Moisture Effects on Slant Shear Strength

Material	Effect	Mean Square ($\times 10^6$)	F	Significance
M1	Age	0.017	0.09	N.S.
	Moisture	0.023	0.12	N.S.
	Interaction	1.004	5.29	5%
	Residual	0.189	error	
M1(G)	Age	0.010	0.01	N.S.
	Moisture	2.534	2.68	> 5%
	Interaction	0.349	0.37	N.S.
	Residual	0.946	error	
M2	Age	0.508	0.95	N.S.
	Moisture	0.008	0.16	N.S.
	Interaction	0.304	0.57	N.S.
	Residual	0.533	error	
M2(G)	Age	0.279	0.85	N.S.
	Moisture	0.685	2.1	> 5%
	Interaction	0.684	2.1	> 5%
	Residual	0.327	error	
P1	Age	0.902	3.14	> 5%
	Moisture	11.541	40.2	1%
	Interaction	8.694	30.3	1%
	Residual	0.287	error	
P2	Age	0.215	0.47	N.S.
	Moisture	12.552	27.6	1%
	Interaction	0.855	1.88	N.S.
	Residual	0.455	error	
U	Age	0.627	6.1	5%
	Moisture	3.770	36.6	1%
	Interaction	0.111	1.1	N.S.
	Residual	0.103	error	

N.S. = Not significant

of these materials (P1). Figure 7.9 indicates that the effect of moisture is to mitigate, and in some cases reverse, the effect of age on dry patched specimens. Indeed, the effect of age fails to attain significance in any of the materials tested, when the effect of moisture is added.

7.5.2 Flexure Tests

(a) Static Loading

The results for the ultimate static load of patched specimens (Fig. 7.12) show very high variability in behavior, expressed as strong interactions between material and patch depth. The low result for shallow patch of M1 is particularly surprising, since shallow patches are not expected to have much effect on the static load behavior since they are entirely in the cracked zone under flexure.

Statistical analysis of the results shows relatively high variability. The only effect which attains significance at 5% level is the interactions of patch depth with material type. If, however, results for shallow patches are ignored and the analysis performed for half and full depths only, the interaction is small. When the interaction variance is combined with the residual variance for error estimate, material affect just reaches 5% significance level while the depth effect is significant only at the 10% level (Table 7.12). Ignoring shallow patches is justified on the grounds that such patches are not recommended in practice since they are subject to delamination. The strong interaction is due largely to the methacrylate materials, which, at shallow depth do not contain gravel.

The following tentative hypothesis is proposed to account for the unexpected behavior of shallow patches of methyl methacrylate and particularly M1. The methacrylates which do not contain gravel are subject to substantial shrinkage. This shrinkage probably accounts for the deterioration with age of the cylindrical specimens. The relatively high tensile and bond strength of this material, and particularly M1, allow this shrinkage to introduce local prestress in

Table 7.12 ANOVA of Static Flexure Tests (Dry)
for Half and Full Depth Patches

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Material	2.175	4	0.544	3.1	- 5%
Depth	0.421	1	0.421	2.4	10%
Interaction	0.637	4	0.159	}	error
Residual	1.825	10	0.182		
Total	5.506	19			

the concrete adjacent to the patch (Fig. 720). The magnitude of the prestress depends on the tensile strength of the patch material since low tensile strength results in cracking of the patch material and relieving of the stress. The prestress effects result in high tensile stress concentration and possibly cracking of the parent concrete in the vicinity of the patch boundary which enhance crack initiation and propagation under stress. This hypothesis is supported by the cracking and failure mode of static and cyclic loading tests and the comparison of dry and moist patch behavior. Further analytical and experimental work is needed to confirm it.

The analysis of variance of effects of patch depth and moisture each material separately is shown in Table 7.13. Moisture effect reached a 5% significance level only for the water based magnesium phosphate. Comparing Fig. 7.12(b) with Fig. 7.12(a), it can be seen that the effect of moist patching on shallow methacrylate patches appears to mitigate the shrinkage effect on strength reduction. Such behavior can be attributed to reduced bond strength. Further analytical and experimental work is needed to clarify this behavior.

(b) Fatigue Tests

The results of fatigue tests are very erratic, as apparent from Table 7.4 and Figs. 7.13 and 7.14. This is the reason Figs. 7.13 and 7.14 were drawn as block rather than line diagrams. This high variability makes statistical analysis meaningless. A general trend, however, emerges.

As in static tests, and perhaps even more so here, patch depth does not appear to have significant effect. With the exception of material M2 all materials performed very well, most specimens sustaining in excess of 1 million cycles and extent of cracking at 30,000 cycles comparable to that of the control. The reason for the apparent inferiority of M2 is not clear. It could indicate high variability in the performance of MMA in general, high sensitivity to small

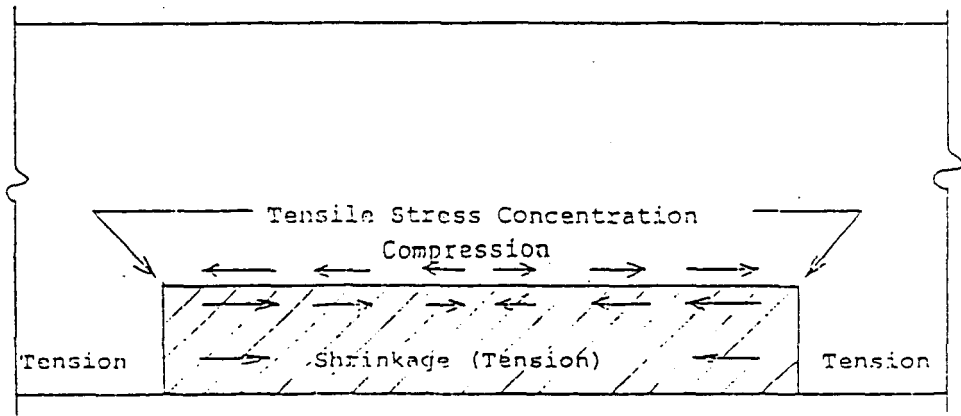


Fig. 7-20: Effect of Patch Shrinkage on Stresses

Table 713 Results of ANOVA of Patch Depth and Moisture Effects on Each Material

Material	Effect	Mean Square	F	Significance
M1	Depth	1.238	11.28	1%
	Moisture	0.460	4.19	10%
	Interaction	0.590	3.38	10%
	Residual	0.110	error	
M2	Depth	0.188	2.07	N.S.
	Moisture	0.021	0.23	N.S.
	Interaction	0.403	4.46	10%
	Residual	0.090	error	
P1	Depth	0.544	7.94	5%
	Moisture	0.542	7.91	5%
	Interaction	0.331	4.81	10%
	Residual	0.069	error	
P2	Depth	0.666	1.93	N.S.
	Moisture	0.067	0.2	N.S.
	Interaction	0.002	0.005	N.S.
	Residual	0.346	error	
U	Depth	0.439	2.99	N.S.
	Moisture	0.285	1.94	N.S.
	Interaction	0.058	0.395	N.S.
	Residual	0.147	error	

N.S. = Not significant

variations in composition and, hence, variability of sources, or it may be due simply to a faulty batch of material received.

Contrary to expectation, moist patched specimens performed better than dry patched specimens in terms of the number of cycles sustained. All specimens sustained over one million cycles. Even the polyurethane which was partly or fully debonded from the start of the test sustained the full number of cycles. This unexpected result could be due to weakened bond in the moist patched specimens which reduced stress concentrations, or it could be due to improved batches of parent material. Although there is no evidence for the latter possibility, in terms of compressive strength of the parent material, there is some support for this interpretation in cyclic load test results of freeze-thaw specimens as can be seen from Table 7.7 and the accompanying discussion in Section 7.6.3.

7.5.3 Durability Tests

Only qualitative judgement can be made of durability tests. In general, durability, as judged by visual deterioration, appears good with the exception of water based magnesium phosphate. Reductions in dynamic modulus suggest some internal cracking but this could be due to deterioration of parent concrete. No statistical significance of this effect can be established due to the high scatter of results (see standard deviations in Table 7.5).

Some internal cracking or microcracking of patch material is suggested also by half cell potential results for MMA and polyurethane materials. Since the polymers themselves are impermeable, the ion movement indicated by equalization of potential across patch boundaries can only be attributed to the presence of microcracks. Magnesium phosphate based materials did not produce changes in half cell potential due probably to the presence of phosphate ions. The implications of this phenomenon for the corrosion process is not quite clear

at this stage. Further investigation is required to establish whether the potential equalization would prevent the establishment of corrosion cells or whether the phosphate ions themselves would have a corrosive effect. The visual inspection of the extent of corrosion after completion of the test, strongly suggest the latter possibility (Table 7.7). This is an important aspect of the material performance which requires in-depth testing.

The effect of moist patching on freeze thaw durability does not appear to be significant for the M1, M2 and P2 materials. The polyurethane (U) should not be used in the presence of moisture, as observed previously. The effect of moisture on this material is to cause complete de-bonding.

The water based magnesium phosphate (P1) appears to have sustained an even more severe wear under the moist patch conditions than under dry patching. Although other tests (slant shear, static flexure) suggest sensitivity of this material to moisture, it seems unlikely that the boundary conditions of the patch would affect the wear of the material itself. It can be concluded that this material has inferior freeze-thaw durability as compared to other materials tested.

As in the case of cyclic loading of flexure specimens, moist patched specimens performed better under cyclic load than the corresponding dry patched specimens. It can also be observed that most dry patched specimens failed in shear in the parent concrete. This observation supports the assumption that the improved behavior is due to improved batches of parent concrete rather than to the effect of moist patching, taking into consideration that moist patching and testing was carried out subsequent to the dry operations.

8. SLAB TESTS

8.1 Experimental Design of Slab Tests

A series of tests on patched slab specimens was carried out following completion of the prism specimen tests, to assess the two-dimensional effects relating to the patch plan dimensions and boundaries. In addition to patching materials, the parameters considered included: aspect ratio of the patch dimensions (width to length) and the roughness of the boundaries. The polyurethane material was dropped from this test series due to its inferior performance in the prism tests. The methyl methacrylate materials were represented by one material only (M1). In view of the low significance of patch depth in the prism tests, only one patch depth - half depth - was used in the slab tests. The specimens are shown in Fig. 8.1 and the experimental design is summarized in Table 8.1. The experiment is, thus, a full factorial experiment with three factors at three levels, two levels and two levels, respectively, comprising 12 specimen tests. In addition, two control unpatched slabs were tested.

Table 8.1 - Slab Tests - Experimental Design

Factor	Levels
Material	M1, P1, P2
Aspect Ratio	6"/10" (long), 10"/6" (wide)
Boundary Roughness	Smooth, Rough

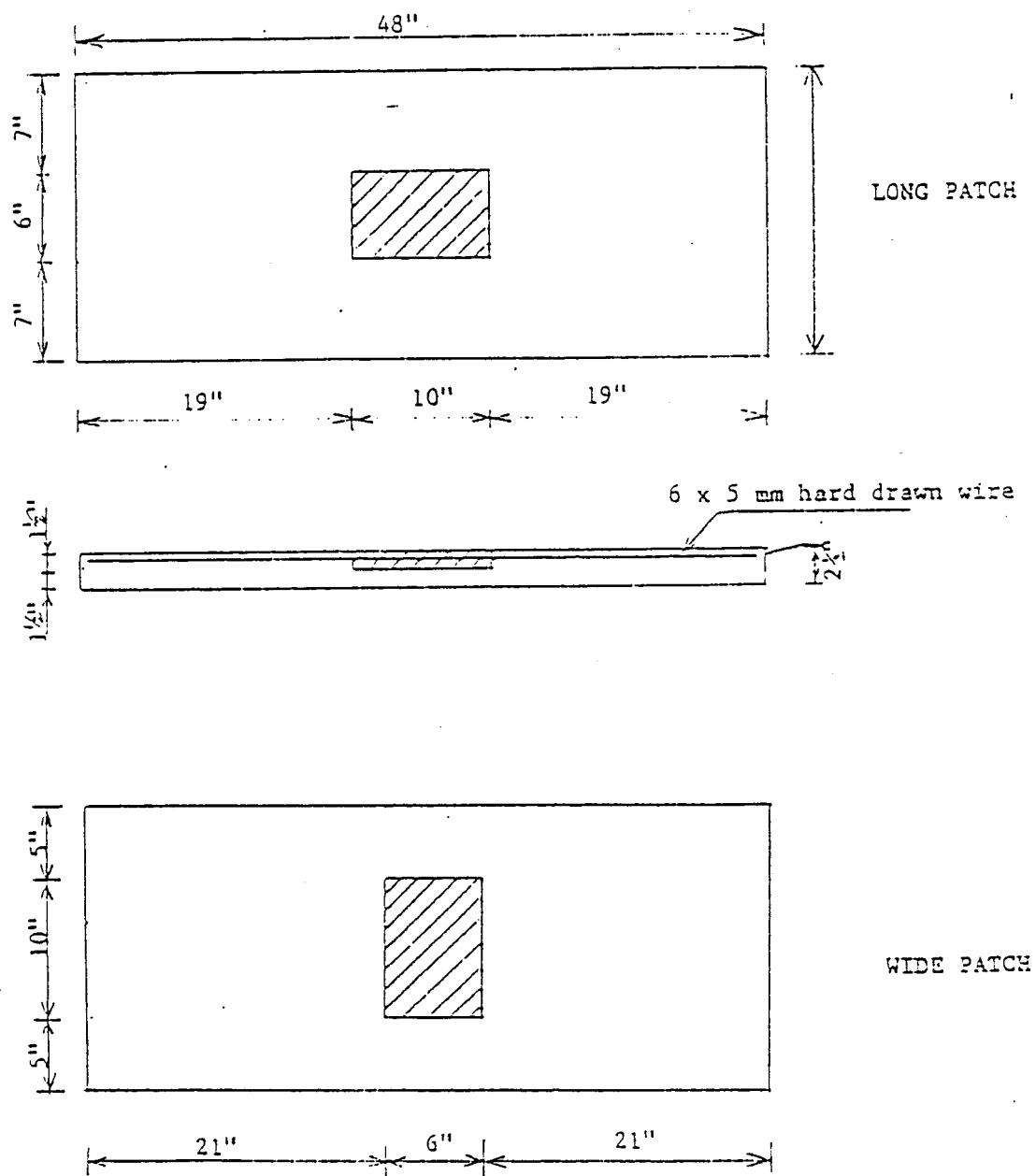


Fig. 8-1: Patch Slab Specimens

8.2 Testing Procedure

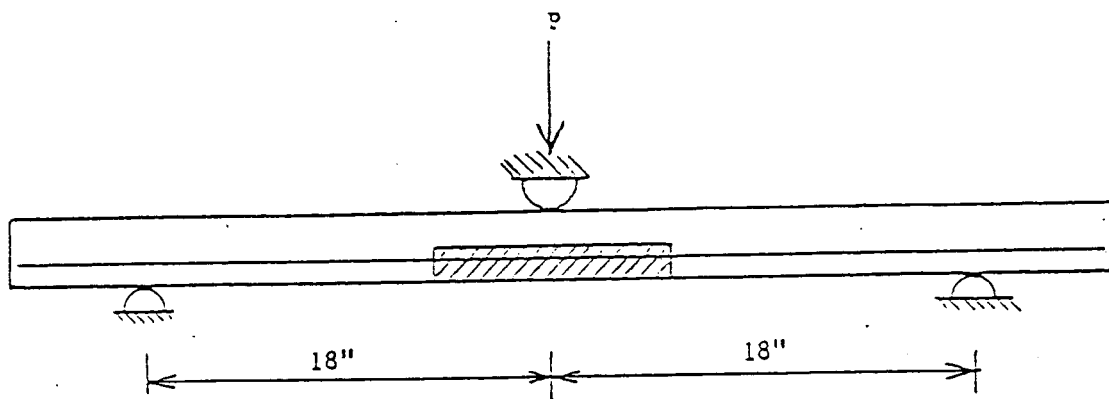
Slab specimens were cast of the same type of concrete mix as the prism specimens and well in advance of testing (approximately six months). In this manner, the parent concrete at the time of patching and subsequent testing was mature. Smooth patches were formed out, allowing for passage of reinforcement. Rough boundary patches were trowelled out to a rough finish.

Specimens were patched in the laboratory cold chamber, following the same procedure used in preparing the prism specimens (§7.3), and tested after seven days of storage in the cold chamber at temperatures of 15°F. The test frame is shown in Fig. 8.2. Testing consisted of loading under slow cyclic loading of 4 cycles per second, up to 100,000 cycles, followed by static loading to failure. The cyclic load ranged from 250 lbs. to 1750 lbs. Load-deflection curves due to cyclic as well as to static loading were recorded. Typical curves are shown in Fig. 8.3 and additional curves are reproduced in the Appendix B. Typical failure modes are shown in Fig. 8.4 and photographs of all slabs after failure are presented in Appendix C.

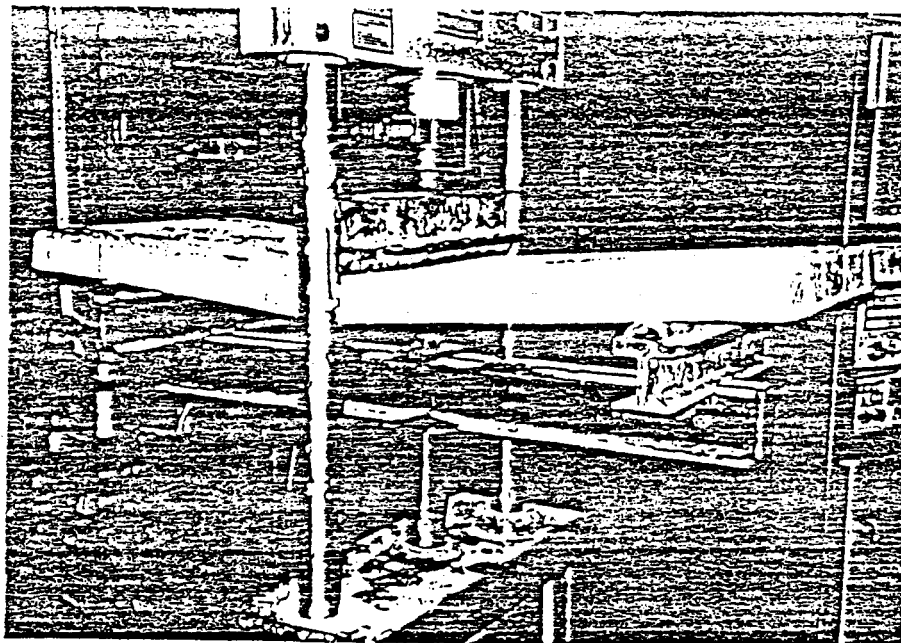
8.3. Test Results

Slab test results are presented in Table 8.2. An estimate of the reduction in stiffness due to cracking was obtained by comparing the initial slope of the load deflection curve with that after 100,000 cycles (i.e., at the static loading), see Fig. 8.3. The figures in the table present the ratio of the initial displacement per 10 kip of load to the final displacement in units of 0.124 in.

In addition, the table also contains failure load, the slab thickness t , the effective depth of slab d from the top fiber to the reinforcement and the concrete compressive strength at the time of test, obtained from cylinders cast and cured with the slabs.



(a) Dimensions



(b) View

Fig. 8-2: Slab Test Setup

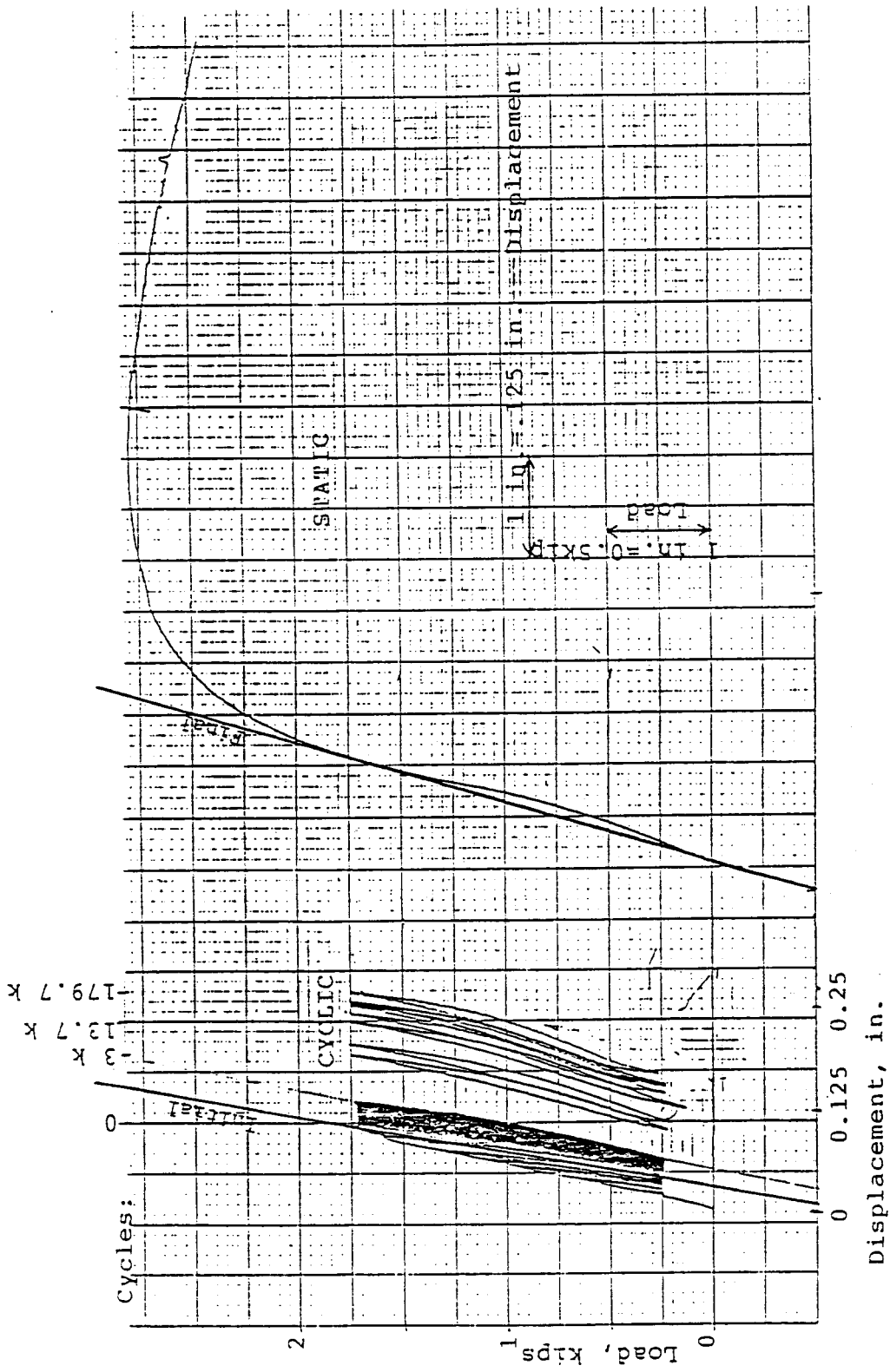
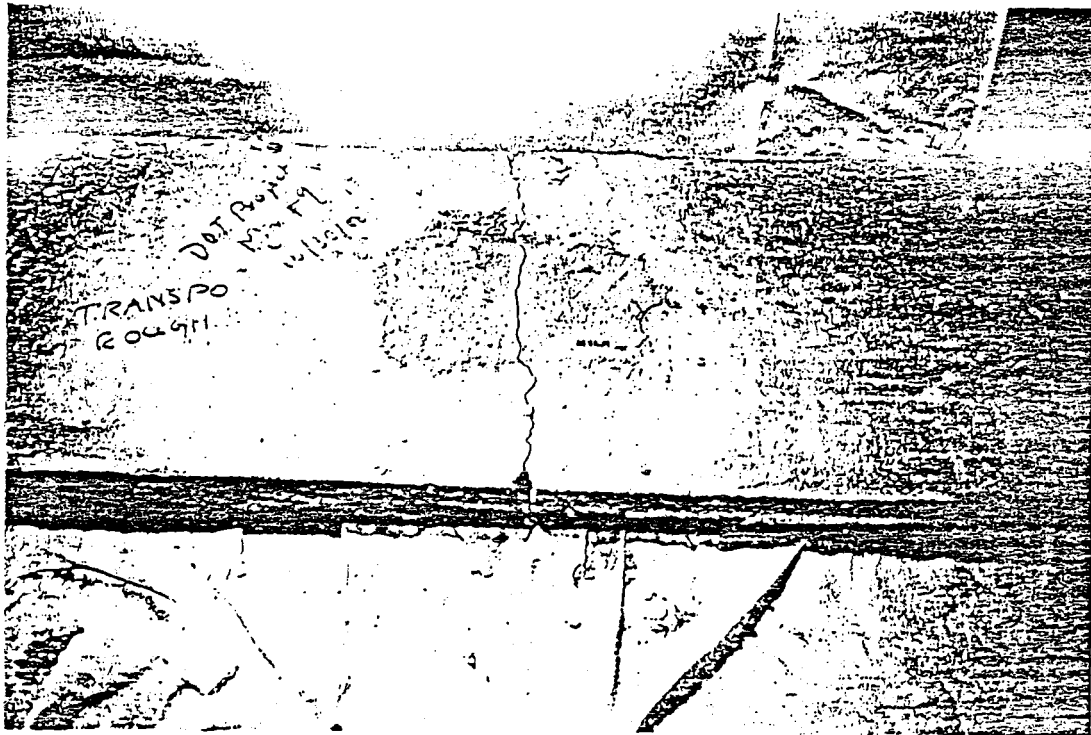
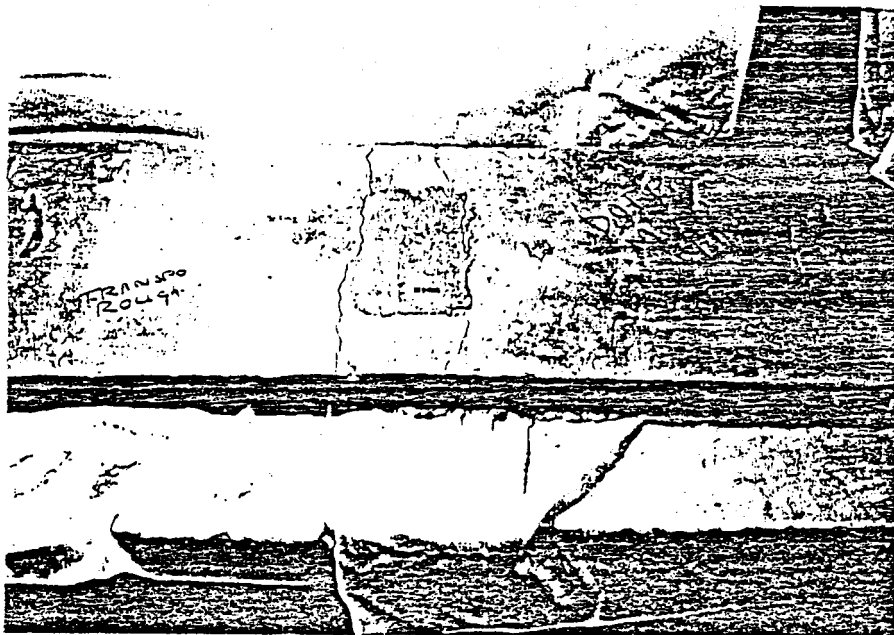


Fig. 8-3: Load-Deflection Curves of Slab Specimens



(a) Crack ng across patch



(b) Cracking around patch boundary

Fig. 8-4: Typical Failure Modes of Slab Specimens



(c) Close Up View of cracked slab at failure

Figure 8-4: Typical Failure Modes of slab specimens (continued)

Table 8.2 - Slab Test Results

Patch Material	ASP Rat.	Boundary	t (in)	d (in)	f' (psi)	Pu (k)	Final Slope / Initial Slope	Comments	
M1		S	2.34	1.87	3700	2.9	1.64/2.73 = 0.60	Initial bond cracks, central failure crack	
		L	R	2.69	2.05	4100	3.55	1.4/2.27 = 0.62	Initial boundary crack central failure
		W	S	2.59	2.10	2800	3.3	1.75/2.85 = 0	Bond cracks-cyclic and failure
		W	R	2.63	1.88	5200	3.95	1.42/2.93 = 0.48	Bond cracks
P1		S	1)	2.38	1.69	4800	-	1.44/2.8 = 0.51	1) Failed at 10,000 cycles - bond cracks, central failure
		L	2)*	2.63	1.96	3000	-	1.9/4.17 = 0.46	2) Failed at 24,500 cycles
		L	R	2.47	2.02	5500	3.55	1.45/2.12 = 0.68	Bond and central cracks from start
		P1	S	2.59	1.80	3800	3.05	2.4/3.13 = 0.77	Initial diagonal crack in parent concrete, central failure
P2		W	R	2.63	1.95	4500	3.8	Not available	Bond crack
		L	S	2.68	1.94	2800	2.85	1.82/4.08 = 0.45	One good, one central crack from start
		L	R	2.63	2.01	5600	3.6	0.95/2.0 = 0.46	Bond crack @ cyclic, failure in from boundary
		W	S	2.63	2.20	3200	3.8	1.5/2.2 = 0.68	Bond cracks from start
		W	R	2.63	2.11	5500	3.45	1.4/2.1 = 0.67	Bond and central cracks from start
Control 1			2.56	1.88	3300	-	1.97/3.5 = 0.56	Failed at 21,000 cycles, 3 central cracks	
Control 2			2.56	1.97	3300	3.6	0.96/2.4 = 0.40	2 central cracks	

Notes: L = long, W = wide, S = smooth, R = rough, t = total thickness, d = effective thickness,

Pu = ultimate load

*The test was repeated to confirm the failure during cycling loading

8.4 Discussion of Results

The results are presented in Table 8.3 in the form of two way tables, containing the values of P_u/d , namely the ultimate load divided by the effective depth, for each material. This procedure eliminates the effect of the variability in effective depth on the results. Consideration of the stress block in the under-reinforced cross-section, leads to the following expression for the ultimate load of an unpatched concrete slab:

$$P_u = \frac{4}{L} A_s f_u \left[d - \frac{A_s f_u}{1.7 b f'_c} \right]$$

where P_u is the ultimate load, L is the span of the slab, A_s is the steel area, f_u is the tensile strength of steel, d is the effective depth, b is the width of the slab and f'_c is the compressive strength of the concrete.

The following values can be substituted: $L = 36$ in., $A_s = 0.1826$ in², $b = 20$ in., $f_u = 86.9$ Ksi (from tension tests) and f'_c ranges from 3 Ksi to 6 Ksi (Table 8.2). This substitution yields:

$$P_u = 1.763d - \frac{0.823}{f'_c}$$

or

$$\frac{P_u}{d} = 1.76 - \frac{0.823}{f'_c d} = 1.62 \text{ to } 1.70 = \text{const.}$$

This value of P_u/d is approximately equal to the overall mean for patched slabs, suggesting that patching, in general, does not significantly affect the ultimate strength. This result is to be expected, since the patch lies entirely in the cracked zone.

Table 83 - Two-Way Tables for P_u/d

Material	Aspect	Boundary		Mean
		Smooth	Rough	
M1	L	155	173	164
	W	157	210	184
Mean		156	192	174±0.25
P1	L	-	176	(176)
	W	169	195	182
Mean		(169)	186	180±0.14
P2	L	147	179	163
	W	173	163	168
Mean		160	171	166±0.140

Overall mean: 1734±0.175
 95% Confidence interval 1.38 to 2.08
 Computed value 1.64 to 1.70

Material effects, as expressed by the variation in the overall mean for each material (underlined in Table 8.3) are probably not significant. The largest effect is the surface roughness effect on the methacrylate, but considering the low effect of patching in general, this effect is probably due to the variability of test conditions rather than a true effect.

It is significant to note that no two-dimensional effects were observed on patch performance in the form of bond or shrinkage cracks. Also, no delamination of patches was observed during the cyclic or ultimate loading, and no shear bond cracks were observed along patch edges parallel to the span axis.

The crack pattern observed during loading provides an indication of the upper and lower bounds on the tensile bond strength of patches. In general, cracks occurred at patch boundary for wide patches and at the center for long patches.

$$\frac{M_{\text{boundary}}}{M_{\text{max}}} = \begin{cases} 0.72 - \text{long patch} \\ 0.83 - \text{wide patch} \end{cases}$$

From this, one can infer that the upper limit on the bond strength is approximately 80% of the patch material tensile strength, and the lower bound is 70% of the patch material strength or the parent concrete strength (whichever is lower).

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of Material Performance

A preliminary screening program identified four generic materials as potentially suitable for sub-freezing temperature applications. These four materials are based on the following compounds: 1) methyl methacrylate based polymer, 2) water activated magnesium phosphate, 3) liquid activated magnesium phosphate, 4) polyurethane.

An extensive experimental investigation on cylindrical and prism specimens confirmed the overall suitability of all four materials for low temperature applications. The polyurethane material, however, proved considerably inferior to the other three materials in almost all performance criteria and is, therefore not recommended for general application purposes in cold weather concreting. The remaining materials are compared herein on the basis of the following criteria:

- 1) Slant shear bond strength.
- 2) Flexural response. This included static and cyclic response in terms of strength, failure mode and bond between patch and parent concrete.
- 3) Freeze-thaw durability. Comparison is based primarily on visual inspection of the condition of the patched specimens and of the bond between patch and parent material after freeze-thaw cycling and after cyclic load testing.
- 4) Effect on reinforcement corrosion of patch boundaries. This is based primarily on visual inspection of broken specimens after testing.
- 5) Effect of surface moisture on patch performance.

particularly on patch bond to parent material.

- 6) Environmental factors. These include ease of handling of the material, toxicity, corrosiveness to skin, unpleasant odors, ease of cleaning tools.

Items (1) through (4) are evaluated on the performance of both dry and moist patches. Material strength is not included in the comparison since all materials possess more than adequate strength.

Although two different brands of methyl methacrylate compounds were tested, with substantial variability in performance, the two materials are nominally identical and are considered together, based on their average performance. It is assumed that patches are deep enough to allow use of methyl methacrylate compounds mixed with pea gravel at least 3/8 inches in size. The use of methyl methacrylate without gravel is not recommended due to its high shrinkage.

Comparison of the performance of the three materials is summarized in Table 9L. In an attempt to quantify the comparison, each criterion has been assigned a weight, based on its perceived importance and on the reliability of the results. The performance of each material under each criterion has been assigned a rank from 1 to 5, 1 being poor to fair, 5 being excellent. The weighted average then provides an estimate of the overall performance of each material. Two weighted averages are provided, one for overall performance, including environmental factors, the other for tested criteria only, excluding environmental effects, whose significance assessment is highly subjective.

9.2 Conclusions

The following conclusions can be drawn from the investigation:

1. Of the four materials tested, three perform satisfactorily under sub-freezing temperatures. These

Table 9.1 - Comparison of Material Performance

Criterion	Weight	Methyl Methacrylate	Magnesium Phosphate	
			Water	Liquid
1. Slant shear	2	4	2	3
2. Flexure	1	3	4	4
3. Freeze-thaw	2	4	2	4
4. Corrosion	3	1	1	2
5. Moisture	1	4	2	4
6. Environmental	4	1	5	3
Weighted average	23	23	28	31
Weighted average #1-5		29	22	31

are: methyl methacrylate, water activated magnesium phosphate, and liquid activated magnesium phosphate.

2. Polyurethane is inferior in performance to the other three materials.
3. The magnesium phosphates emerge from a comparative performance assessment as somewhat better than the methacrylate, taking into account environmental factors.
4. On the basis of tested performance alone, excluding environmental considerations, methyl methacrylate and liquid activated magnesium phosphate are better than water based magnesium phosphate.
5. Water based magnesium phosphate has poor freeze-thaw durability as compared to the other tested materials.
6. All materials tested are subjected to significant corrosion of reinforcement at patch boundaries under the severe test conditions of high chlorine ion concentration and water saturated specimens. Polyurethane shows the most severe corrosion, while liquid activated magnesium phosphate the least.
7. Methyl methacrylate and both magnesium phosphates may be applied under mild surface moisture conditions. Polyurethane requires surface-dry conditions.

9.3 Recommendations

1. Liquid activated magnesium phosphate or gravel containing methyl methacrylate are recommended for use when improved patch performance and

durability are needed.

2. When using methyl methacrylate, patch depth should not be less than 1 1/2 inch, so as to expose the top layer of reinforcement.
3. When environmental factors such as ease of handling and absence of unpleasant odors are a consideration, in addition to performance, liquid activated magnesium phosphate is recommended. Although it has moderate odor and is not as convenient to handle as the water activated variety, its odor is not as aggressive as that of methyl methacrylate.

Heavy molecular weight methacrylates are currently under development, which are expected to mitigate the environmental deficiencies of the ordinary variety. Should their performance prove equivalent to that of lightweight methacrylate, they may become preferable.

4. Water activated magnesium phosphate should be used only for limited term patching (five years lifespan), unless further research indicates that it has adequate freeze-thaw durability.
5. Large-scale field testing of the performance of the three recommended patching material is recommended.
6. Further investigation is needed of the following parameters:
 - (a) Freeze-thaw durability of water activated magnesium phosphate and ways to improve its long term performance.

- (b) The corrosion of bridge deck reinforcement at patch boundaries under realistic field conditions, and ways to control it.
- (c) The variability in strength and performance of methyl methacrylate compounds and the factors influencing it.

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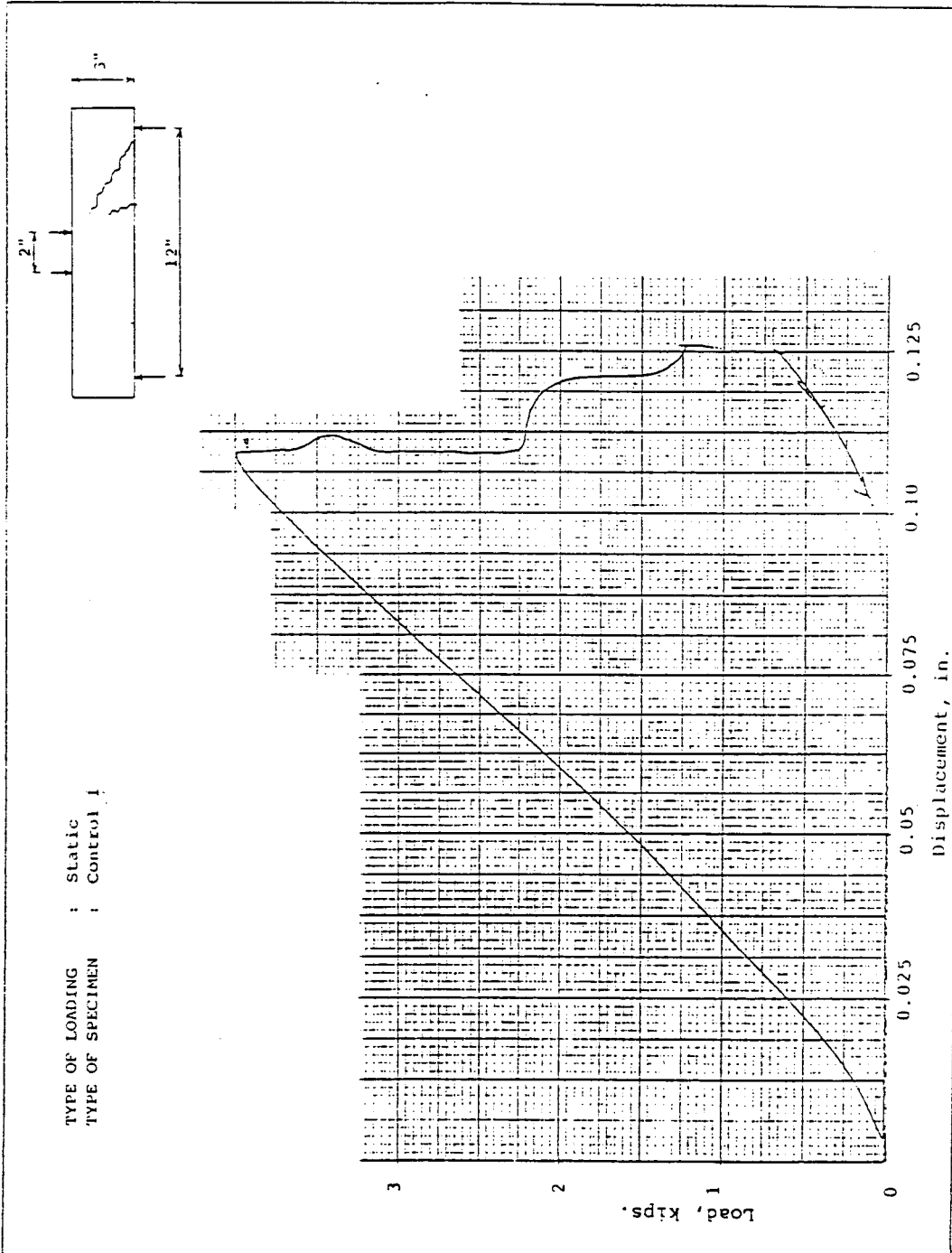
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APPENDIX
SELECTED TEST RESULTS

APPENDIX A

A.1 STATIC TESTS OF PRISM SPECIMENS



ic I vs. lect Control I n Specimen

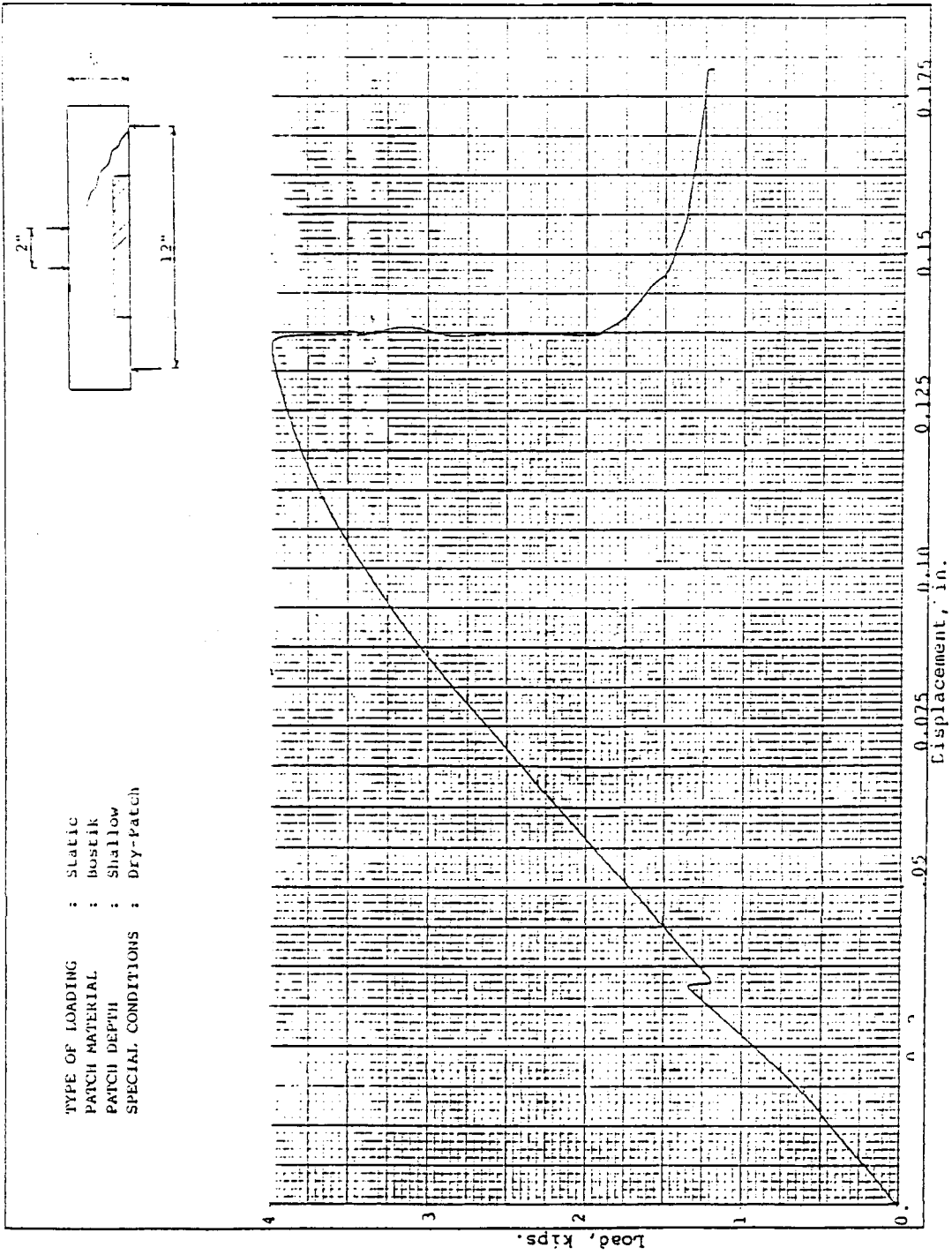


Fig. A1-2: Static Load vs. Deflection - Shallow Depth Patch Prism Specimen
P2S (Dry Patch)

TYPE OF LOADING : Static
 PATCH MATERIAL : Bostik
 PATCH DEPTH : Shallow
 SPECIAL CONDITIONS : Dry-Patch; Replication

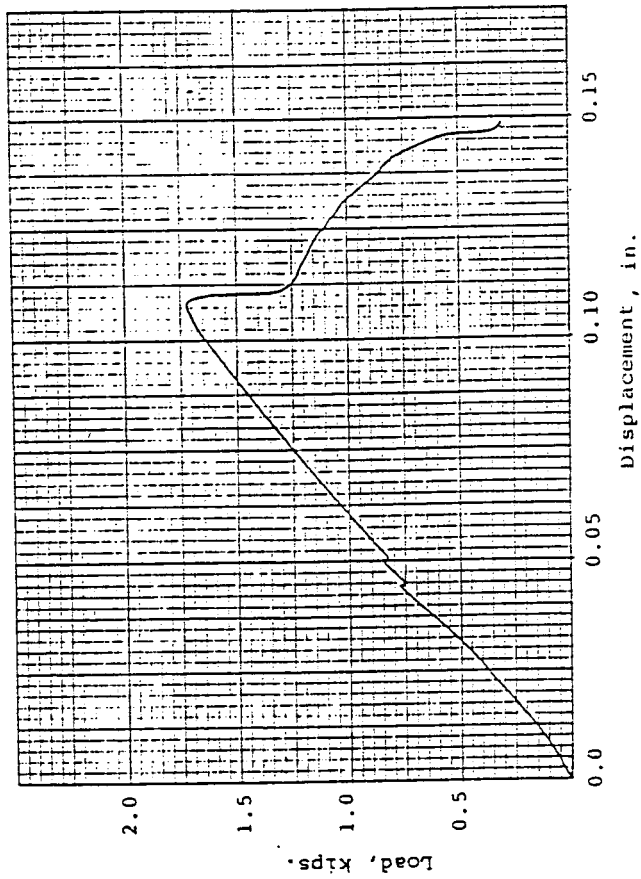
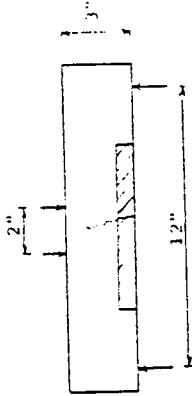


Fig. A1-3: Static Load vs. Deflection - Shallow Depth Patch Prism Specimen
 P2S (Dry Patch, Duplicate)

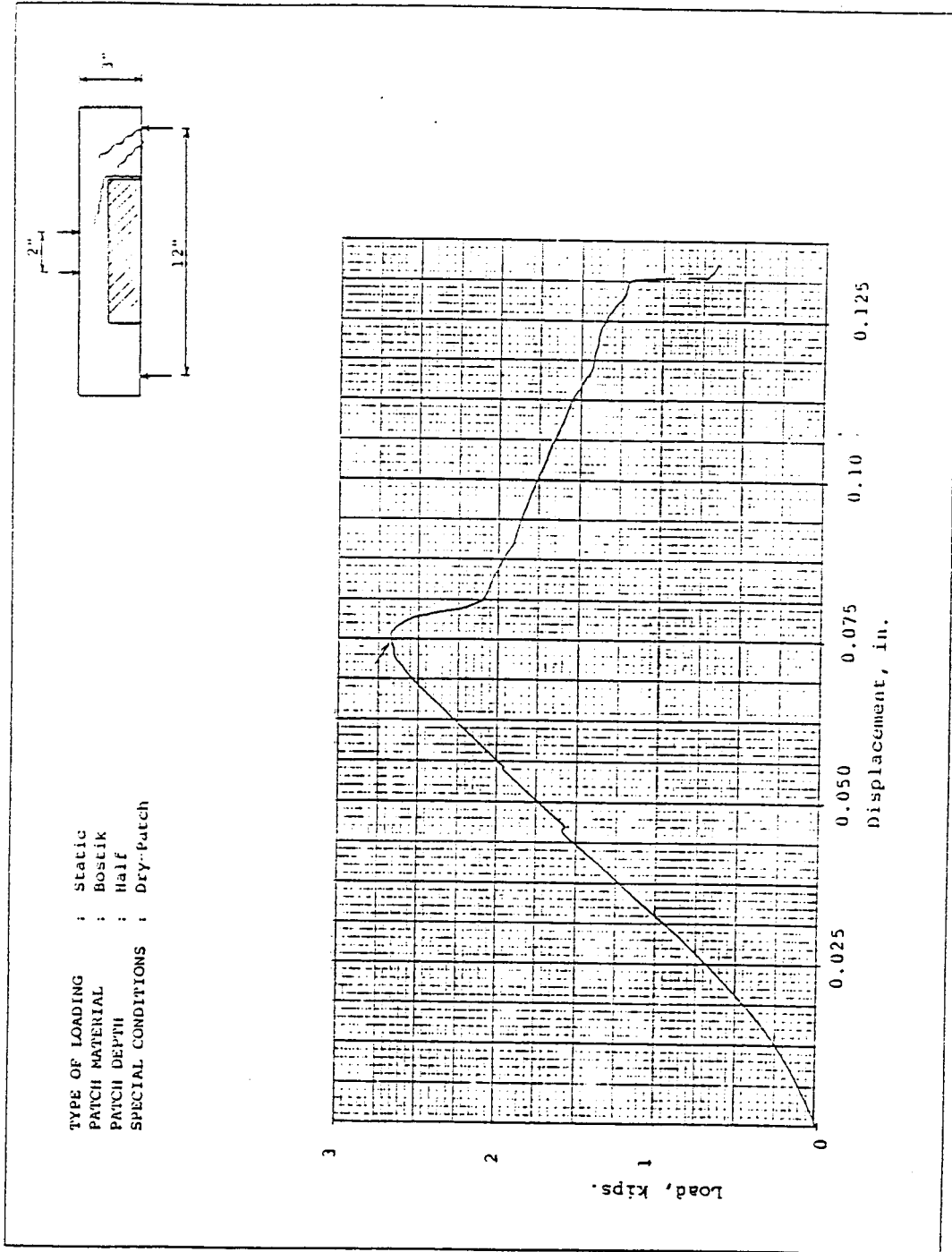


Fig. A1-4: Static Load vs. Deflection - Half Depth Patch Prism Specimen
P2H (Dry Patch)

TYPE OF LOADING : Static
 PATCH MATERIAL : Bostlik
 PATCH DEPTH : Half
 SPECIAL CONDITIONS : Dry-Patch; Replication

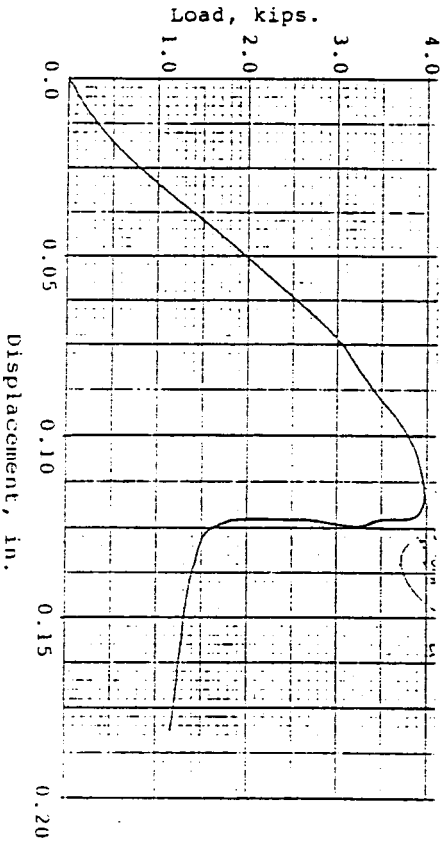
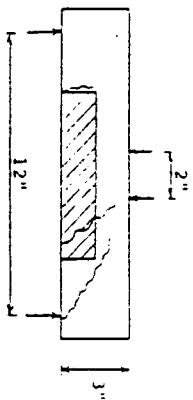


Fig. A1-5: Static Load vs. Deflection - Half Depth Patch Prism Specimen
 P211 (Dry, Duplicate)

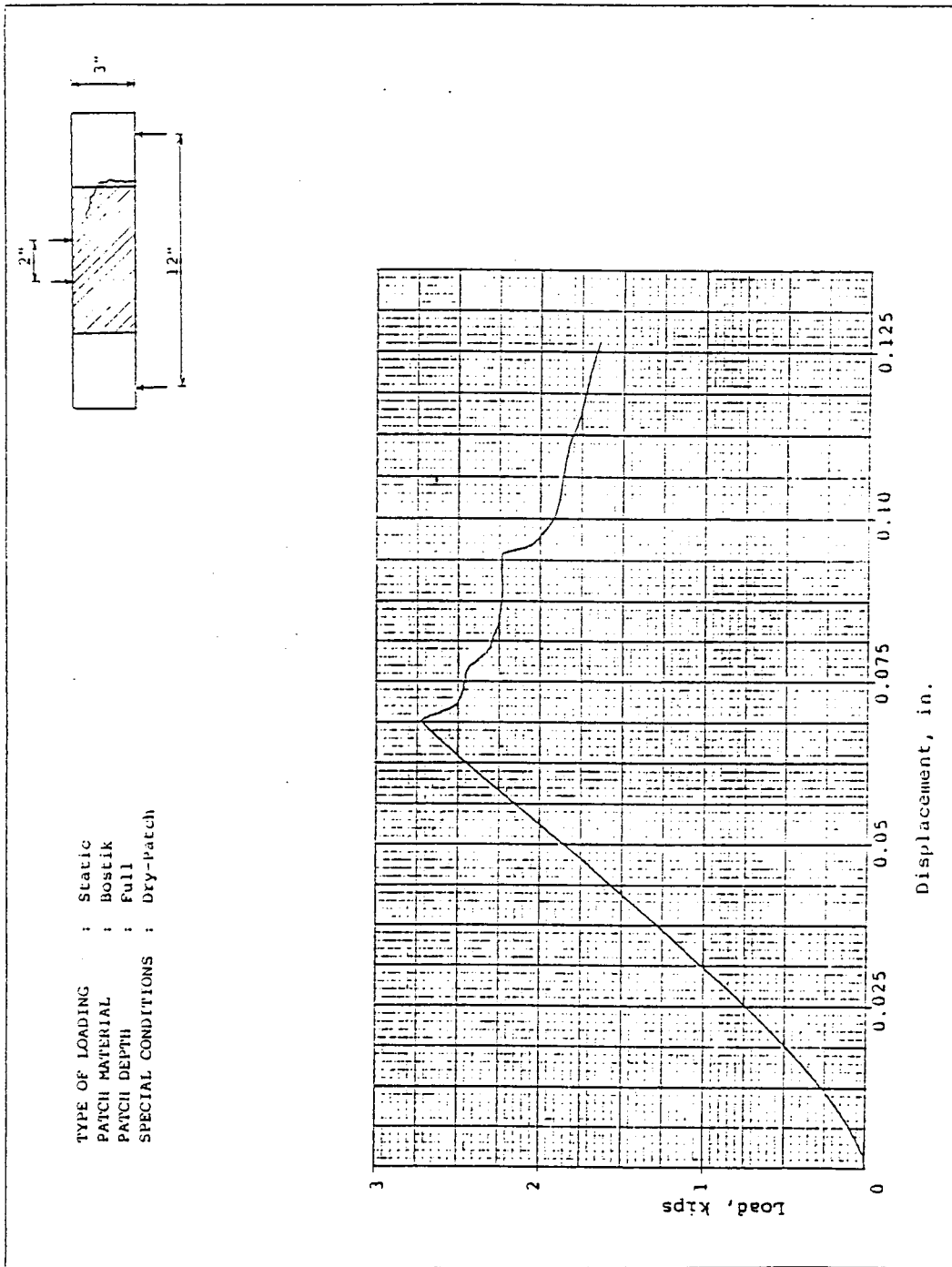


Fig. A1-6: Static Load vs. Deflection - Full Depth Patch Prism Specimen P2F (Dry Patch)

TYPE OF LOADING : Static
 PATCH MATERIAL : Bostik
 PATCH DEPTH : Full
 SPECIAL CONDITIONS : Dry-Patch; Replication

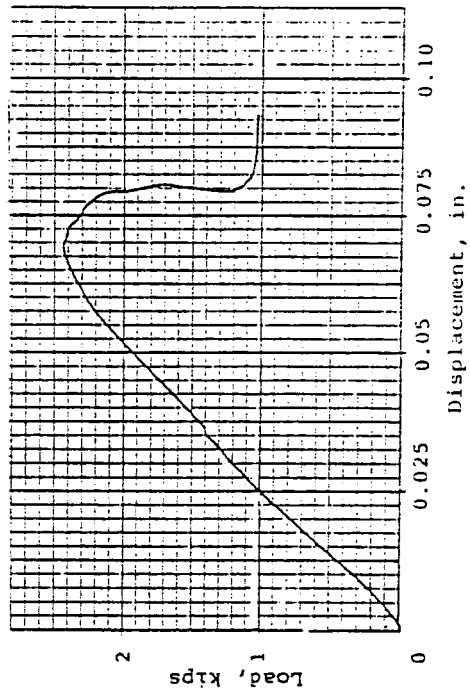
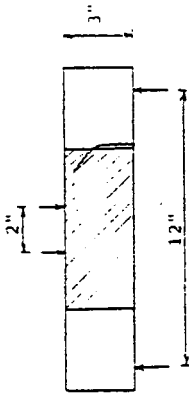


Fig. A1-7: Static Load vs. Deflection - Full Depth Patch Specimen

P2F (Dry, Duplicate)

TYPE OF LOADING : Static
PATCH MATERIAL : Bostik
PATCH DEPTH : Full
SPECIAL CONDITIONS : Dry-Patch, Replication

1"

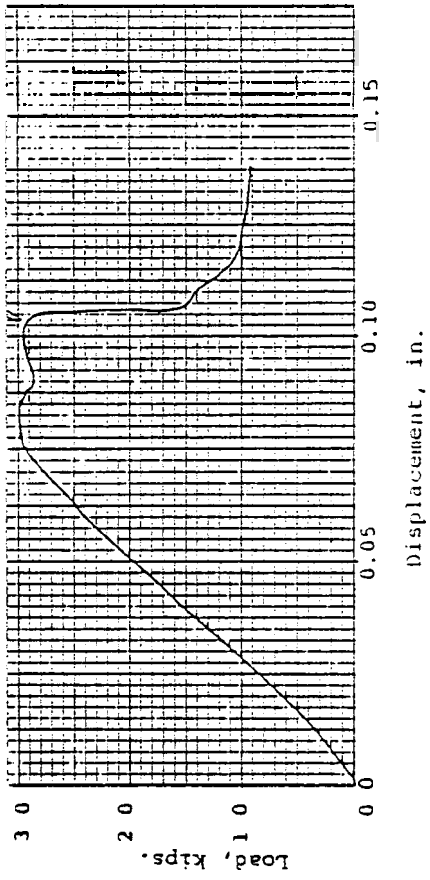


Fig. A1-8: Load vs. Deflection - Full Depth Patch Specimen
P2F (Dry Duplicate)

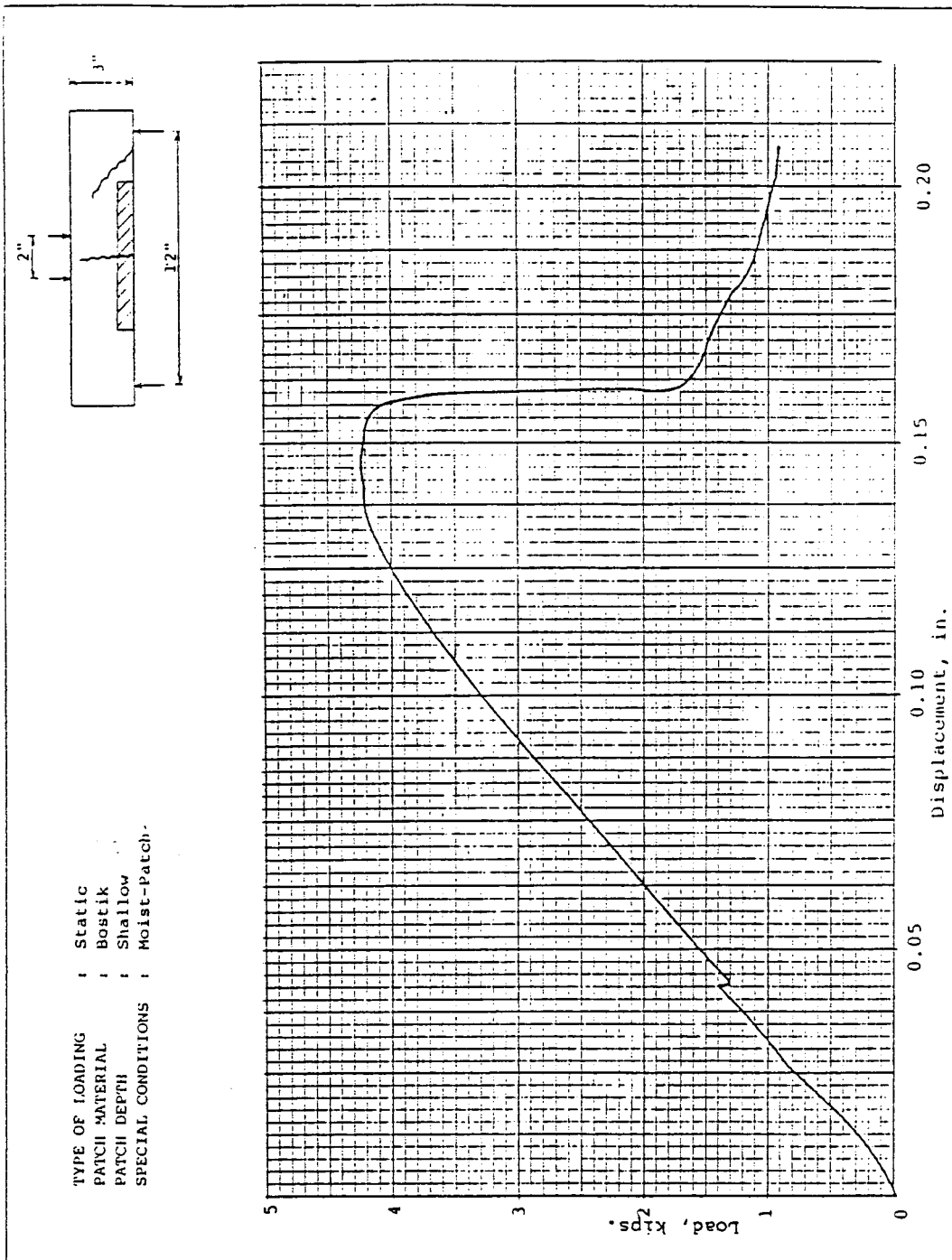


Fig. A1-9: Load vs. Deflection - Shallow Depth Patch Depth Prism Specimen

P2S (Moist Patch)

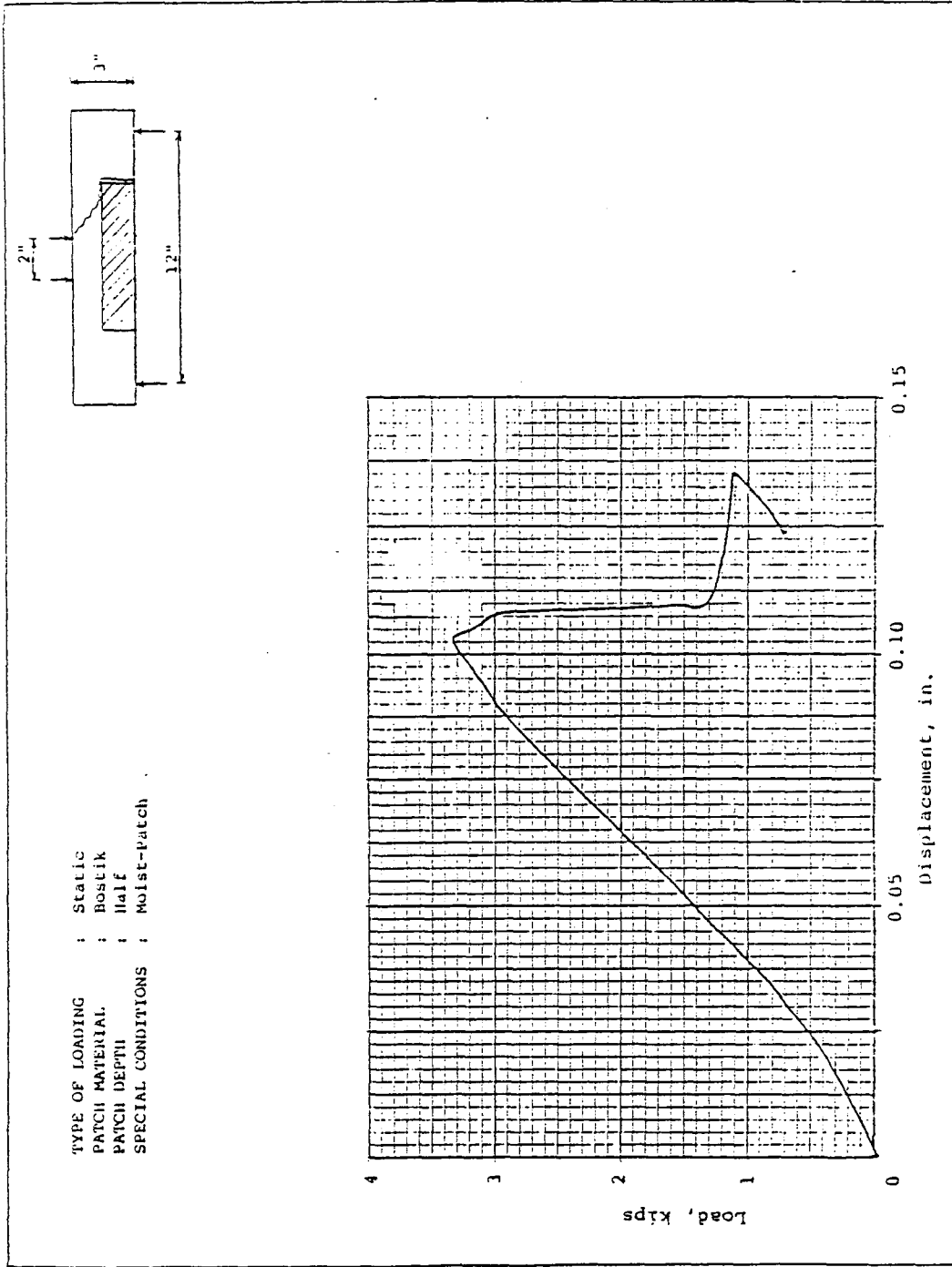


Fig. A1-10: Load vs. Deflection - Half Depth Patch Prism Specimen
P211 (Moist Patch)

TYPE OF LOADING : Static
 PATCH MATERIAL : Bostik
 PATCH DEPTH : Full
 SPECIAL CONDITIONS : Moist-Patch

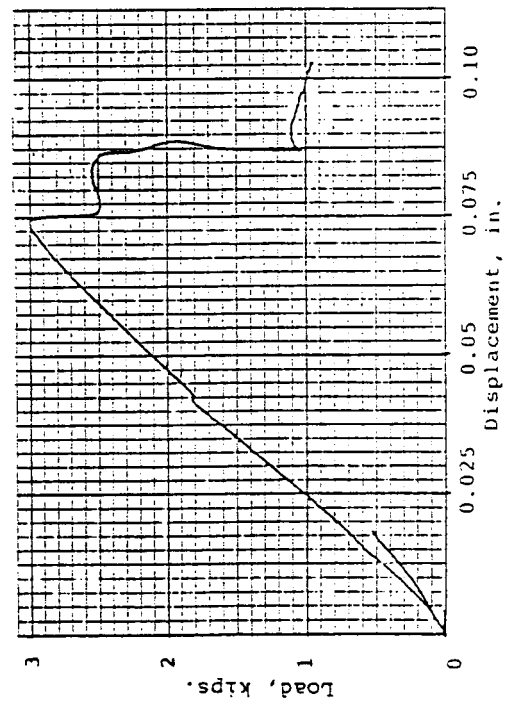
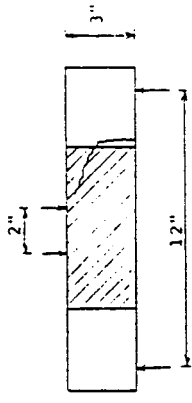


Fig. A1-II: Load vs. Deflection - Full Depth Patch Depth Prism Specimen
 P2F (Moist Patch)

APPENDIX A

A.2 CYCLIC TESTS OF PRISM SPECIMENS

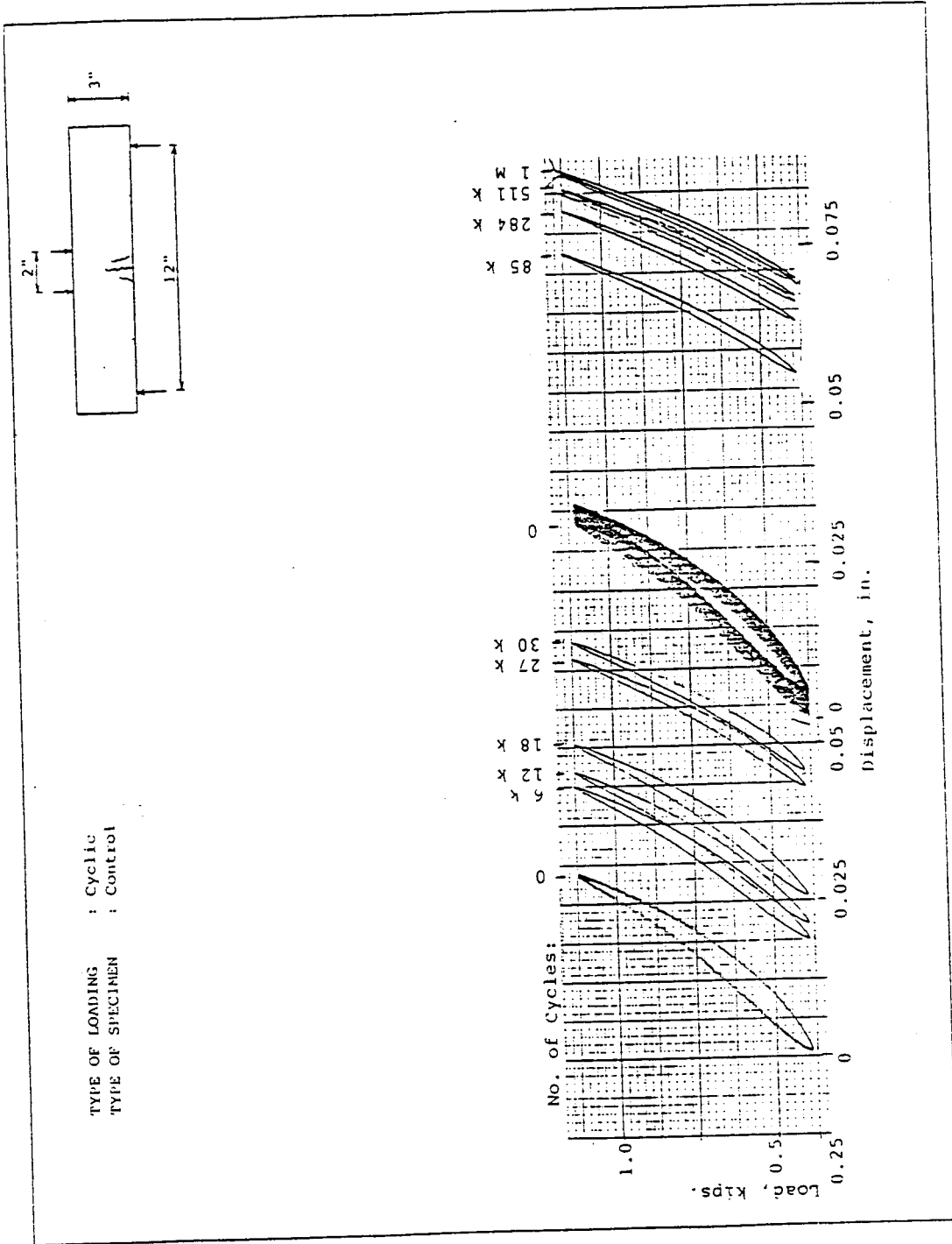


Fig. A2-1: Cyclic Load vs. Deflection - Control Prism Specimen

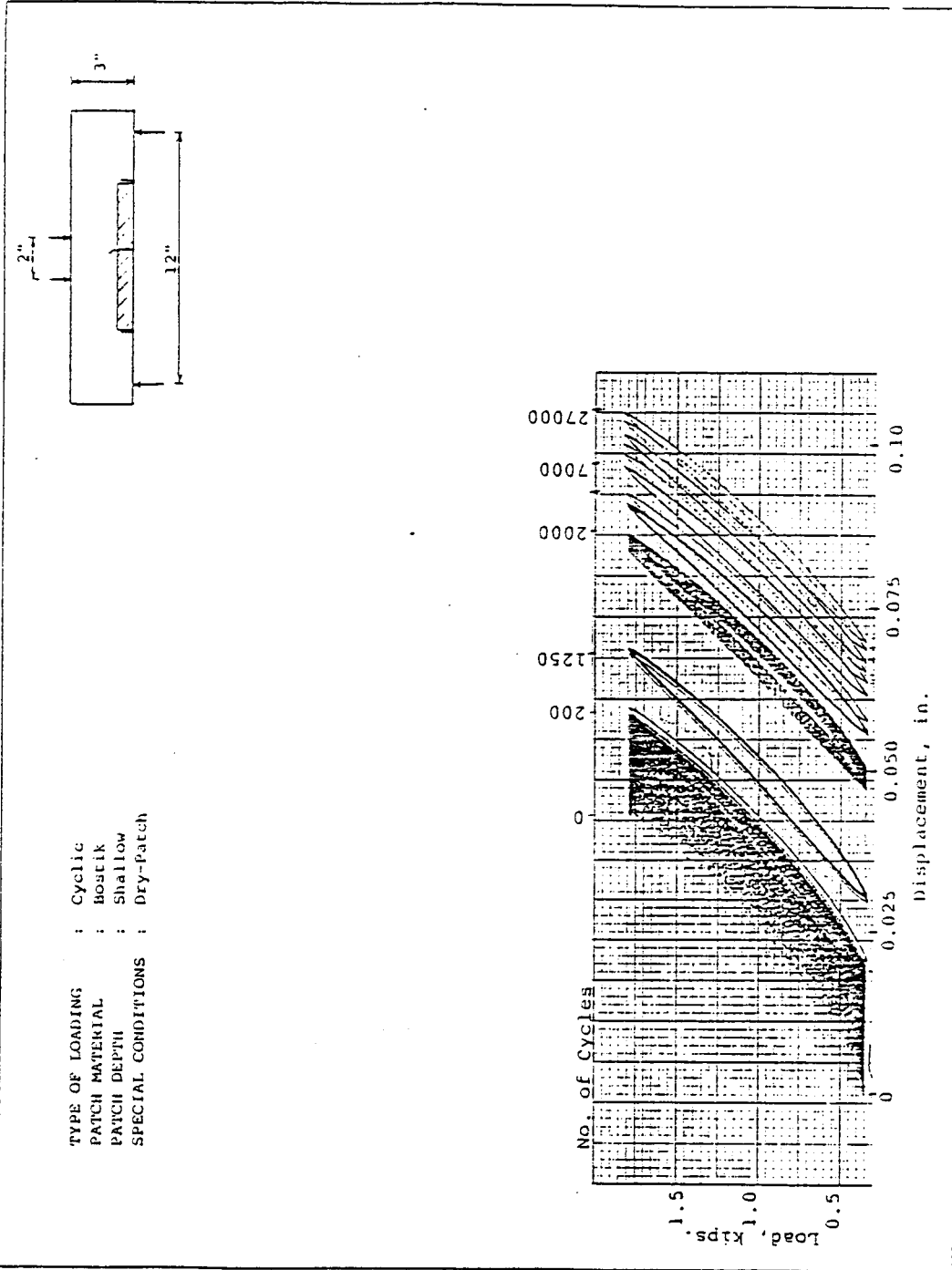


Fig. A2-2: (a) Cyclic Load vs. Deflection - Shallow Patch Depth Prism
Specimen
P2S (Dry Patch)

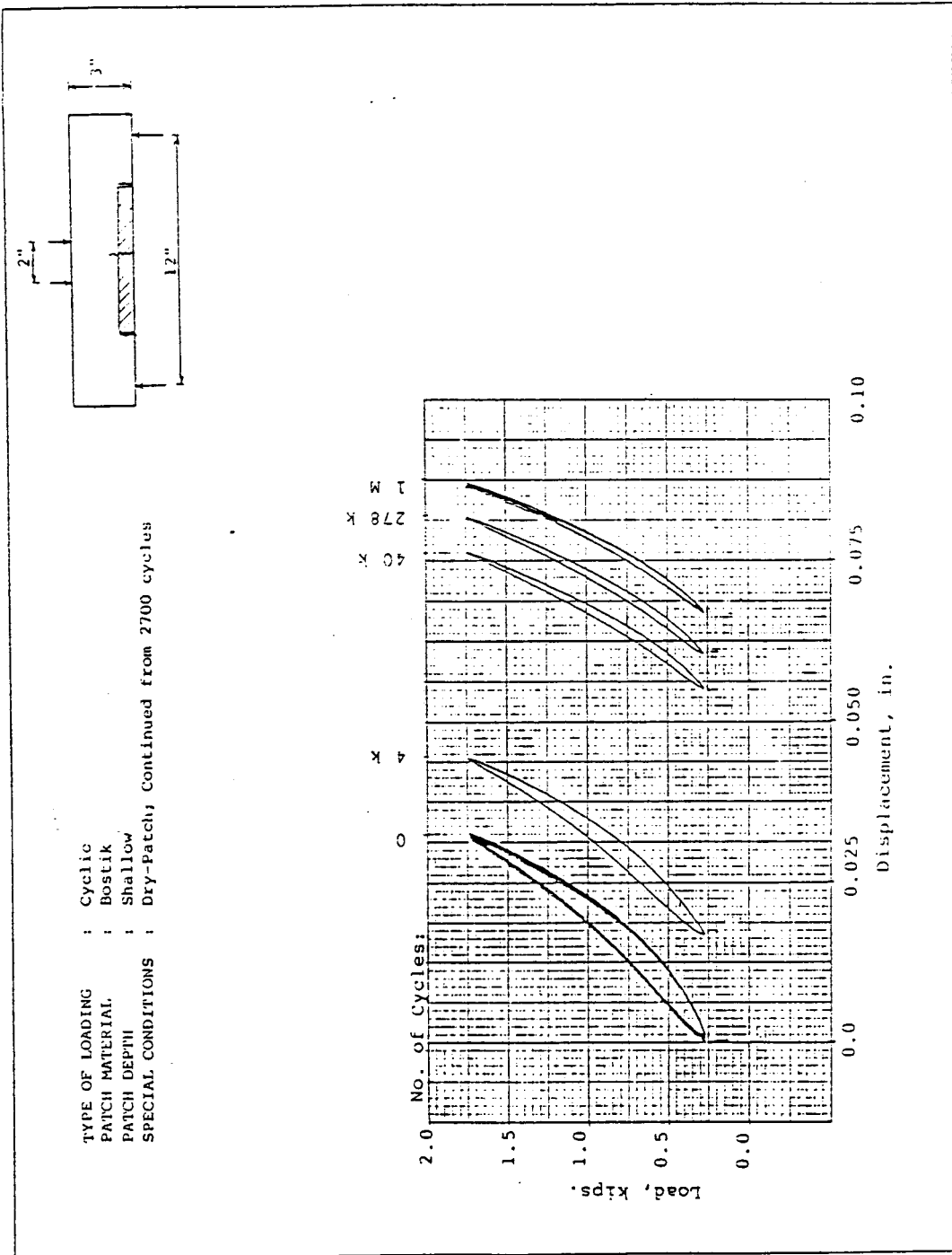


Fig. A2-2: (b) Cyclic Load vs. Deflection - Shallow Patch Depth Prism

P2S (Dry Patch, Continued from 2700 cycles)

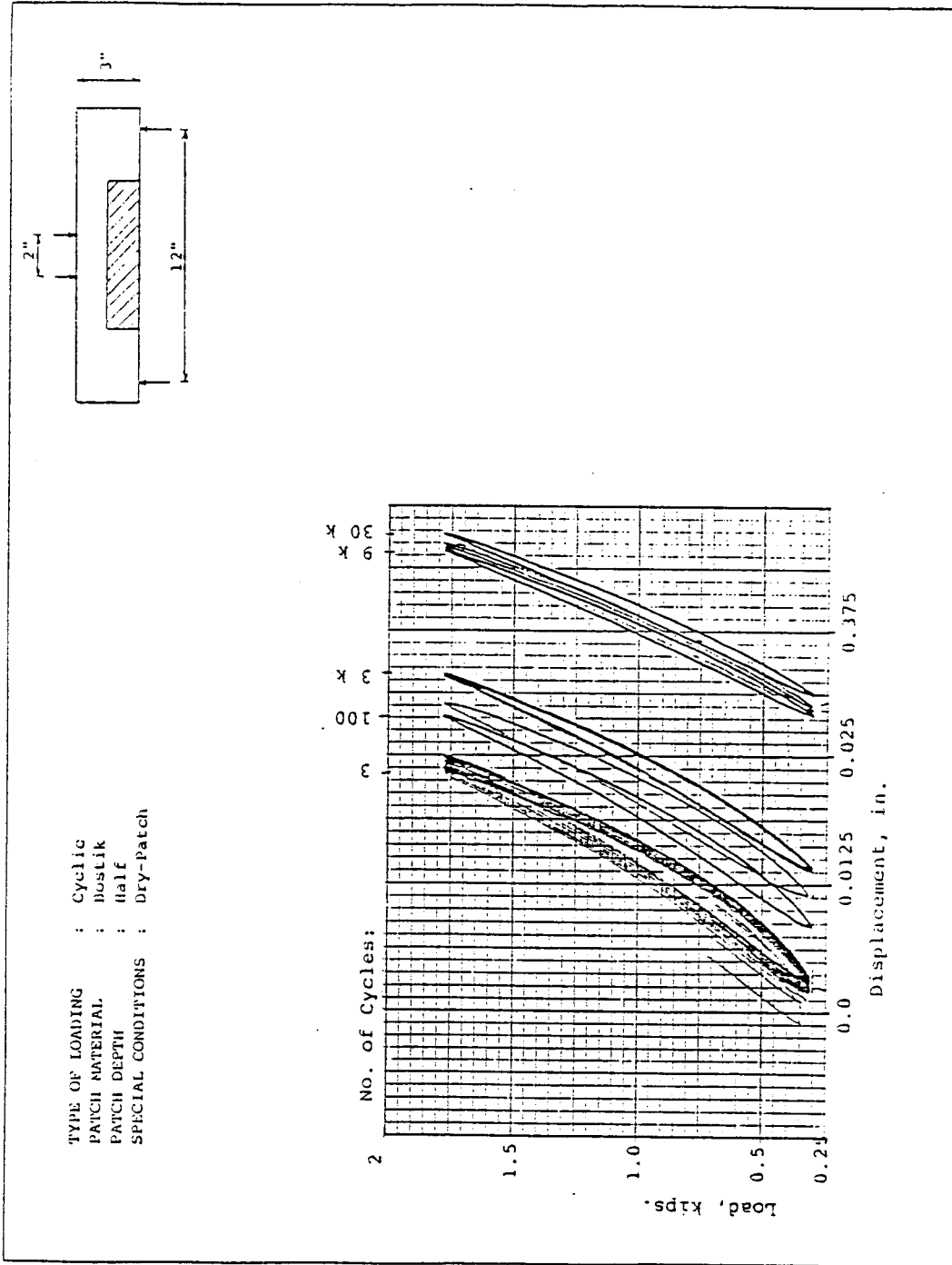


Fig. A2-3: Cyclic Load vs. Deflection - Half Patch Depth Prism Specimen
P2H1 (Dry Patch)

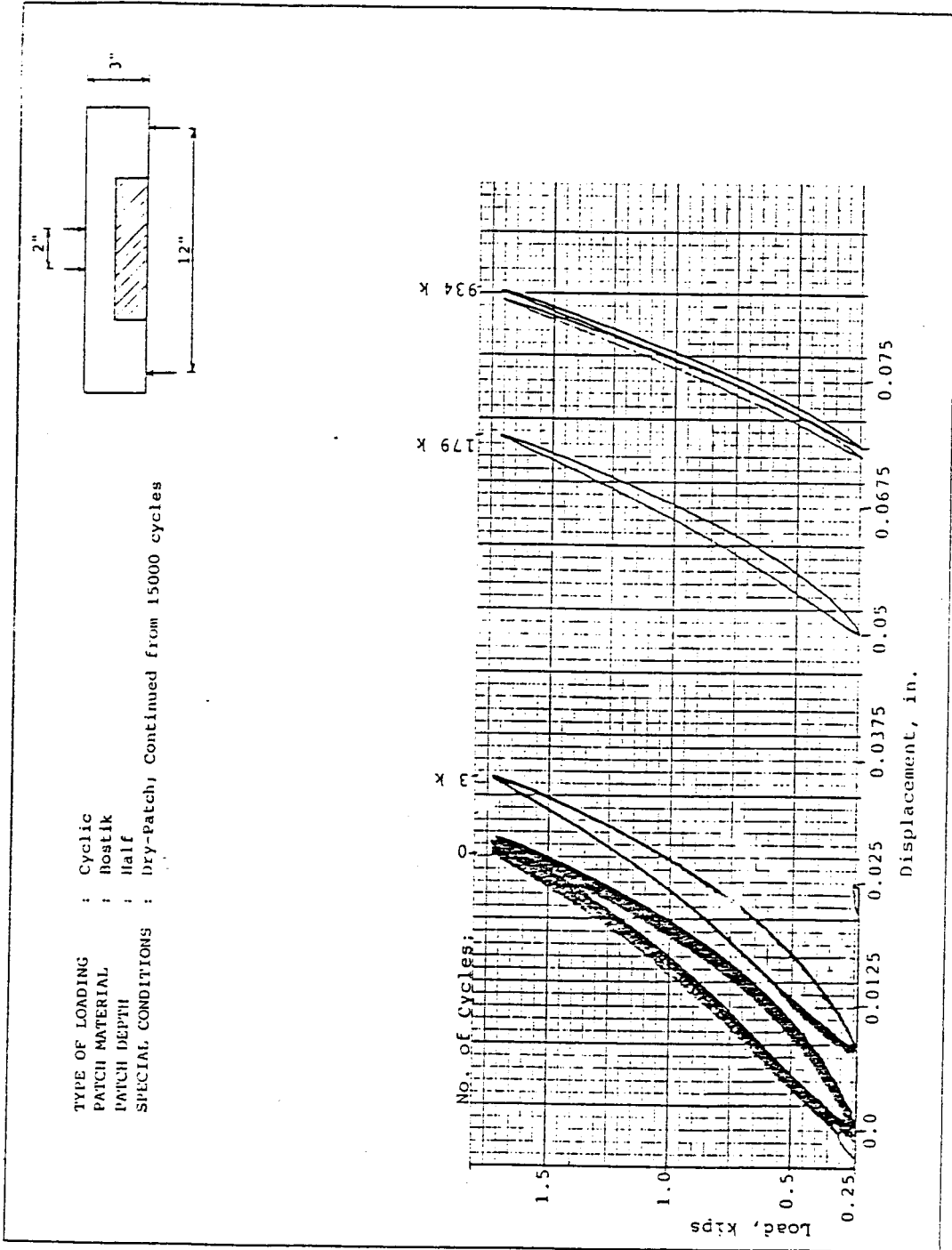


Fig. A2-4: Cyclic Load vs. Deflection - Half Patch Depth Prism Specimen P2H (Dry Patch, Continued from 15,000 cycles)

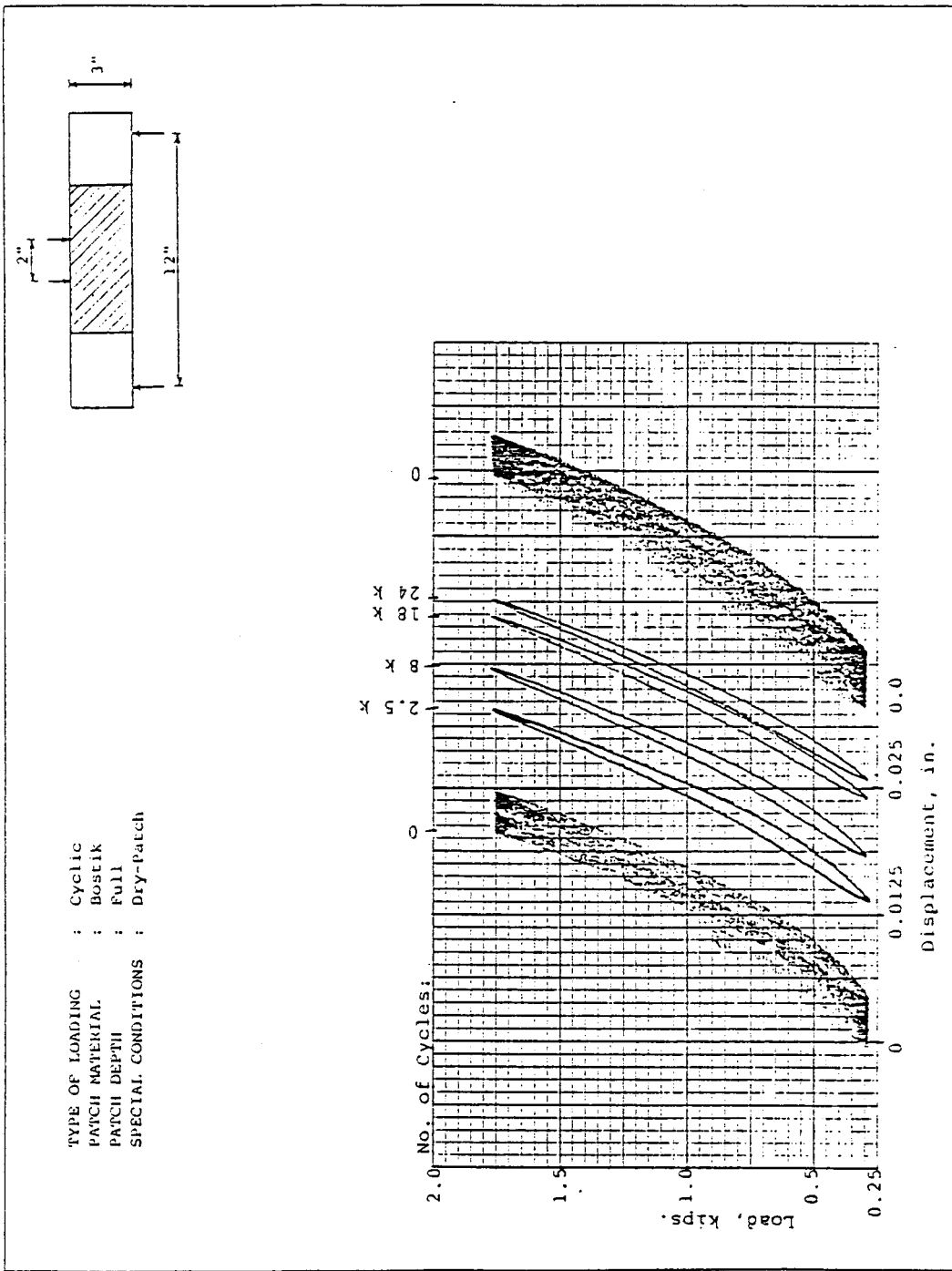


Fig. A2-5: Cyclic Load vs. Deflection - Full Depth Patch Prism Specimen P2F (Dry Patch)

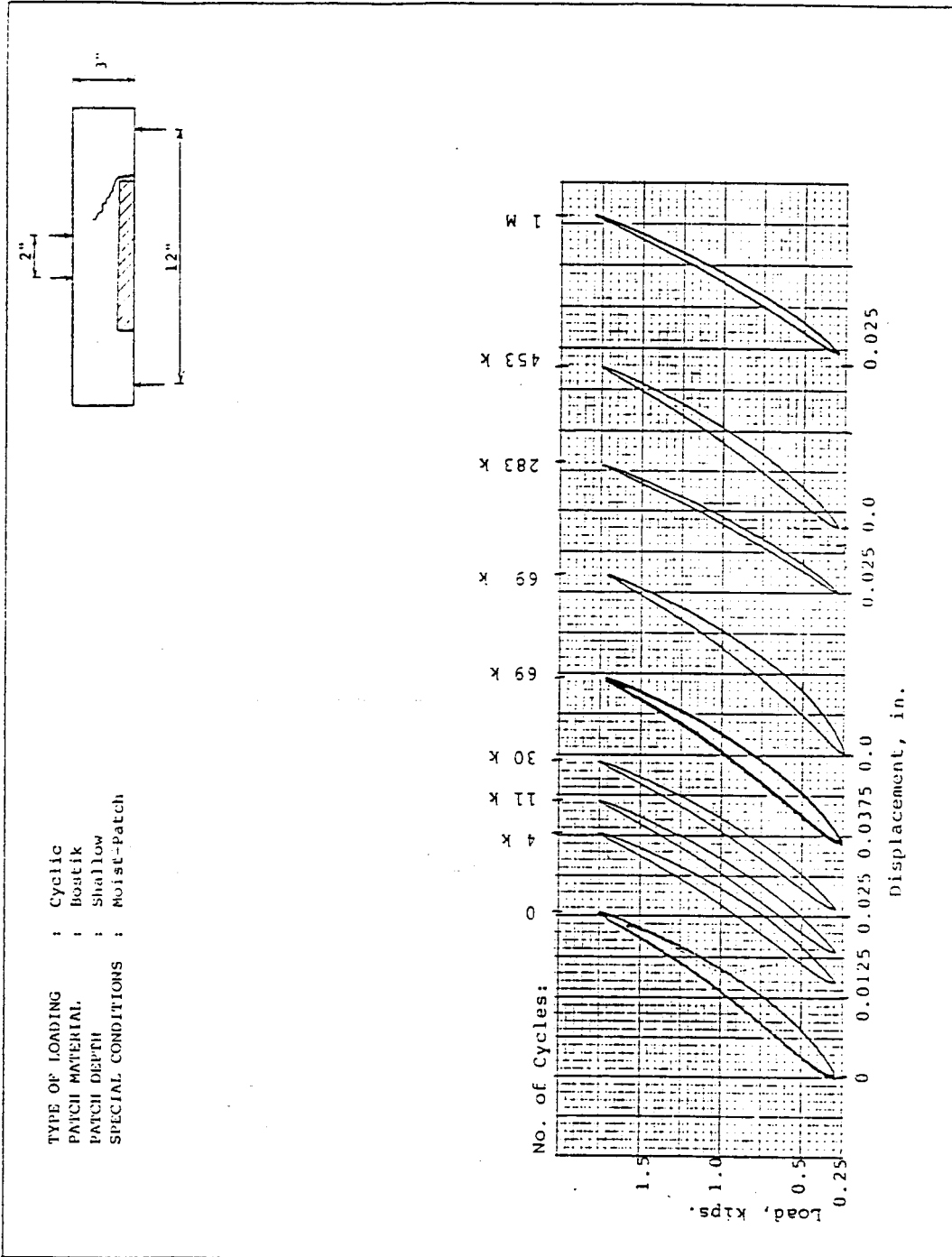


Fig. A2-6: Cyclic Load vs. Deflection - Shallow Depth Patch Prism
 Specimen
 P2S (Moist Patch)

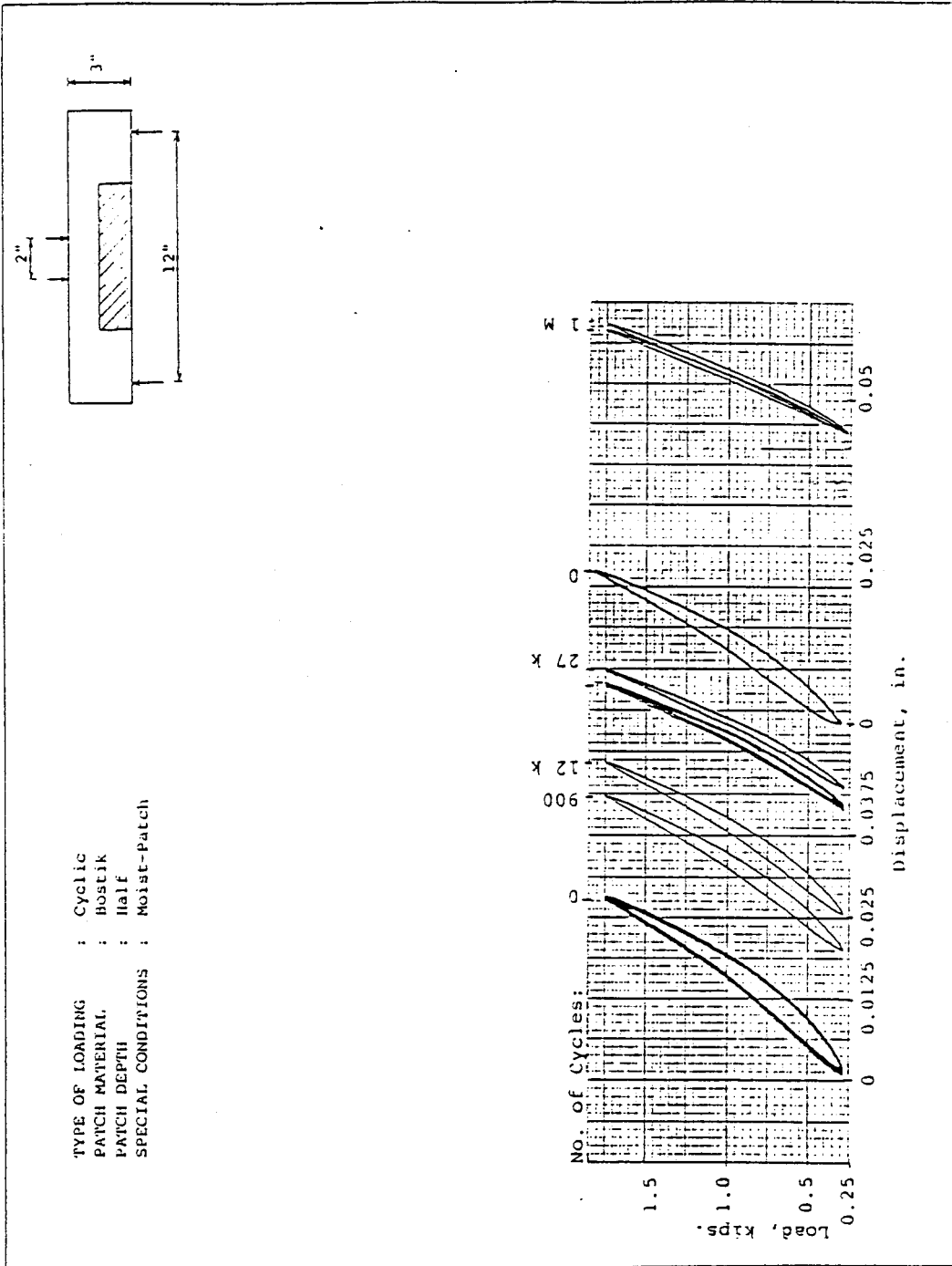


Fig. A2-7: Cyclic Load vs. Deflection - Half Depth Patch Prism Specimen
P2H (Moist Patch)

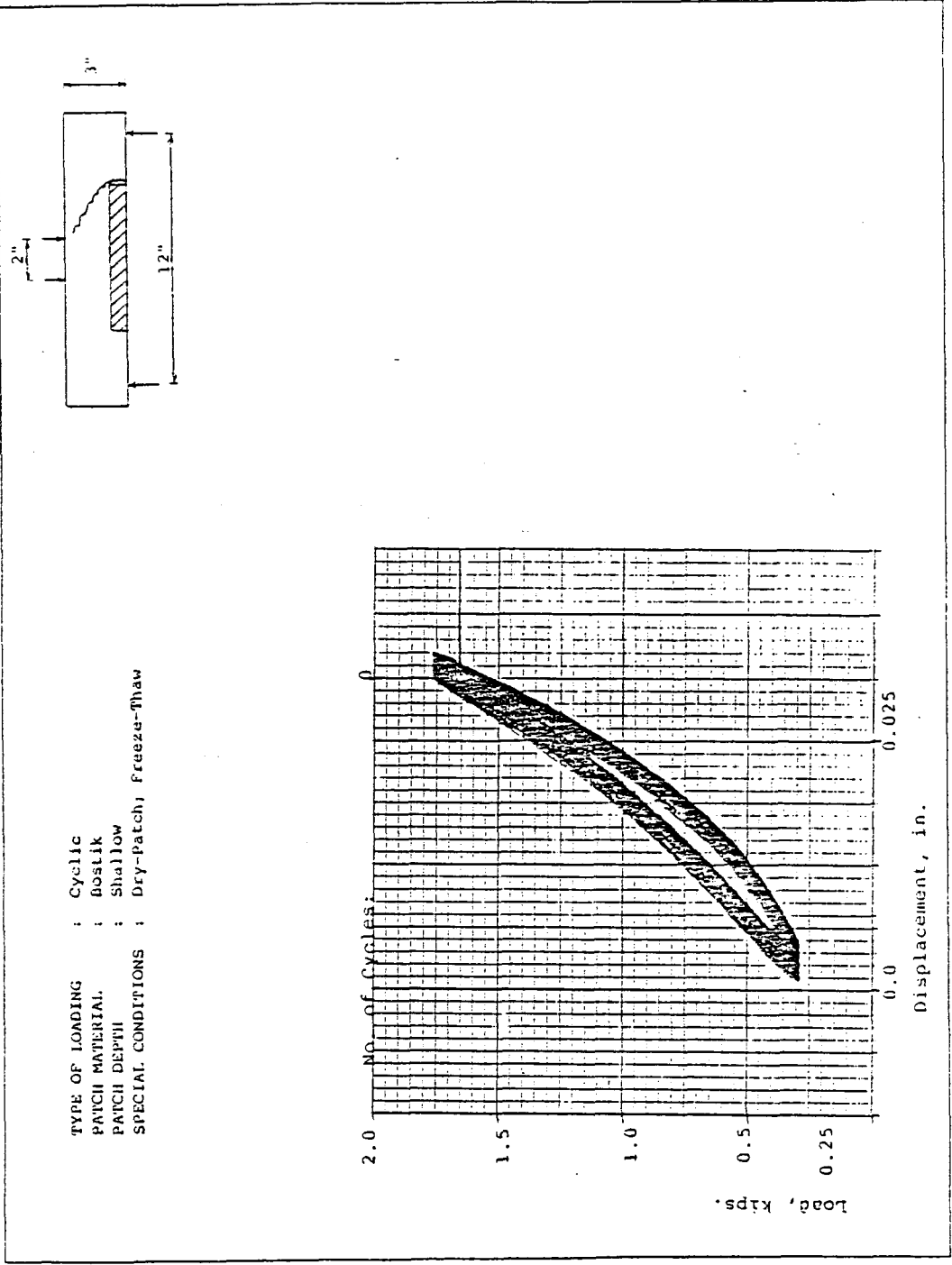


Fig. A2-9: Cyclic Load vs. Deflection - Shallow Depth Patch Prism
Specimen
P2S (Dry Patch, Freeze-Thaw)

TYPE OF LOADING : Cyclic
 PATCH MATERIAL : BOSLIK
 PATCH DEPTH : HALF
 SPECIAL CONDITIONS : Dry-Patch, Freeze-Thaw

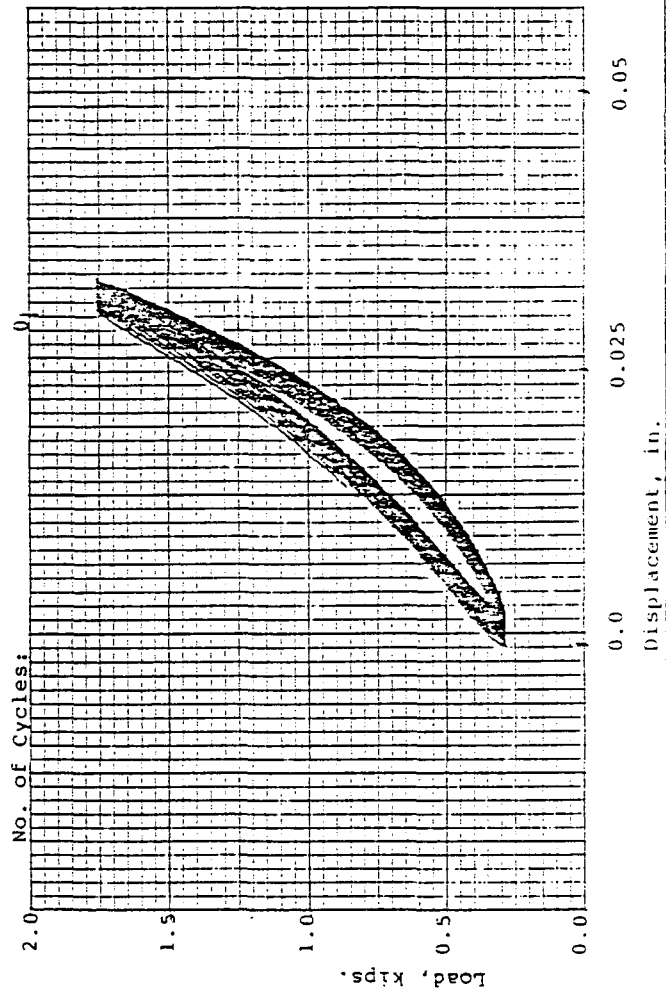
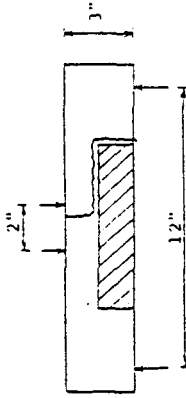


Fig. A2-10: Cyclic Load vs. Deflection - Half Depth Patch Prism Specimen
 P211 (Dry Patch, Freeze-Thaw)

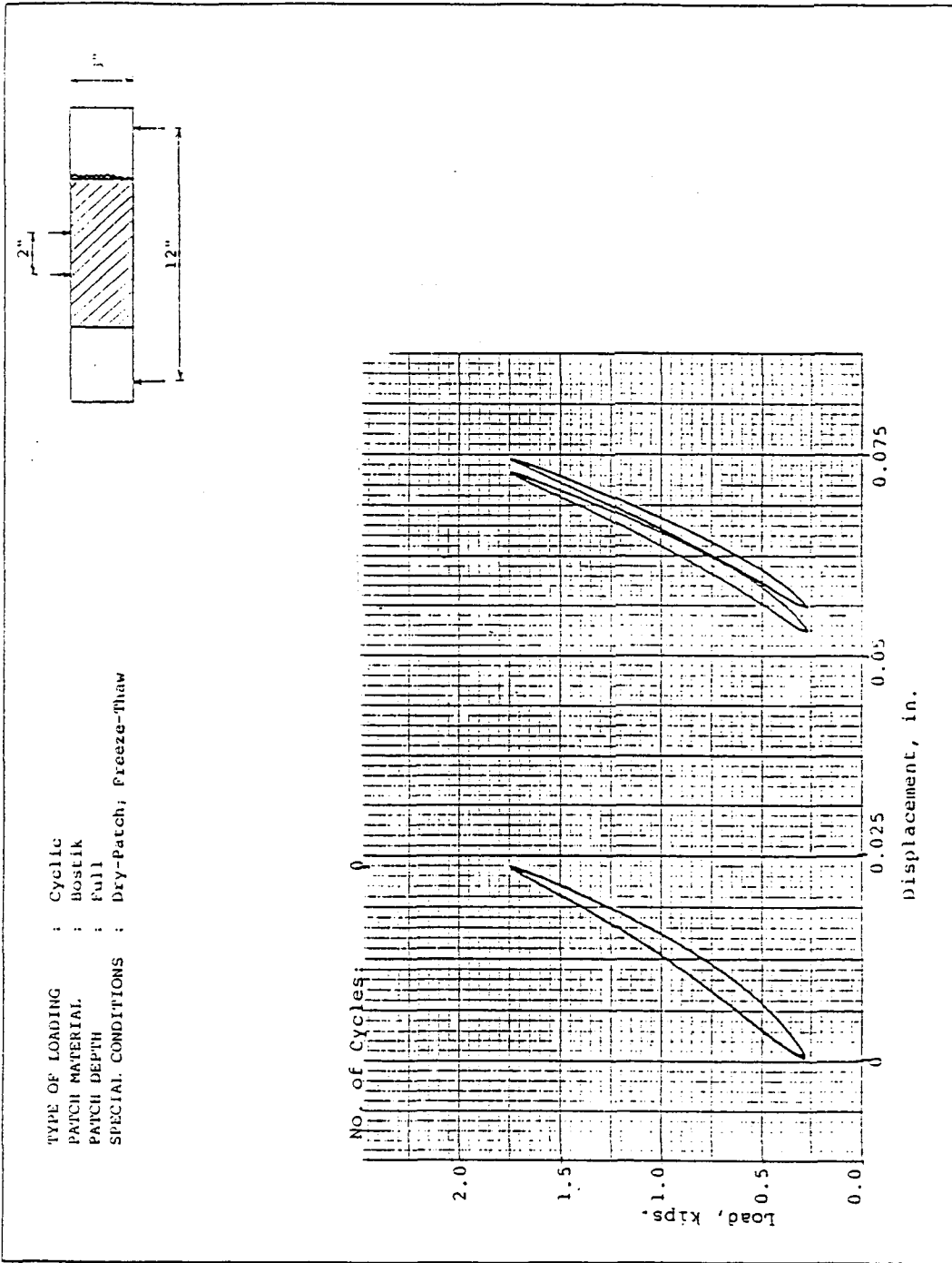


Fig. A2-II: Cyclic Load vs. Deflection - Full Depth Patch Prism Specimen
P2F (Dry Patch, Freeze-Thaw)

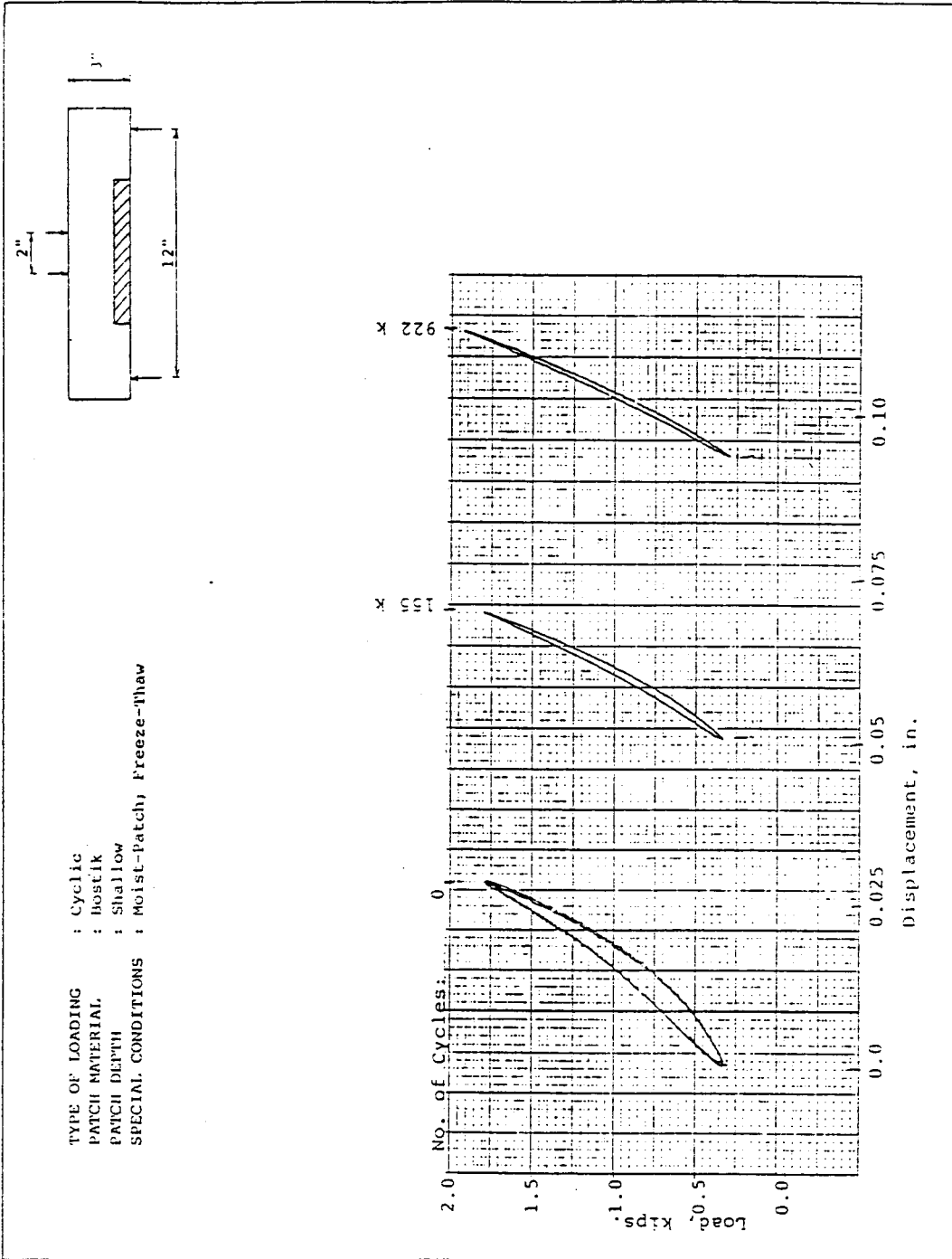


Fig. A2-12: Cyclic Load vs. Deflection - Shallow Depth Patch Prism
Specimen
P2S (Moist Patch, Freeze-Thaw)

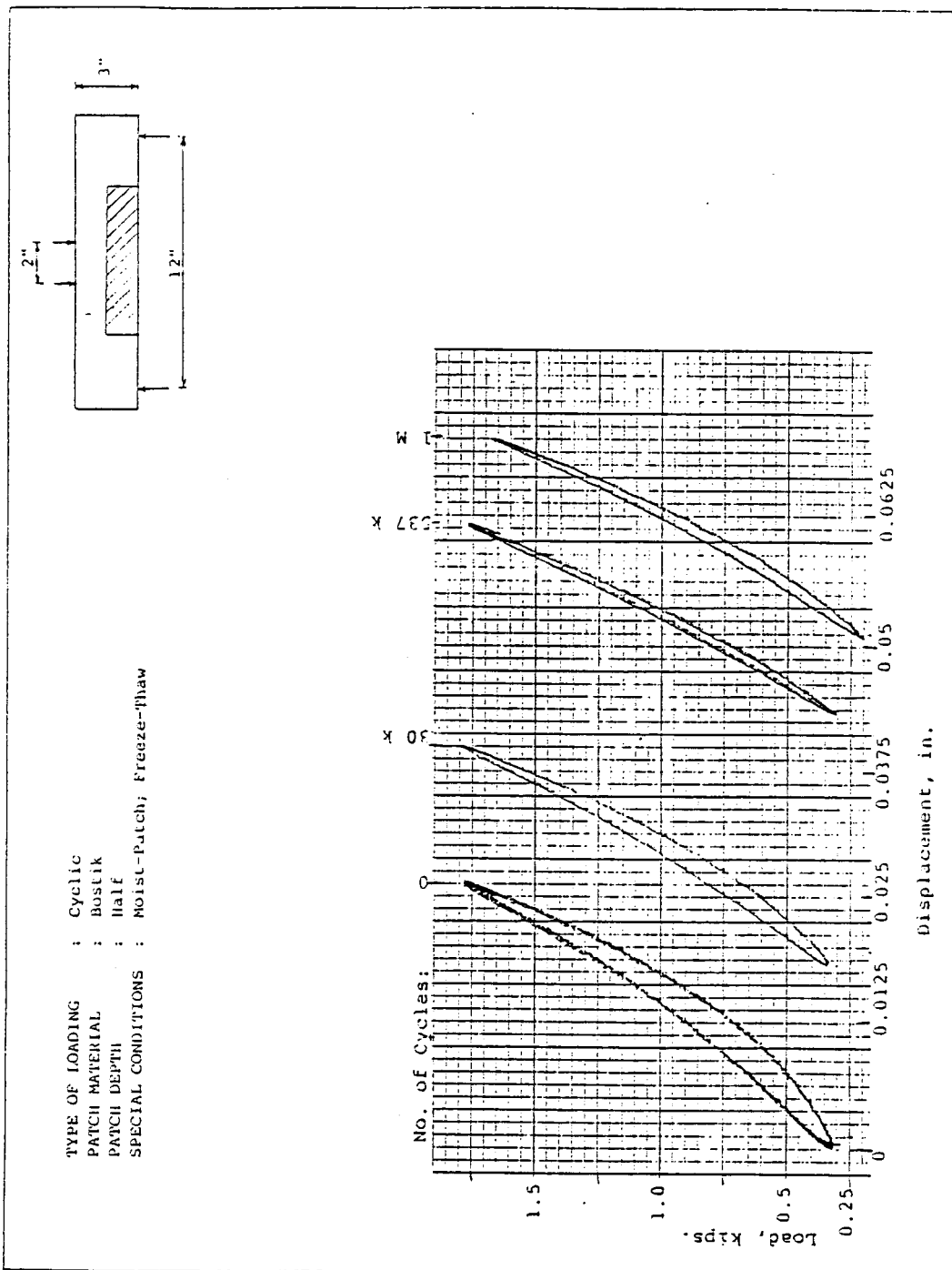


Fig. A2-13: Cyclic Load vs. Deflection - Half Depth Patch Prism Specimen
 P2H (Moist Patch, Freeze-Thaw)

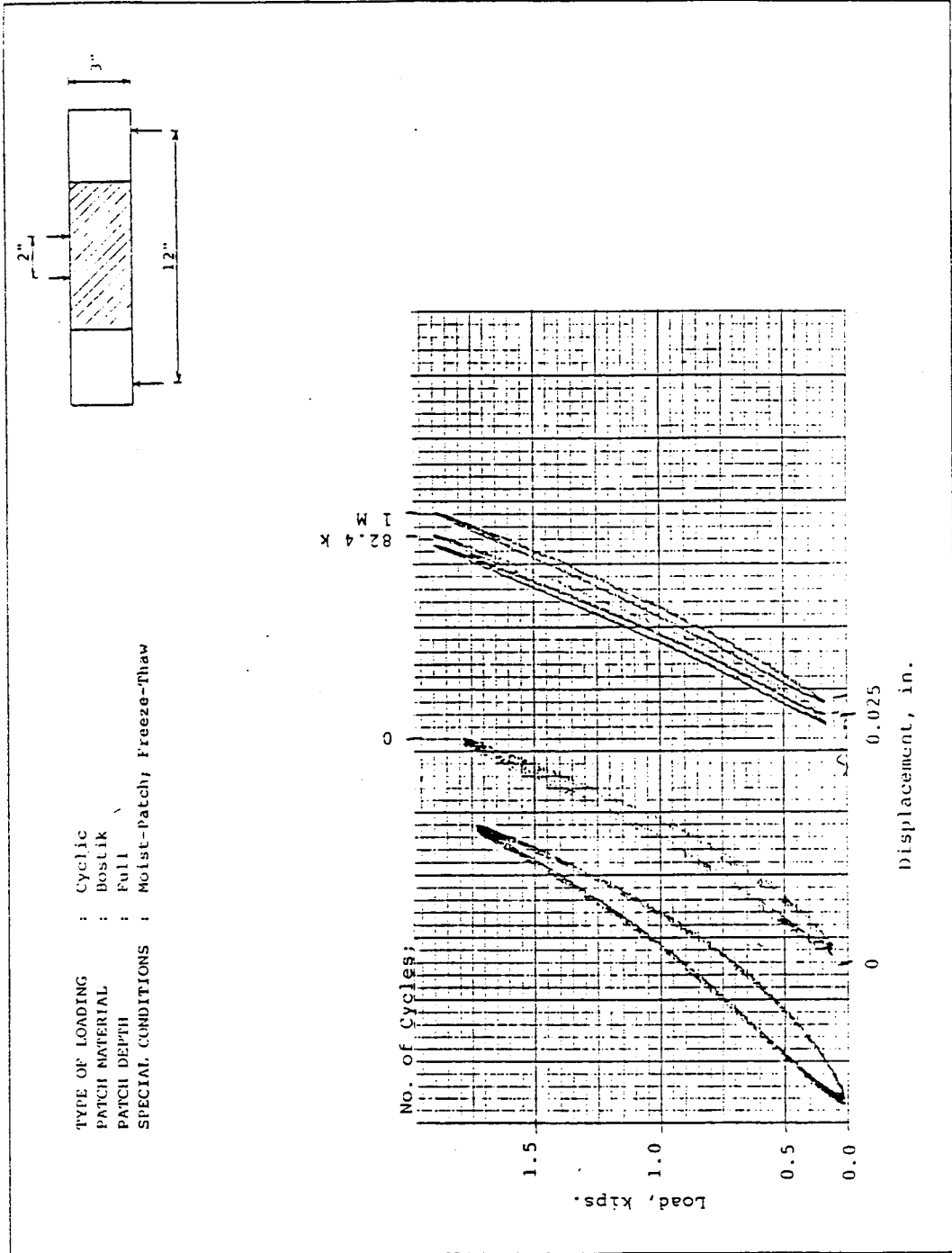


Fig. A2-14: Cyclic Load vs. Deflection - Full Depth Patch Prism Specimen
 P2F (Moist Patch, Freeze-Thaw)

APPENDIX B

STATIC AND CYCLIC TESTS OF SLAB SPECIMENS

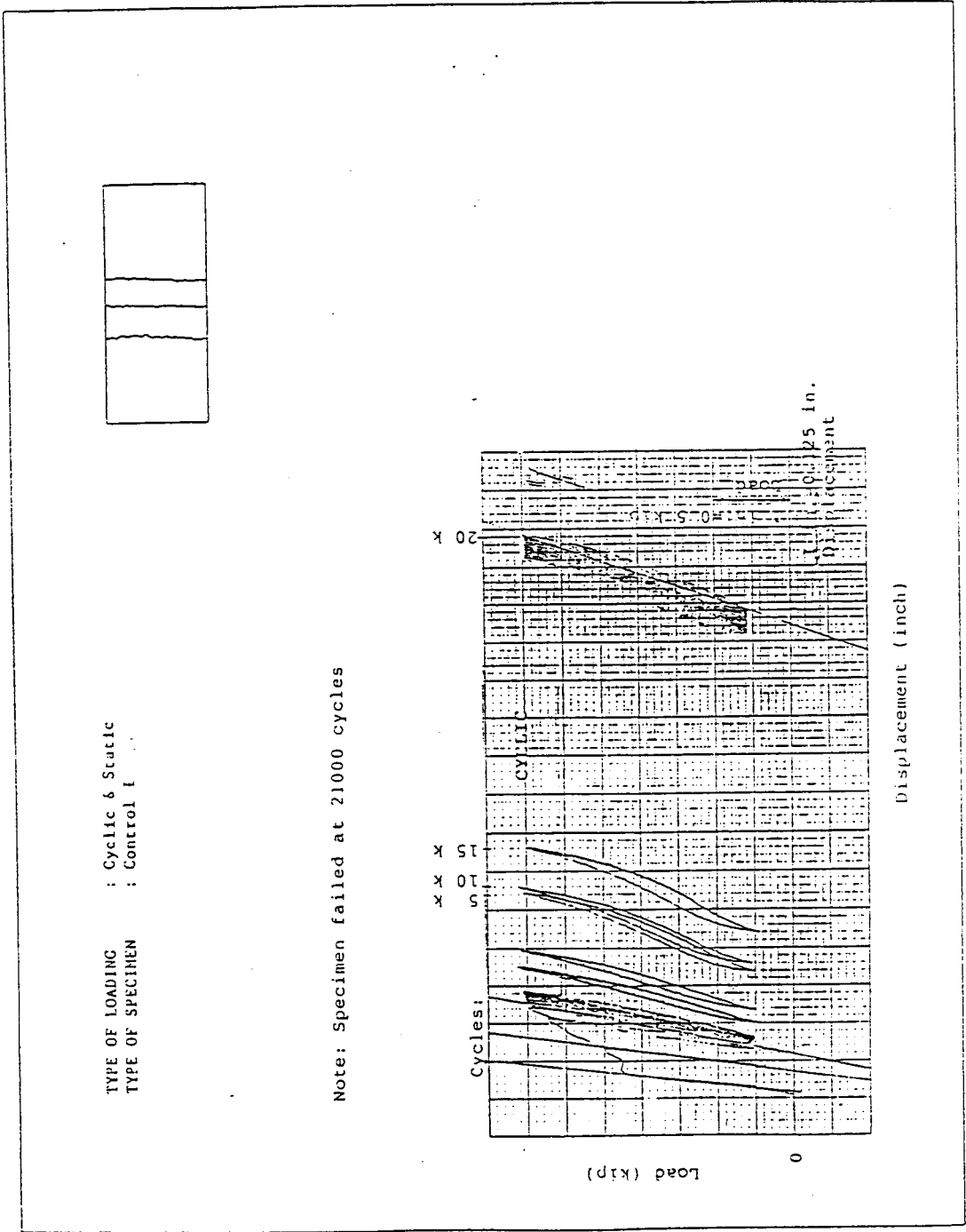


Fig. B-1: Slab Load vs. Deflection - Control Specimen, Cyclic and Static Loading

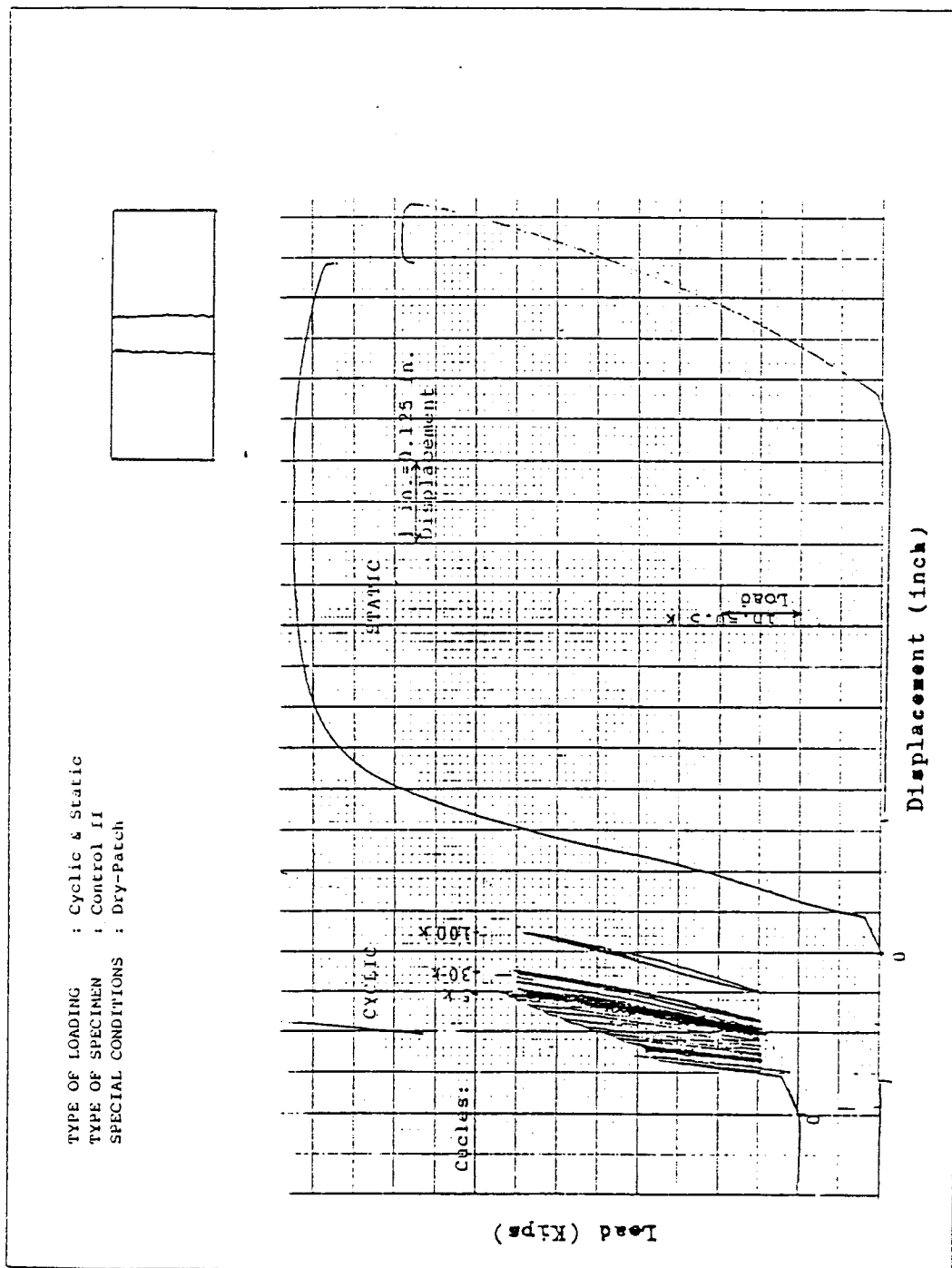
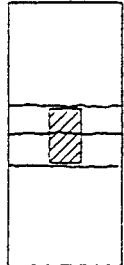


Fig B-2: Slab Load vs. Deflection - Control Specimen, Cyclic and Static Loading

TYPE OF LOADING : Cyclic & Static
 PATCH MATERIAL : Set-45
 SPECIAL CONDITIONS : Dry-Patch ; Smooth Surface; Long Patch



Note: Specimen failed at 24510 cycles

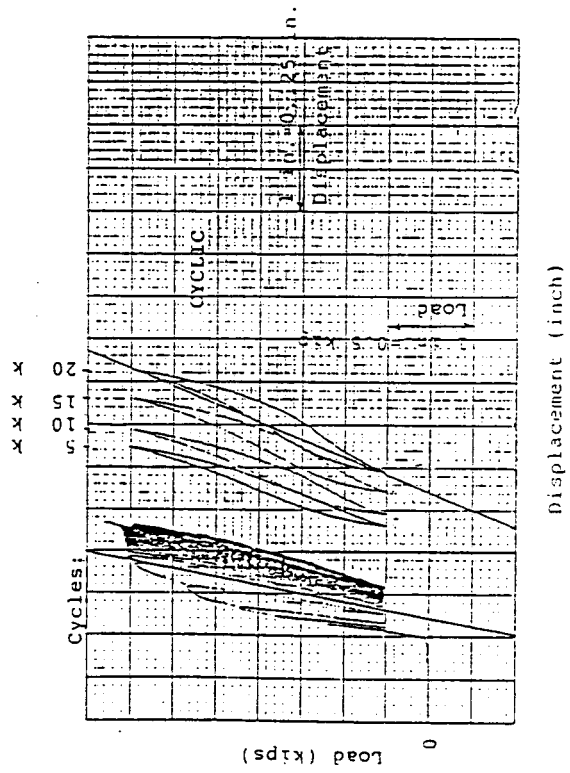


Fig. B-3: Slab Load vs. Deflection - Set -45, long smooth surface patch, cyclic and static loading

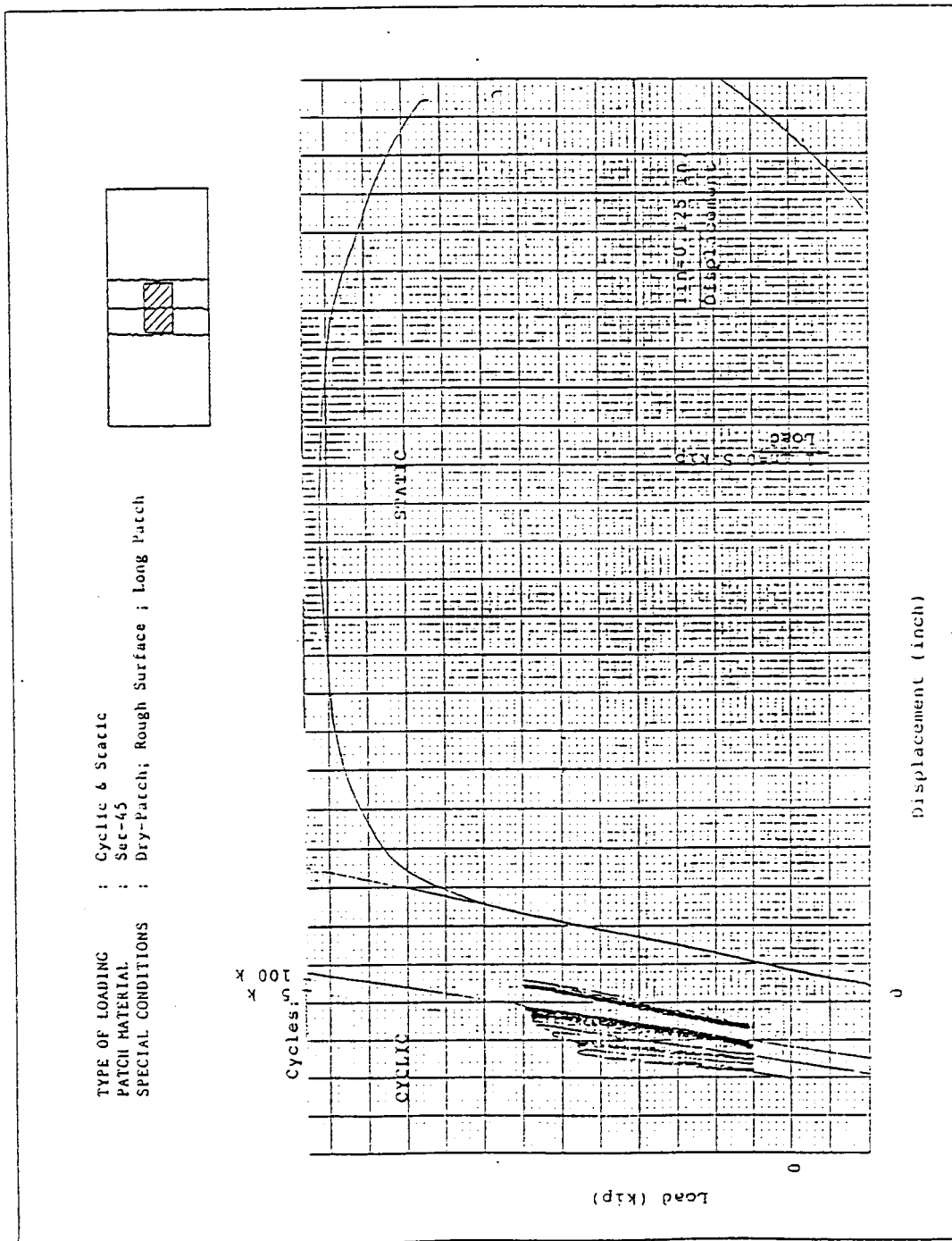


Fig. B-4: Slab Load vs. Deflection, - Set-45, long rough surface patch, cyclic static loading

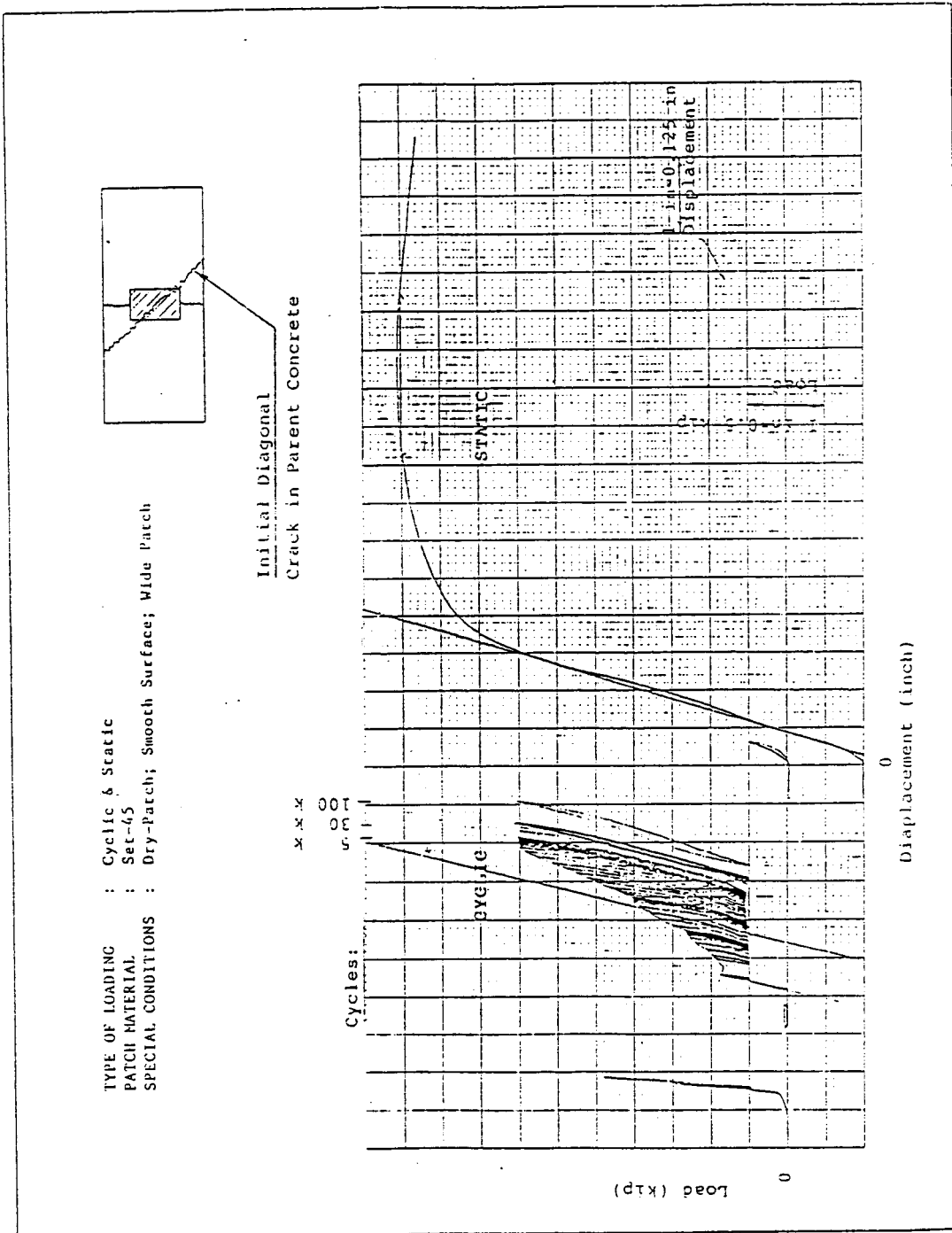


Fig. B-5: Slab Load vs. Deflection - Set 45, wide smooth surface patch, cyclic and static loading

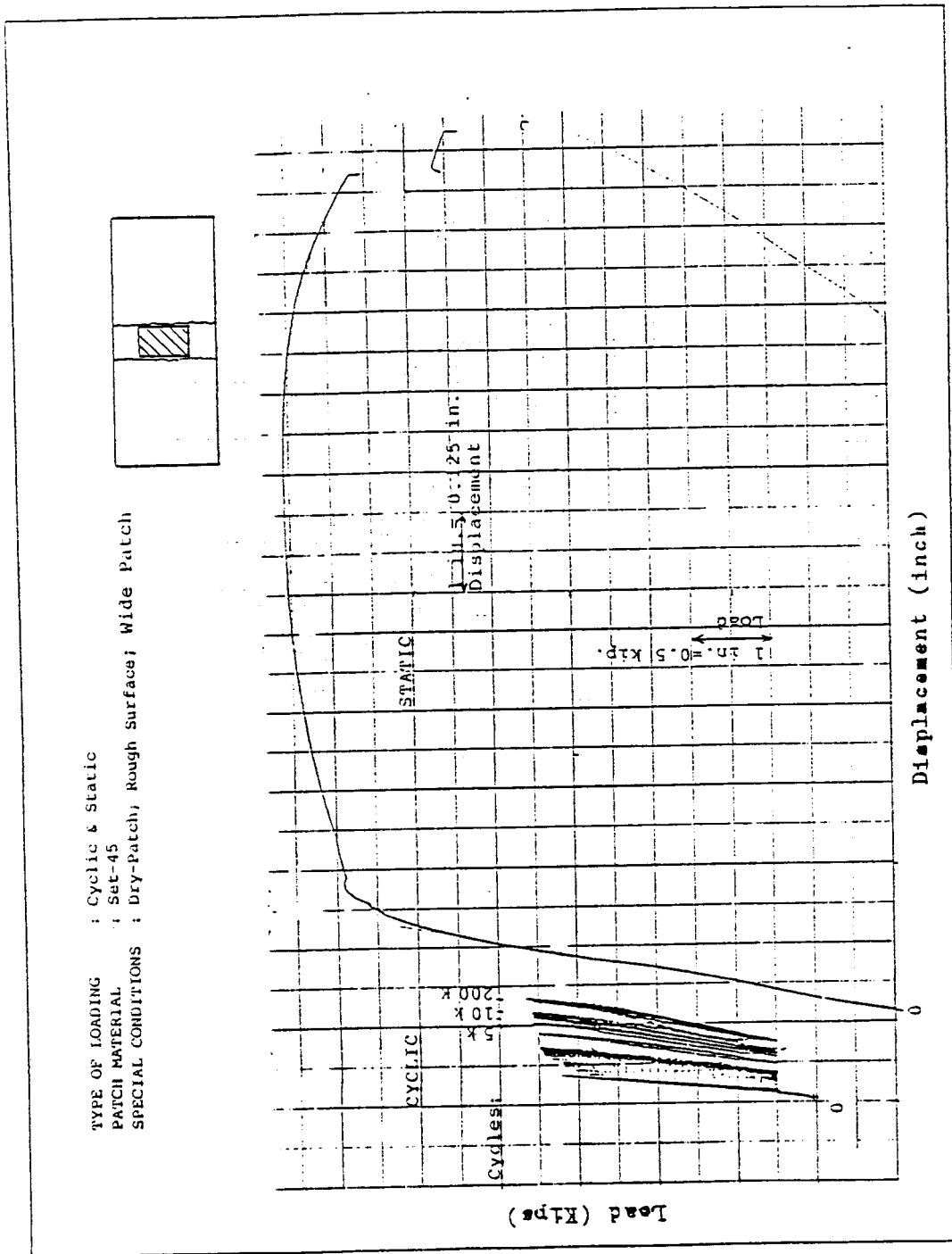


Fig. B-6: Slab Load vs. Deflection - Set-45, wide rough surface patch, cyclic and static loading

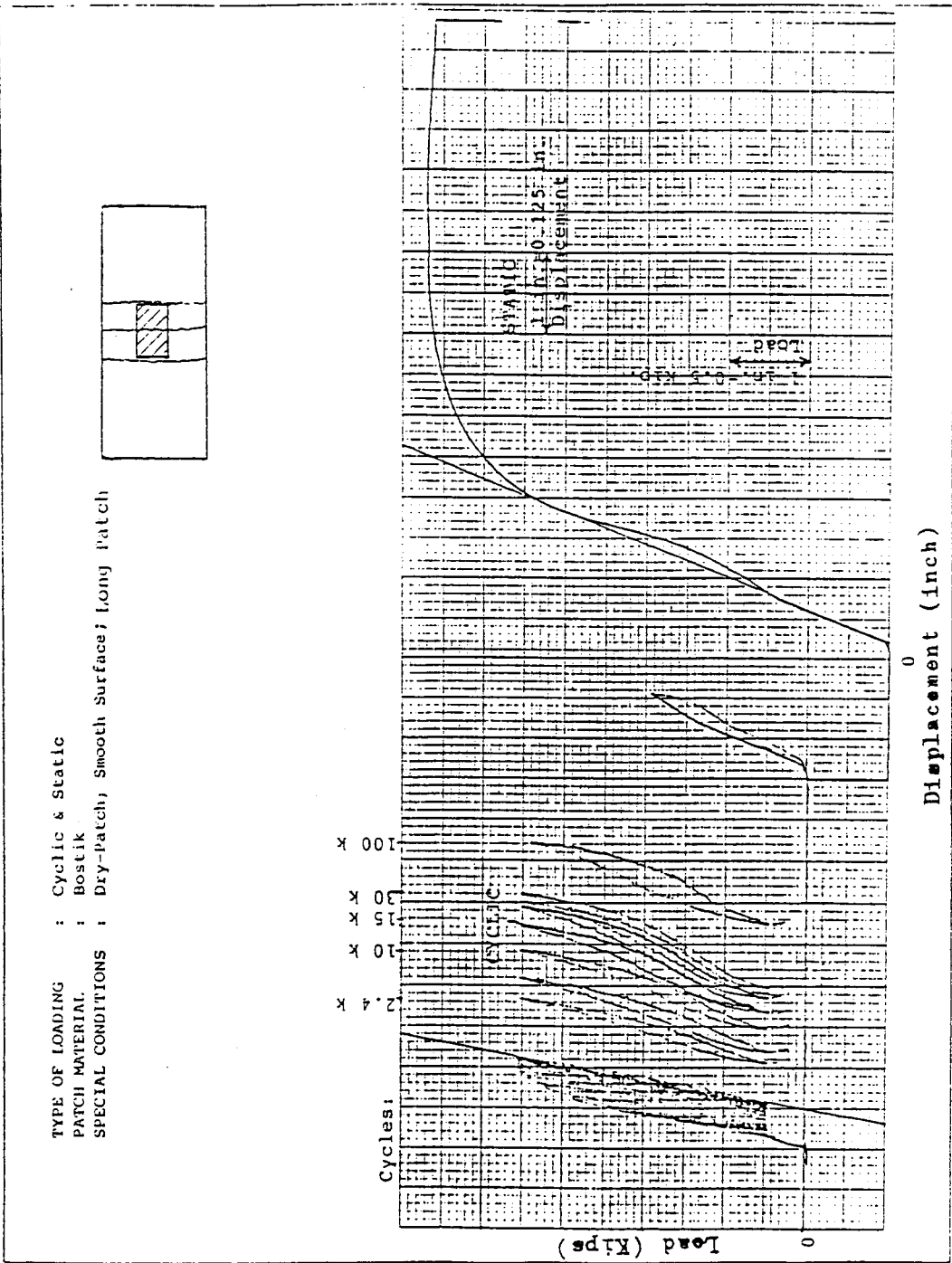


Fig. B-7: Slab Load vs. Deflection, Bostik, long smooth surface patch, cyclic and static loading

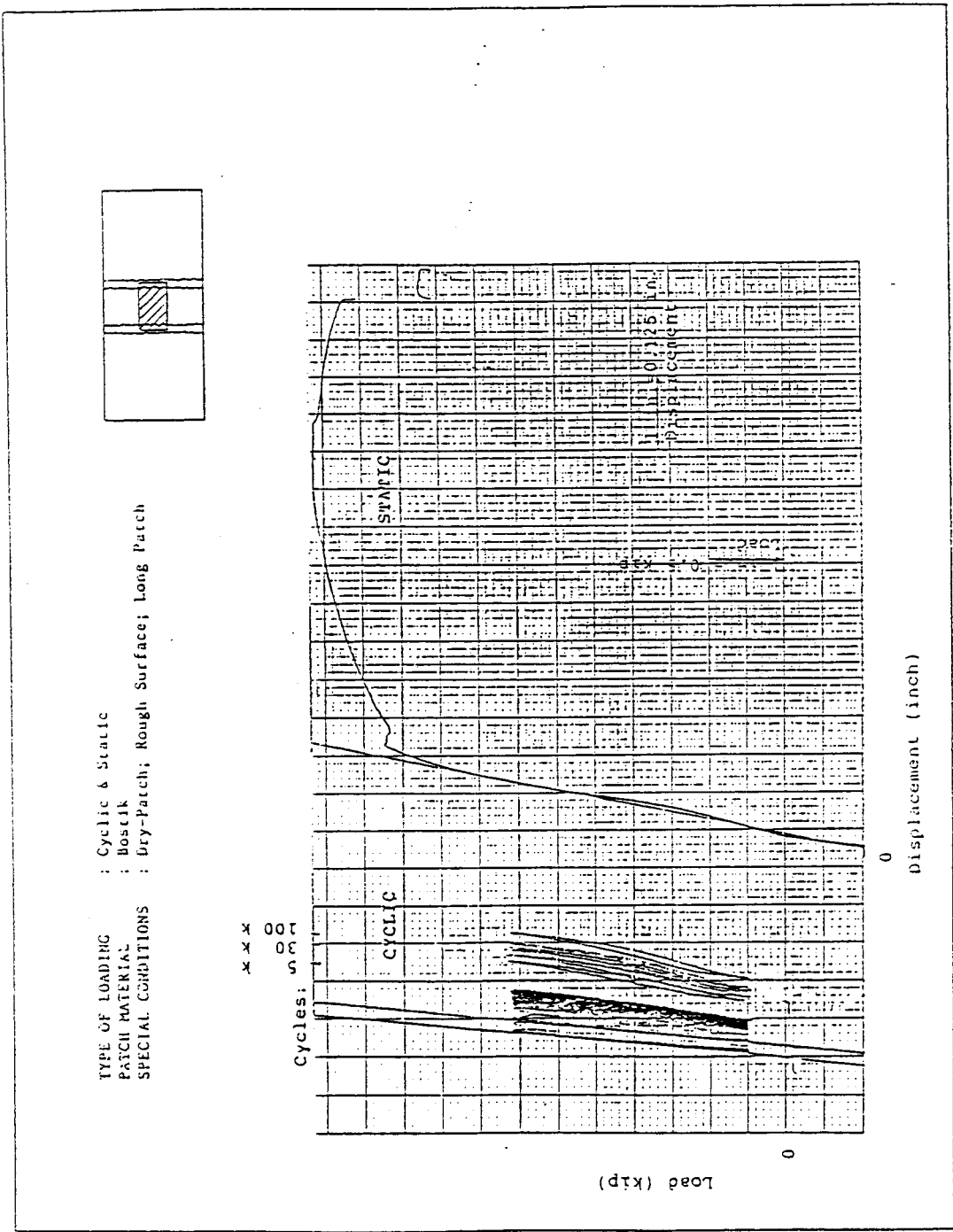
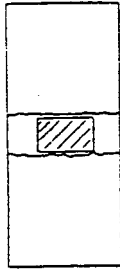


Fig. B-8. Slab Load vs. Deflection - Bostok, long rough surface patch, cyclic and static loading



TYPE OF LOADING : Cyclic & Static
 PATCH MATERIAL : Bostik
 SPECIAL CONDITIONS : Dry-Patch; Smooth Surfaces; Wide Patch

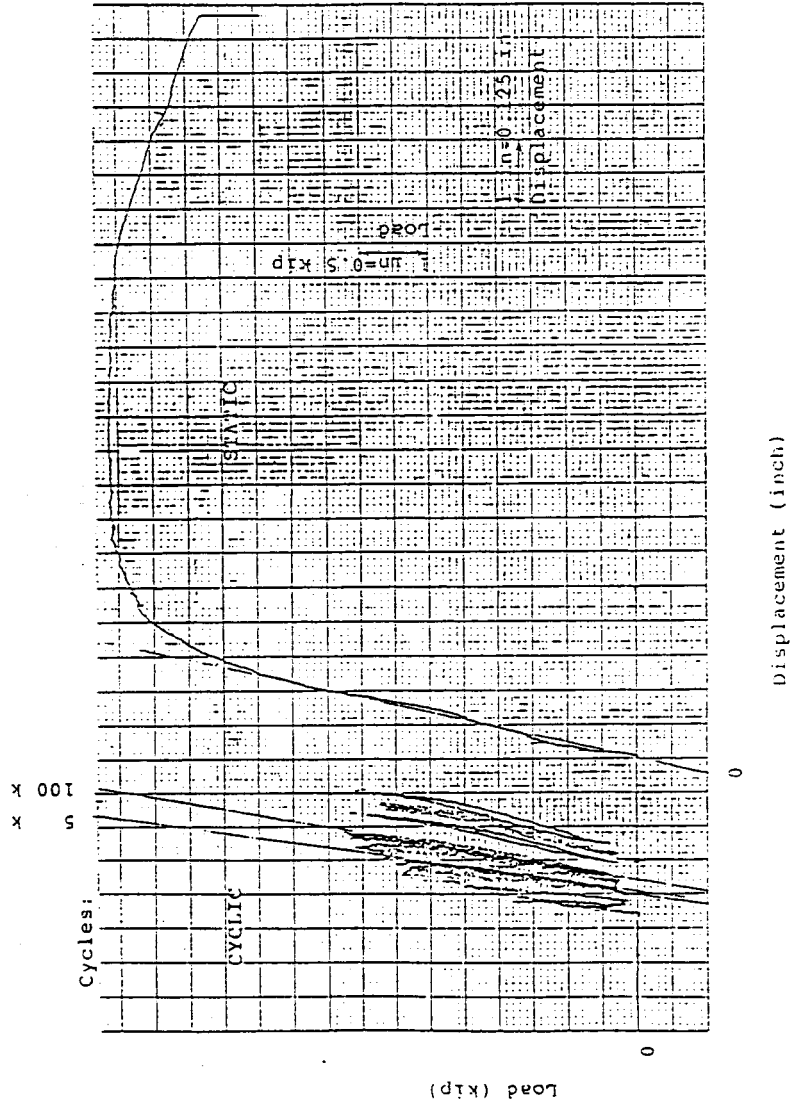


Fig. B-9: Slab Load vs. Deflection - Bostok, wide smooth surface patch, cyclic and static loading

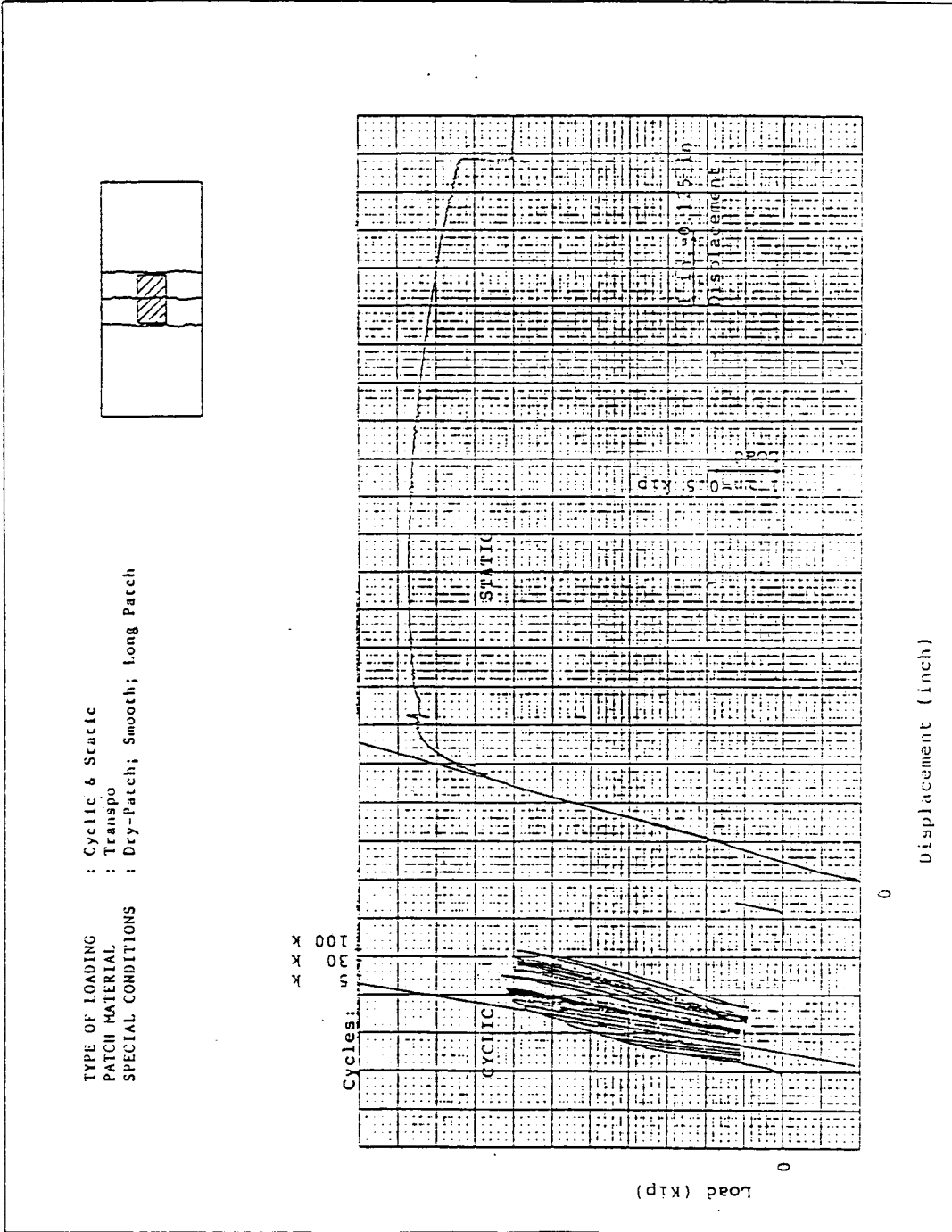


Fig. B-II: Slab Load vs. Deflection - Transpo, long smooth surface patch, cyclic and static loading.

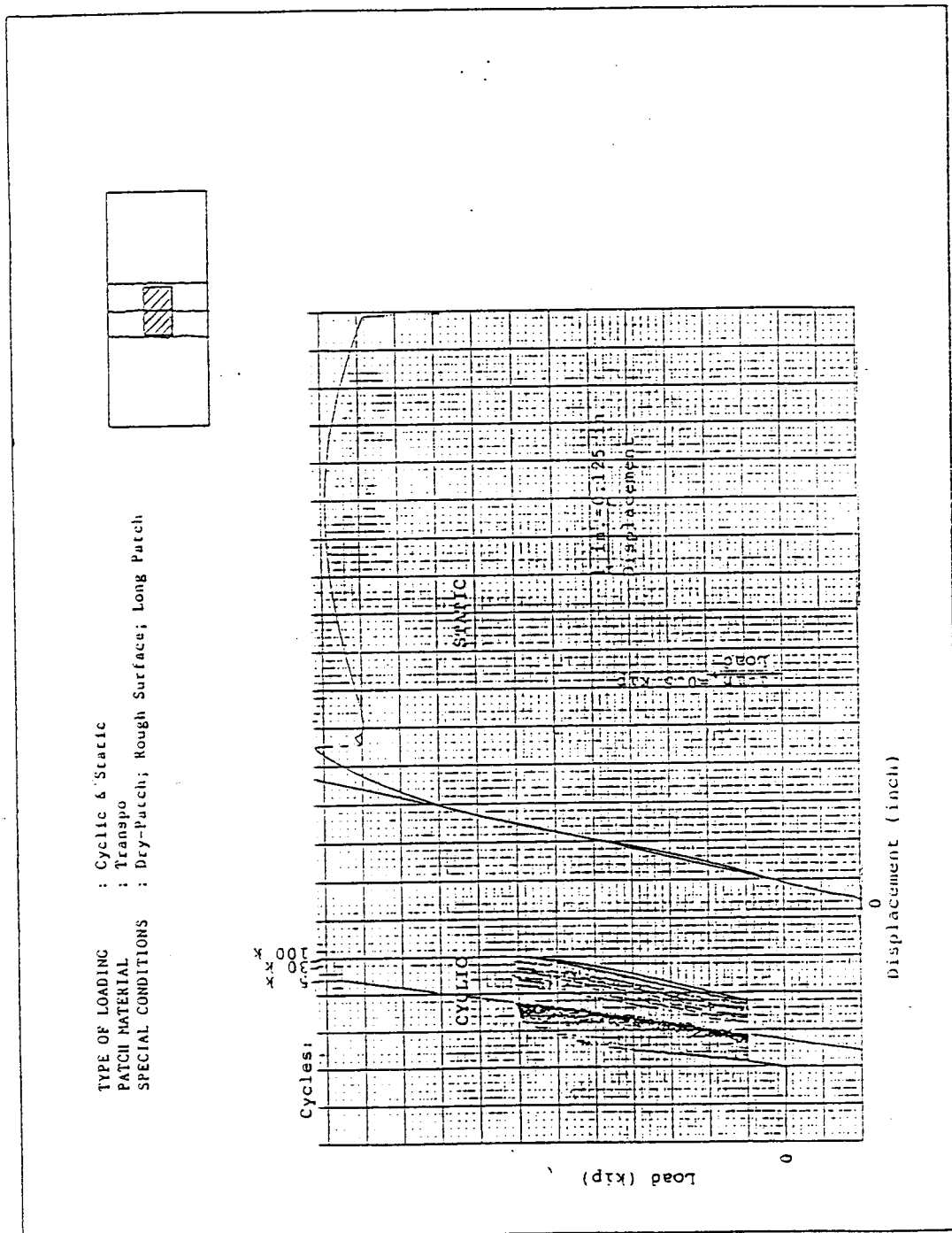


Fig. B-12: Slab Load vs. Deflection - Transpo, long rough surface patch, cyclic and static loading.

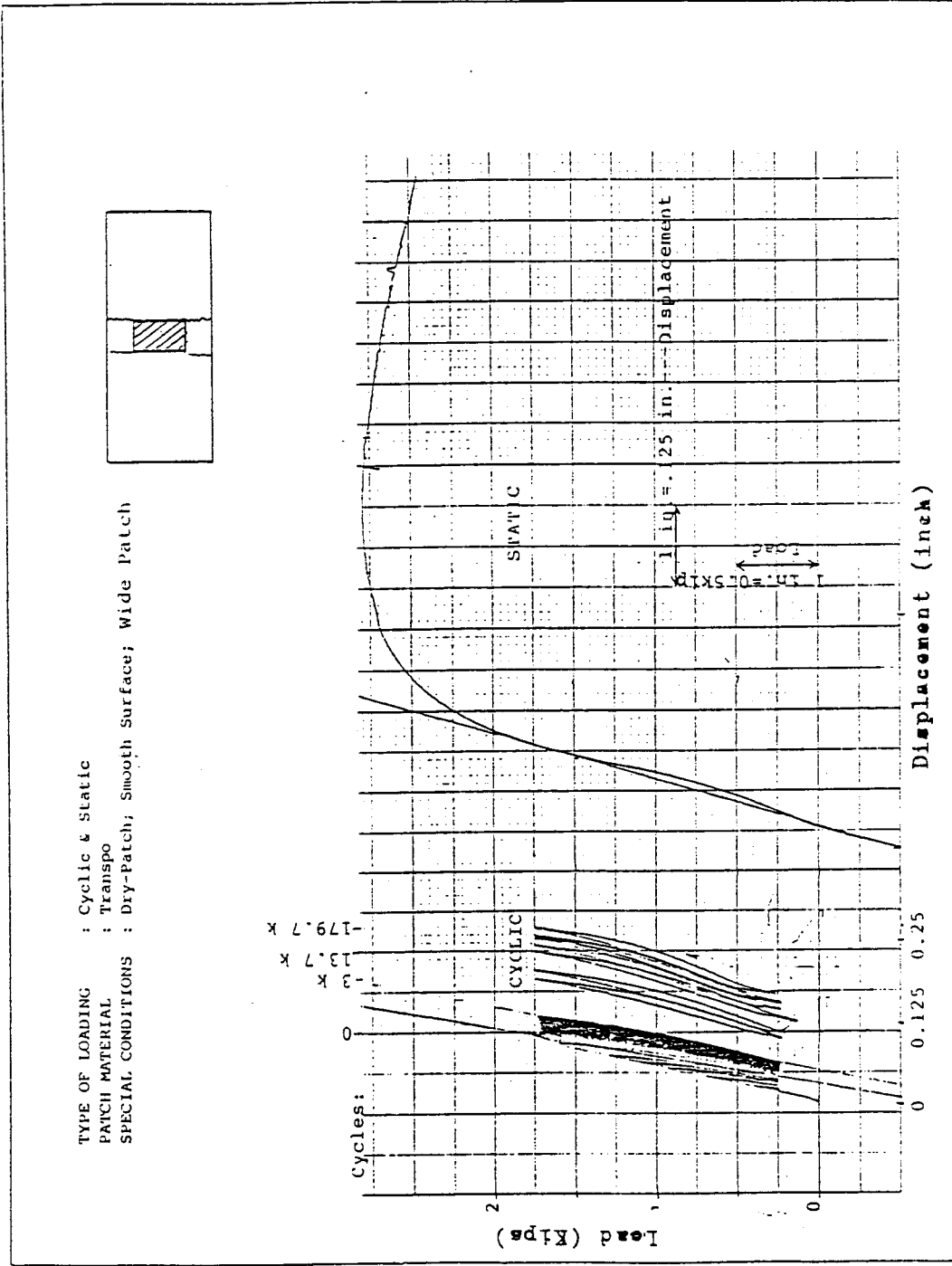


Fig. B-13: Slab Load vs. Deflection - MMA, wide smooth patch, cyclic and static loading

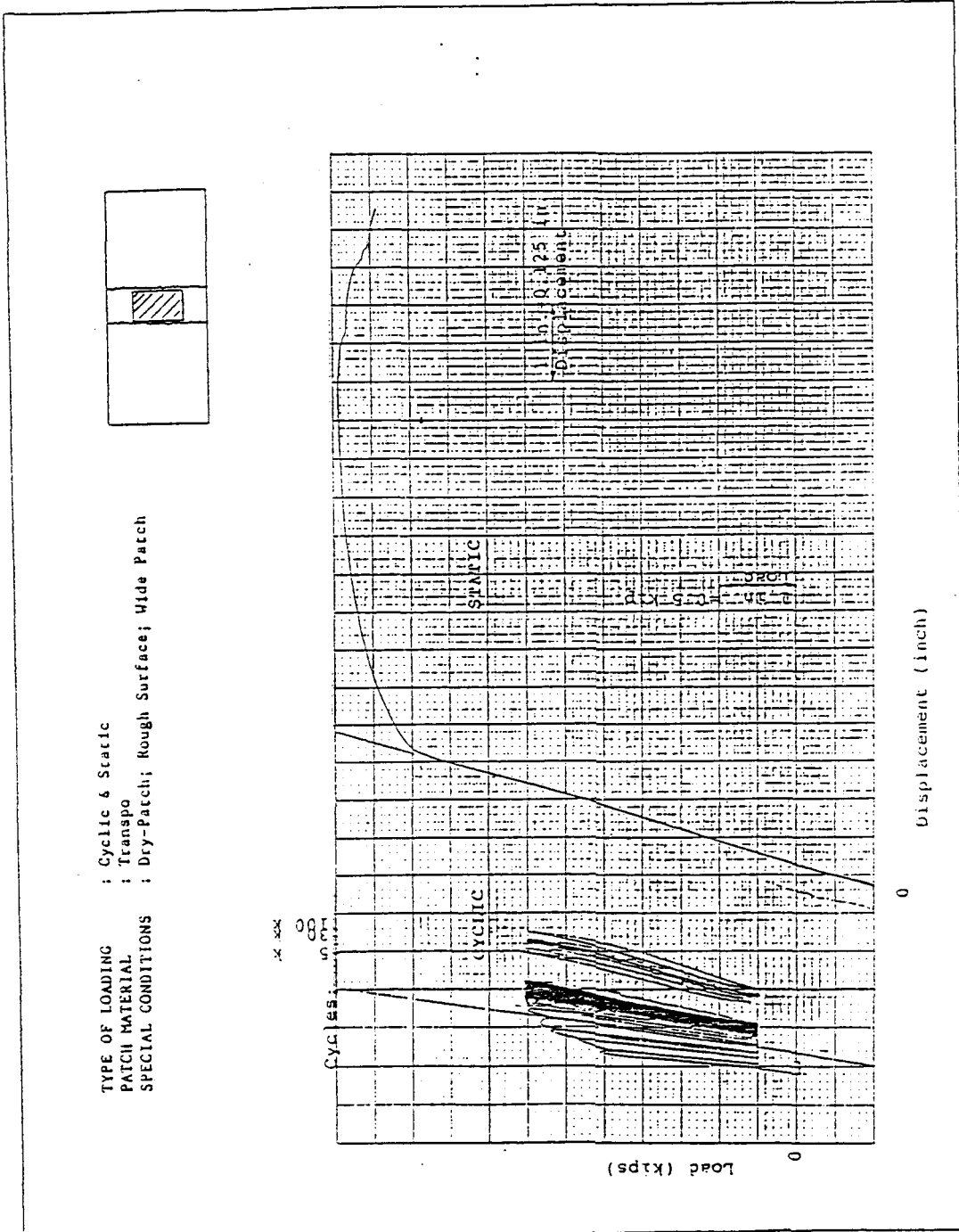


Fig. B-14: Slab Load vs. Deflection - Transpo, wide rough surface patch, cyclic and static loading.

APPENDIX C

FAILED SLAB SPECIMENS

Fig. C-2: Test Slab C2

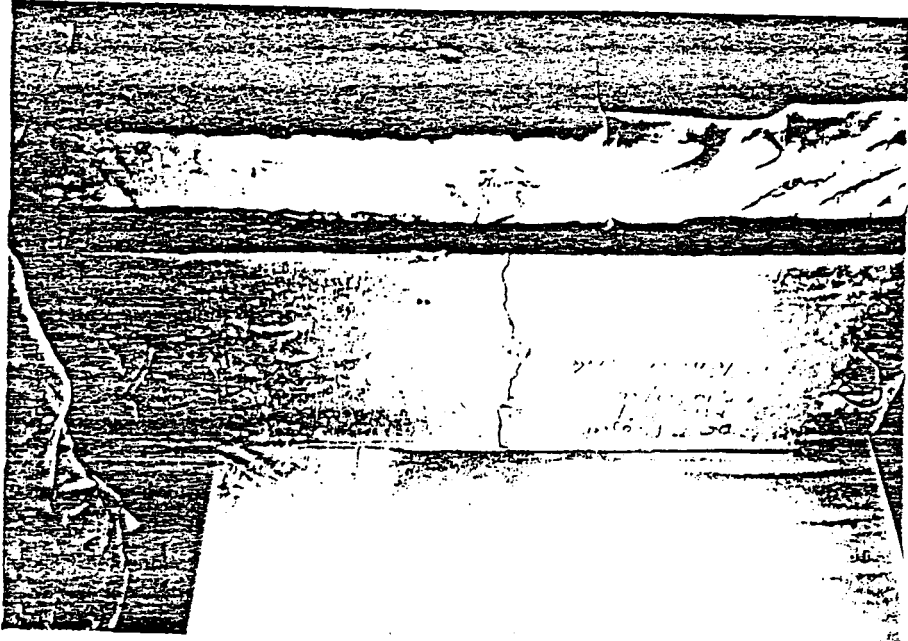


Fig. C-1: Test Slab C1



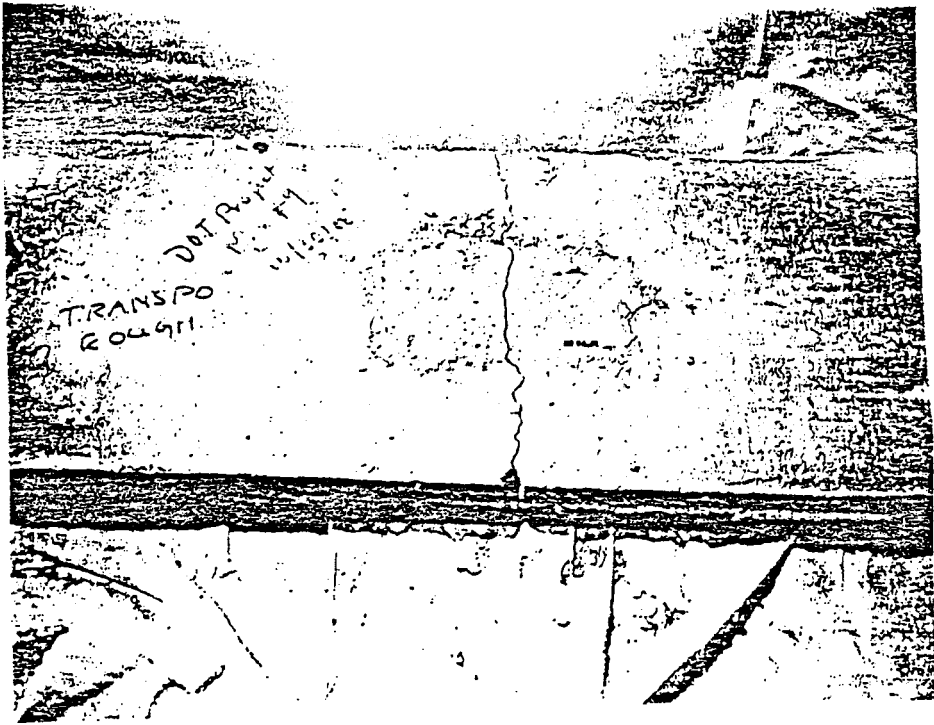


Fig. C-3: Test Slab M1LR

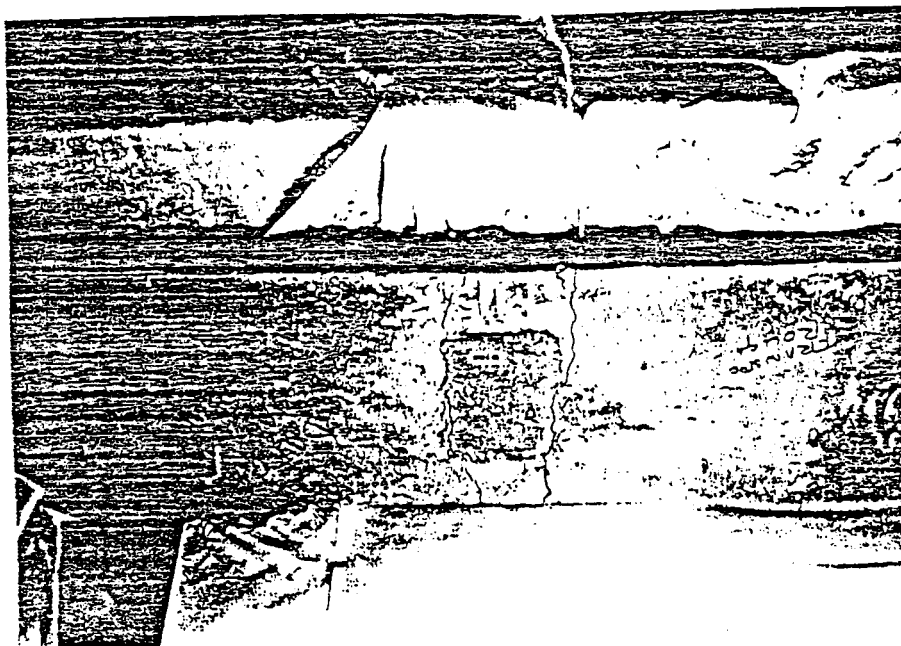


Fig. C-4: Test Slab M1WR

Fig. C-6: Test Slab P1CR

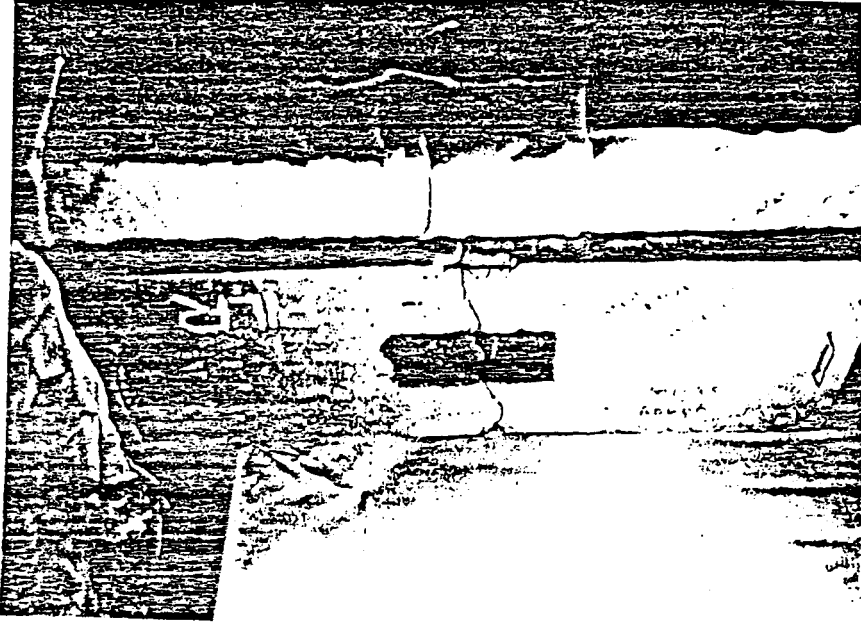
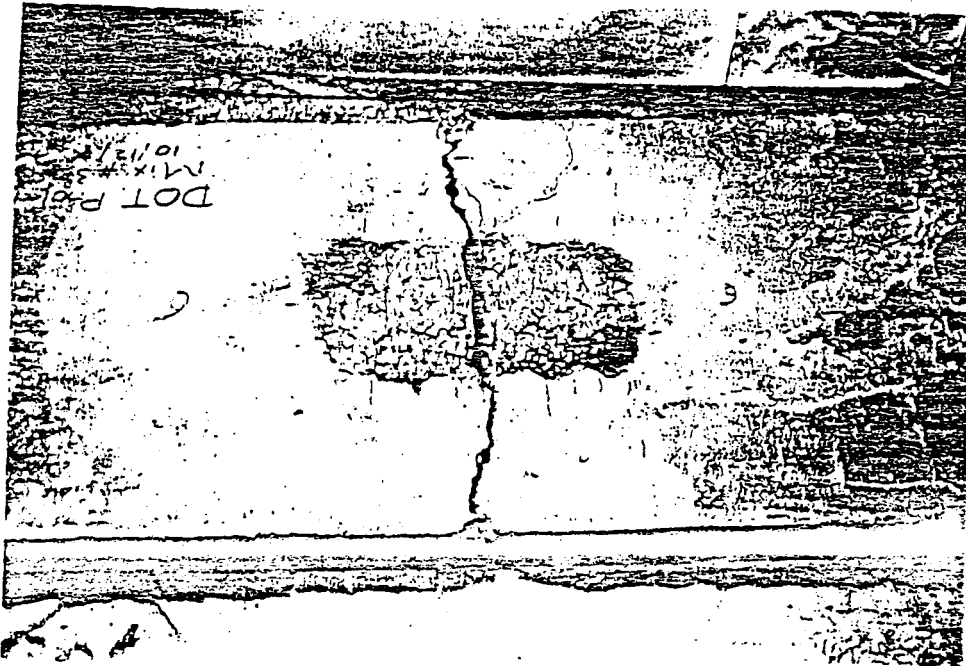


Fig. C-5: Test Slab P1CS



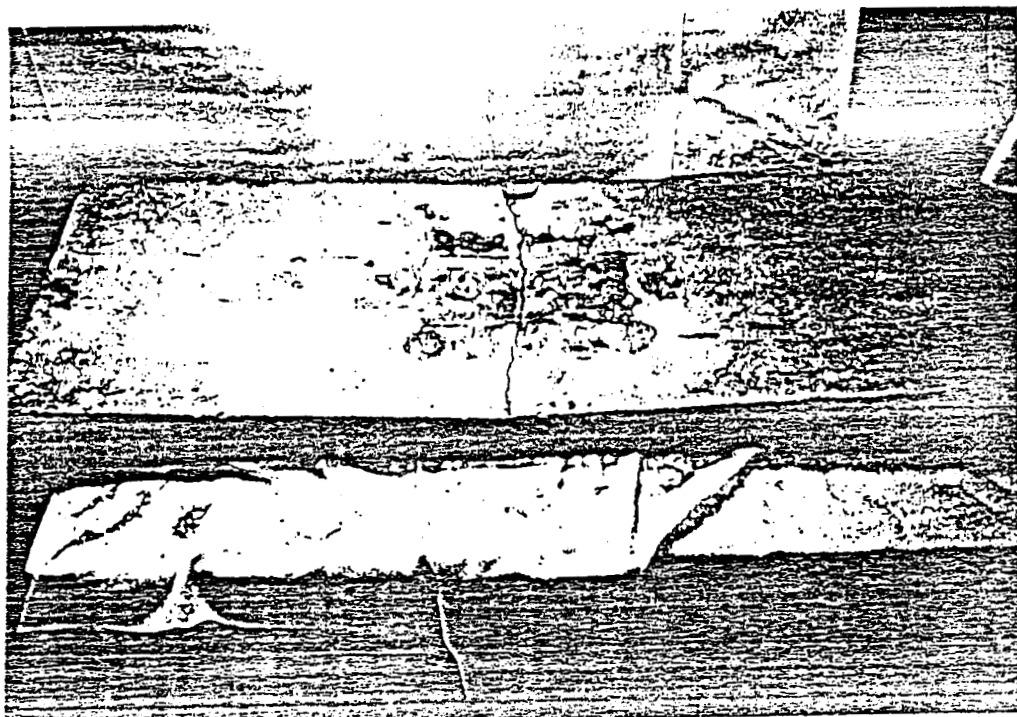


Fig. C-7: Test Slab P2LS

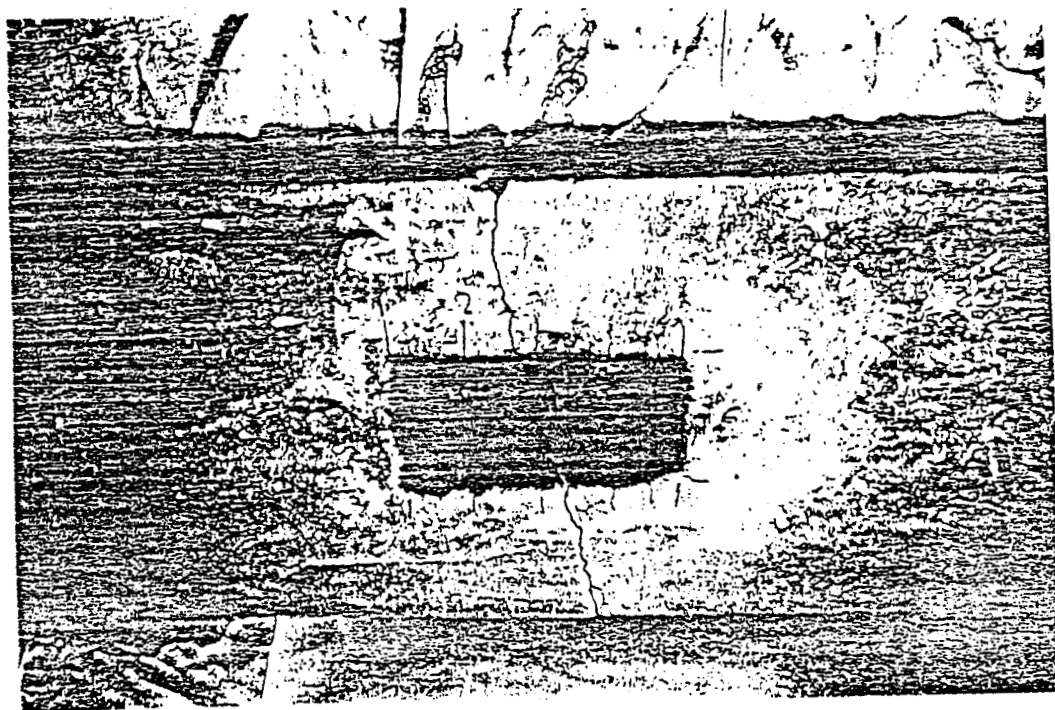


Fig. C-8: Test Slab P2LR

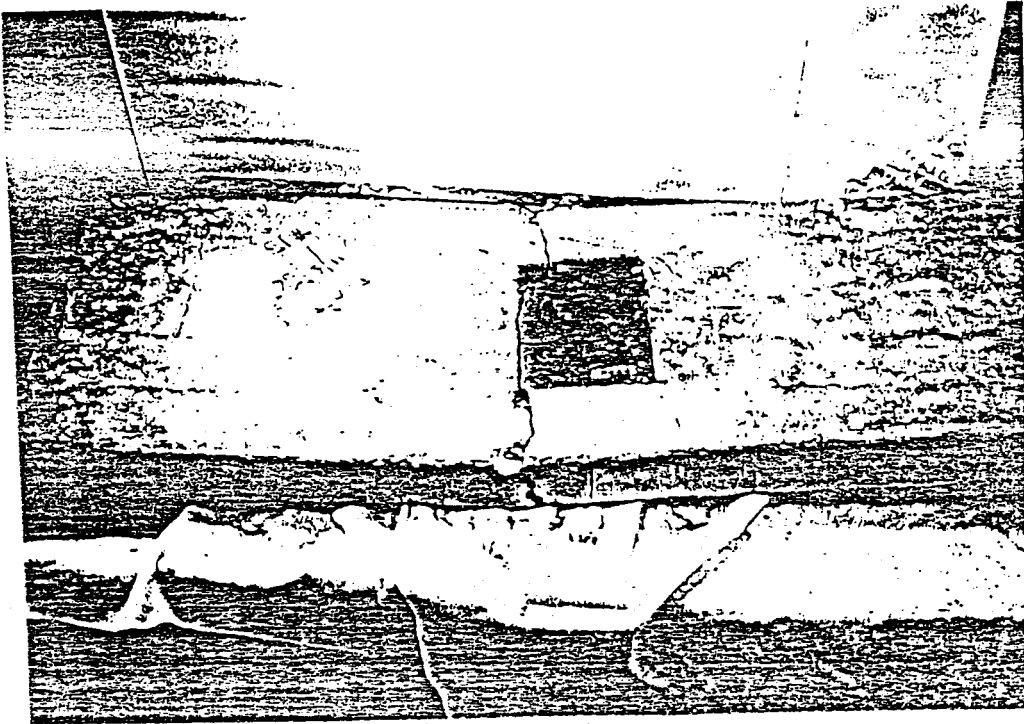


Fig. C-9: Test Slab P2LR

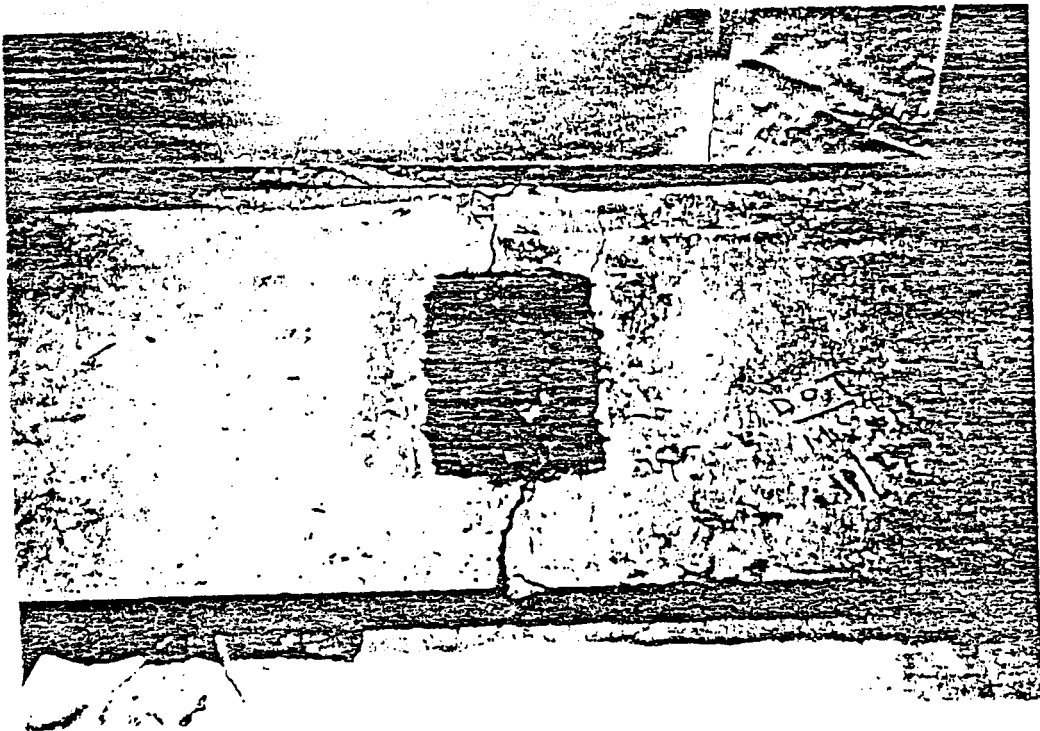


Fig. C-10: Test Slab P2WR

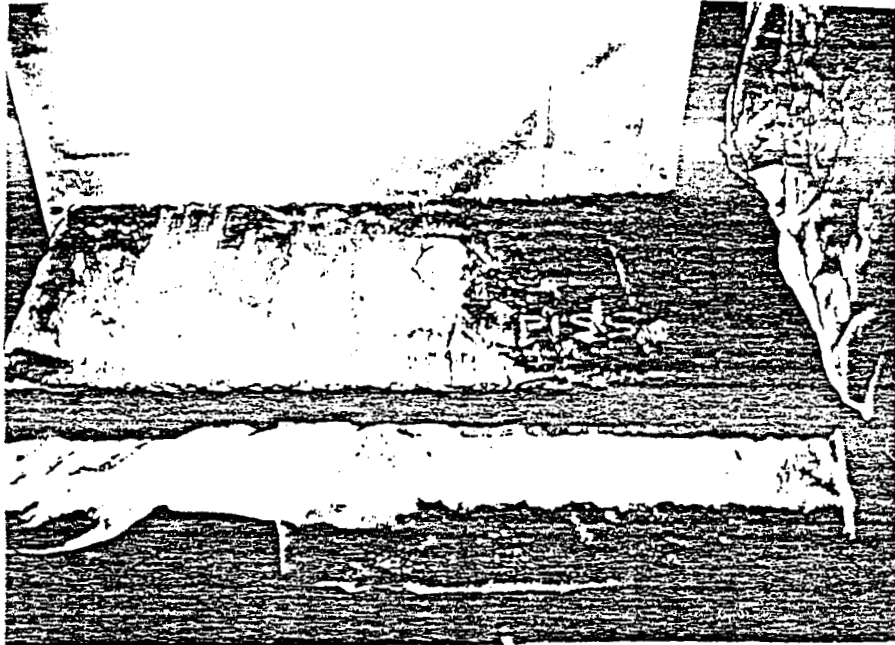


Fig. C-11: Test Slab P1WS

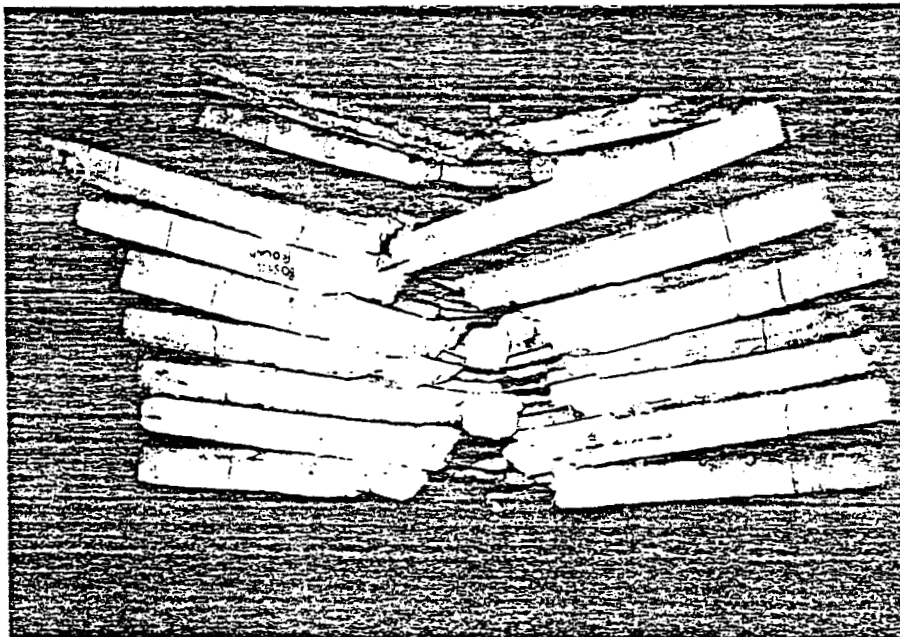


Fig. C-12: End View of Slab Specimens Tested to Failure

END