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16. ABSTRACT

The purpose of this investigation was to rapidly evaluate the feasibility of galvanizing prestressing steel and to determine other alternative means for deterring the corrosion of prestressing steel tendons. This report summarizes the results of this investigation to date.

This investigation was undertaken because it was felt that galvanizing might be the most positive means of protecting prestressing steel from damage by corrosion attack. Concern over corrosion has developed over a number of years of observing various degrees of attack on prestressing steel in transit, in storage, and prior to encasement in concrete. Immediate urgency for this investigation was precipitated by the severely corroded condition of several prestressing wires which were extracted from a number of post-tensioned concrete girders under fabrication during the summer of 1964.

For this reason a joint Bridge Depart-Materials and Research Department committee was appointed in September 1964 to gather information and make general recommendations relative to the corrosion protection of prestressing steel with particular emphasis on the feasibility of galvanizing these highly stressed tendons.

This investigation by the Materials and Research Department was conducted with the cooperation and in conjunction with the Bridge Department and the aforementioned joint Committee. Valuable information and cooperation were received from the Prestressed Concrete Manufacturers' Association of California and various members of the steel industry.

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STATE OF CALIFORNIA
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DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

A PROGRESS REPORT of AN INVESTIGATION OF METHODS of INHIBITING CORROSION of PRESTRESSING TENDONS

– 1965

State of California
Highway Transportation Agency
Department of Public Works
Division of Highways
Materials and Research Department

October 1965

Proj. W. O. 463558
19601 - - - 951012

Mr. A. L. Elliott
Bridge Engineer - Planning
Bridge Department
Sacramento, California

Dear Sir:

Submitted for your consideration is:

A PROGRESS REPORT OF

AN INVESTIGATION OF METHODS OF

INHIBITING CORROSION OF PRESTRESSING TENDONS

Study made by . . . . Structural Materials Section
Under direction of . . . . E. F. Nordlin
Laboratory work supervised by . . . . J. R. Stoker
Report prepared by . . . . J. R. Stoker

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

JRS:mw

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I. INTRODUCTION

The purpose of this investigation was to rapidly evaluate the feasibility of galvanizing prestressing steel and to determine other alternative means for deterring the corrosion of prestressing steel tendons. This report summarizes the results of this investigation to date.

This investigation was undertaken because it was felt that galvanizing might be the most positive means of protecting prestressing steel from damage by corrosion attack. Concern over corrosion has developed over a number of years of observing various degrees of attack on prestressing steel in transit, in storage, and prior to encasement in concrete. Immediate urgency for this investigation was precipitated by the severely corroded condition of several prestressing wires which were extracted from a number of post-tensioned concrete girders under fabrication during the summer of 1964.

For this reason a joint Bridge Department-Materials and Research Department committee was appointed in September 1964 to gather information and make general recommendations relative to the corrosion protection of prestressing steel with particular emphasis on the feasibility of galvanizing these highly stressed tendons.

This investigation by the Materials and Research Department was conducted with the cooperation and in conjunction with the Bridge Department and the forementioned joint Committee. Valuable information and cooperation were received from the Prestressed Concrete Manufacturers' Association of California and various members of the steel industry.

The results of this investigation are considered to be preliminary in nature and were expedited in order to make recommendations which could be incorporated into an improved specification which will control any adverse corrosion of prestressing steel. It is not intended that the information presented herein is the final recommendation of a conclusive research program. Instead, this report should be considered as a syllabus of current technical information and the test data obtained in this investigation. Further research is indicated to corroborate the recommendations made herein or to modify them accordingly.

The writer wishes to acknowledge the valuable engineering assistance of Mr. R. F. Stratfull, Senior Corrosion Engineer, and also the equally valuable assistance of the Concrete Section for their work in performing bond tests.

II. CONCLUSIONS

1. Galvanizing is both practical and feasible from the standpoint of availability. Economically it would be quite expensive and may hurt the competitive position of prestressed concrete construction. The over-all effectiveness of galvanizing in the long term protection of prestressing steel from corrosion is questionable. In the presence of an electrolyte galvanic action between steel and zinc may accelerate corrosion. A large deposit of zinc carbonate or "white rust" on the surface seriously affects bond. To prevent "white rust", the steel would require protection from corrosive media by methods such as used on some other galvanized products.

2. Discussions with affected members of industry indicate that the use of corrosion inhibitors would be a preferable solution to a required use of galvanizing. The use of corrosion inhibitors would be considerably cheaper, present less problems, and may result in a better over-all engineering solution for the protection of prestressing steel against corrosion.

3. For more detailed conclusions the recommendations of the joint Bridge Department-Materials and Research Department Committee on Corrosion of Prestressing Steel are attached.

4. Attached as a result of this study are the current Special Provisions of the Division of Highways for the protection of prestressing steel against physical damage and corrosion.

5. Also attached is a guide for the use of a common volatile corrosion inhibitor known as Shell V.P.I. This attachment is strictly considered to be a guide which was derived from discussions with the Shell Development Company for this particular product, and should not be used as a guide for the use of other types of volatile corrosion inhibitors.

III. DISCUSSION

This investigation was pursued in accordance with the following outline. Each item of the outline will be discussed individually.

1. The availability and/or feasibility of galvanized steel prestressing tendons.
2. The effect of galvanizing on bond of the tendons to concrete and grout.
3. The effect of galvanizing on present anchorage systems.
4. The effect of the contact of galvanized steel and uncoated reinforcing steel with respect to galvanic action.
5. Alternative means of deterring corrosion.

<u>Item No. 1</u>: The availability and/or feasibility of galvanized steel prestressing tendons.

Discussions were held with various members of the industry producing steel for prestressed concrete structures. The members of the industry were unanimous in their opinions that galvanized prestressing steel could readily be produced. All manufacturers of strand are presently producing 7-wire galvanized strand for other applications and could readily furnish galvanized 7-wire prestressing strand even though the strength requirements are higher. Some manufacturers are presently producing galvanized helically wound bridge strand which has been used for prestressing. Galvanized 1/4" prestressing wire is also presently being produced.

When queried on the possibility or danger of hydrogen embrittlement of the steel from the process of galvanizing, the opinions of industry were that there would be little likelihood of this occurring as this is not a problem with their present lower strength products. If such embrittlement did occur with 7-wire strand, it should show up in the stranding process where brittle breaks could occur due to bending of the wires. Opinions were stated that stress relieving after galvanizing would provide further safeguards against hydrogen embrittlement. Although there was not unanimity over this, the consensus of opinion of industry was that stress relieving following galvanizing is necessary to provide a product with proper stress strain characteristics and in the case of strand to eliminate residual stresses caused by the stranding operation.

It was expressed that galvanizing would be quite expensive. The members of industry quoted increases in price of from

10 to 25 percent for furnishing galvanized tendons. There would be an additional cost increase of a minimum of 10% to make up for a loss in strength as a result of the galvanizing of prestressing steel.

Item No. 2: The effect of galvanizing on bond of the tendons to concrete and grout.

With regards to the effect of galvanizing on bond of the tendons to concrete and grout, there is a considerable difference of opinion among researchers. Tests conducted on galvanized plain and deformed reinforcing bars indicate that galvanizing does not adversely affect bond at the stress levels encountered in reinforced concrete. There has been little done on the effect on bond as it applies to prestressing steel, except for a limited number of pilot studies. There is evidence, however, from preliminary pilot tests that the bond resistance of galvanized prestressing steel may not be equivalent to that of bare steel.

To garner more information on the effect of galvanizing or other promising protective coatings on bond, a series of bond tests were performed here in the laboratory. Specimens were cast using combinations of a normal seven sack prestressed concrete mix or a neat cement grout and cured in the manner practiced in the normal plant fabrication of prestressed concrete. Three specimens were prepared and tested for each test parameter of steel surface conditions. The following surface conditions were evaluated:

1/4" diameter prestressing wire

1. Bare wire.
2. Galvanized wire.
3. Galvanized wire with a coating of "white rust".
4. Bare wire, sandblasted and coated with a vinyl wash.
5. Bare wire, sandblasted and coated with "Rust Ban 191", an inorganic zinc silicate paint.
6. Bare wire coated with Shell "Vapor Phase Inhibitor" (V.P.I.) crystals.

½", 7-wire strand

1. Bare strand.
2. Galvanized strand.
3. Galvanized strand with a coating of "white rust".
4. Bare strand coated with a vinyl wash.

5. Bare strand, sandblasted and coated with "Rust Ban 191", an inorganic zinc silicate paint.

6. Bare strand coated with "Vapor Phase Inhibitor" (V.P.I.) crystals.

The Rust Ban 191 was manufactured by the Humble Oil and Refining Corporation and was formulated by combining the two components by weight, 1 part vehicle to 3.2 parts zinc component. The vinyl wash material was manufactured by Rhino Tec Corporation and was mixed by volume using 4 parts base resin to 1 part acid component. The mixing of components was performed according to manufacturer's instructions. The Vapor Phase Inhibitor (V.P.I.) crystals, a product of the Shell Oil Company, were brought into solution with methyl alcohol. The liquid solution consisted of 70 cc methyl alcohol and 10 grams of V.P.I. Type 250 crystals.

The 1/4-inch wires used for these tests were cut into 28-inch lengths from coils of 1/4-inch galvanized and bare wire. The 1/4-inch bare wire complied with the ASTM specification A421 and had the following average properties: yield strength 220,000 psi, ultimate strength 254,000 psi, modulus of elasticity 30,000,000 psi, and elongation in 10 inches 5.0%. The 1/4-inch galvanized wire possessed the following average properties: yield strength 203,000 psi, ultimate strength 237,700 psi, modulus of elasticity 30,000,000 psi, and elongation in 10 inches 4.0%. The average thickness of the galvanized coating was 2.0 mils. The wires were hand worked until each formed a relatively straight wire. Only the 1/4-inch wires which were to be coated with vinyl wash or Rust Ban 191 were sandblasted prior to their application. Sandblasting was required for good adherence to the steel. Coatings were sprayed on the 1/4-inch wires to an average measured thickness of 4.0 mils for the Rust Ban 191 and 1.0 mils for the vinyl wash. The coated wires were allowed to dry a minimum of 72 hours at room temperature before use. The V.P.I.-methyl alcohol solution was brushed on the 1/4-inch wire to a thickness of 1 to 2 mils and allowed to air dry and crystalize 4 hours before use. The coating thicknesses were determined by measurements taken with a Magne Gage.

All of the lengths of 1/2-inch, 7-wire strand were cut from a coil of galvanized strand into 34-inch lengths and both ends of each strand were brazed to hold them in a straight position and prevent them from unravelling. This produced 7-wire strand specimens with approximately the same lay per foot and with similar physical properties. In order to eliminate the effects of galvanizing, the strands to be coated with vinyl wash, Rust Ban 191, V.P.I., and the strand to remain in the bare condition were treated by removing the galvanizing from the steel down to the base metal by use of an HCl acid solution containing an additive to prevent attack of the steel. Only the strands to be coated with Rust Ban 191 were sandblasted prior to coating. The strands coated with the vinyl wash were not sandblasted as this coating bonded well to the acid cleaned base metal. No sandblasting was required for the strand coated with a thickness

of 1 - 2 mils of V.P.I. crystals. The measured average coating thickness of the vinyl wash was 1.0 mils, and the Rust Ban 191 coating thickness was 2.5 mils.

A continuous coating of "white rust" or zinc carbonate formed on the 1/4-inch galvanized wire specimens after 48 hours exposure in the fog room at 73° F. The white rust coating on the 1/2-inch, 7-wire strands was obtained by placing the strand specimens in the steam cabinet for 3 hours at 150° F. Both methods were effective in obtaining this coating. All of the white rust coated specimens were then air dried prior to use.

The 7-wire strand specimens were cast vertically in the center of 6" x 6" x 6" cubes of concrete. Each of the 1/4-inch wires to be tested was embedded 6 inches in neat cement grout which was placed in the center of a 2-inch diameter flexible steel conduit which had been cast in a 6" x 6" x 6" cube. The average compressive strength of the concrete used was 4600 psi and 6700 psi for the grout.

Bond Testing Procedure

The 1/4-inch wire specimens were pulled on the 5,000-lb. tensile machine in the Structural Materials Section at a loading rate of approximately 500 lbs. per minute. Each of these specimens was loaded until the ultimate or pull-out load was reached. To assure good alignment of the specimens in the machine, a spherically seated bearing device was used. The dial indicator arrangement permitted measurements of slip and elongation, and conformed to the arrangements described in ASTM C234 (see Figure 6). The slip at the loaded end was calculated by averaging the two recorded readings at each 100 lb. increment of load. Corrections were applied to these readings to compensate for elongation of the wire outside the block between the block and the reference yoke of the lower dials.

The 1/2-inch, 7-wire strand specimens were tested on the 60,000-lb. tensile machine, and the same spherically seated bearing device was used. The brazed end of each strand at the unloaded end was ground flat prior to testing. This was done to prevent any restraint at the unloaded end during the loading process and also to establish a bearing surface for the spindle of the dial indicator. For the bond tests with the 1/2-inch strand, only the 0.0001-inch dial indicator at the unloaded end was used. The dials at the loaded end were not used because pilot tests indicated the strand tended to unwind as it was loaded. As a result, the cross-arm assembly would also turn horizontally with the strand and in turn the dial spindles would lose their bearing on the cross-arm assembly and no measurements could be made (see Figure 5).

In order to provide adequate bearing for the concrete during the tests with the 1/2-inch strand, a piece of fiberboard 1/4-inch thick was placed between the concrete block and the steel bearing surface. The 1/2-inch strand was loaded at approximately

1000 lbs. per minute and a dial reading was taken at each 500 lb. increment of load. The loading continued until the ultimate load was reached.

Bond Test Results

The bond stress was calculated using the nominal surface area of 4.71 square inches for the 1/4-inch wire embedded 6 inches in concrete, and 9.42 square inches (based on the nominal diameter) for the 1/2-inch, 7-wire strand embedded the same depth. Using these nominal areas, the stress at each load was determined and Bond Stress vs. Slip Curves were plotted (see Figures 1 - 4). The slip of the 1/4-inch wire was plotted from measurements taken at the loaded end, and the slip of the 1/2-inch, 7-wire strand was plotted from measurements taken at the unloaded end. The strength of the bond between the steel and the concrete was evaluated at the following three stages:

For 1/4-inch wire

1. Initial slip of 0.00005 inch at the unloaded end.
2. Slip of 0.010-inch at loaded end.
3. Ultimate load.

For 1/2-inch, 7-wire strand

1. Initial slip of 0.00005-inch at the unloaded end.
2. Slip of 0.0002-inch at unloaded end.
3. Ultimate load.

Refer to Tables 1 and 2.

Attention is called to the bond values obtained in this investigation. These values are to be used strictly to compare the effect of the various surface conditions on bond and should not be used as a design criteria for bond. A great deal more testing would be required to establish values for design. Also, the method used herein does not necessarily duplicate the loading occurring in a structure.

Bond Test Conclusions

Based on the test data obtained, the following conclusions appear to be warranted:

1. The effects of coating on bond of embedded steel is different for the different forms of reinforcing and method of embedment. In general, galvanizing had a detrimental effect on bond to the 1/2-inch, 7-wire strand whether it had "white rust" or not. This is demonstrated in Table 2 which shows an ultimate bond strength for the galvanized 1/2-inch, 7-wire strand of approximately 56% of the bare uncoated strand. For the galvanized strand coated with white rust, the ultimate bond strength was 45% of the bare uncoated strand.

Table 1, however, shows the galvanized 1/4-inch wire to have a higher bond strength than the bare wire. This was apparently the result of increased surface friction due to the galvanizing. However, the 1/4-inch galvanized wire with the white rust coating exhibited a bond strength of approximately 46% of the bond strength developed by the bare wire.

2. Sandblasted and coated 1/4-inch wire had a significantly greater bond to concrete than did the plain 1/4-inch wire.

   There was no significant difference between the bond strength of sandblasted and coated 7-wire strand and bare 7-wire strand.

3. Depending on which measure of bond is most significant in the design and performance of prestressed concrete members, several of the conditions evaluated may be acceptable as far as bond strength is concerned because the calculated bond strength of some of the conditions exceeded the bond strength of the bare control wire. This was particularly true for the 1/4-inch grouted wire tests. Although the initial slip of galvanized 1/4-inch wire occurred at a lower stress level than for the 1/4-inch bare wire, the ultimate bond was considerably greater.

4. V.P.I. crystals on the 1/4-inch bare wire had about the same effect as white rust on 1/4-inch galvanized wire, as far as bond reduction is concerned. The effect of V.P.I. crystals on bond reduction of 1/2-inch, 7-wire strand was not as significant, however.

Of interest as it relates to the problem of bond reduction of galvanized surfaces as compared to bare steel, reference is made to the article written by C. E. Bird, Chief Research Engineer, National Building Research Institute, South African Council for Scientific and Industrial Research Corrosion Group, entitled "The Influence of Minor Constituents in Portland Cement on the Behavior of Galvanized Steel in Concrete" as published in the issue of Corrosion Prevention and Control, July 1964. Mr. Bird relates that the reduction of bond between galvanized steel and concrete is caused by hydrogen evolution developed from a reaction between zinc and cement. This evolution of hydrogen creates a spongy appearing surface at the interface between the steel and concrete. This spongy surface in turn reduces bond. The surface condition noted by Mr. Bird has also been observed in our bond test specimens. Mr. Bird has concluded from his research that the addition of a small amount of soluble chromate to the mixing water or the cement will inhibit the evolution of hydrogen. The effect of chromates on the subsequent life of a galvanized coating on steel embedded in concrete and exposed to marine atmospheres is under investigation by Mr. Bird.

Item No. 3: The effect of galvanizing on present anchorage systems.

There is concern regarding slippage of galvanized tendons in anchorage systems which function by gripping the tendon. Discussions with members of the prestressing industry indicate that this may be a problem due to the lubricating action of zinc. Some systems allow about 5/8" for anchorage take up and slip. With galvanizing it is speculated that the slip may be considerably more. Any additional loss could cause a problem with short tendons requiring the need for shims or additional shimming to achieve the required stress.

Galvanizing may require redesign of some present anchorage systems. In pretensioned fabrication there is a concern that zinc would build up in the teeth of the temporary anchorage devices and therefore create additional maintenance problems. There is also concern that the zinc would be stripped off an area of the tendon within the anchorage system creating an area for corrosion attack.

To date there is no data available on the effect of galvanizing on anchorages. Further research and testing will be required in this area to develop any positive conclusions.

Item No. 4: The effect of the contact of galvanized steel and uncoated reinforcing steel with respect to galvanic action.

An item requiring considerable contemplation in designing and fabricating prestressed concrete members with galvanized steel tendons is the phenomenon of galvanic action between zinc and uncoated steel. An electrical potential of significant magnitude can exist between zinc and steel in contact with each other in the presence of an electrolyte, in this case moist concrete containing chloride ions. Extreme care would be required to prevent any interconnection of the two dissimilar metals or corrosion would in fact be accelerated in concrete containing chloride ions or structures located in an environment where chlorides can permeate the concrete.

Present practice in pretensioned construction is to tie the bare mild reinforcing steel stirrups to the tensioned strand. In post-tensioned construction the ungalvanized, or at best thinly galvanized, flexible steel conduit is tied to the stirrups and/or other bare reinforcing steel components. In either case the prestressing steel is in direct contact or indirect contact through the conduit with the bare mild steel. If galvanized tendons were to be used and other provisions were made to insulate the two materials, there would always be the danger, considering normal construction practice, of the materials unintentionally coming into contact. In effect, the electrical insulation of galvanized and bare steel would not be practical from a construction standpoint.

To be reasonably assured that galvanic action would not occur during the life of the structure, both types of steel

including all ties, anchorages, conduits, etc. would require galvanizing. The next best alternative would be to galvanize any contacting mild steel and use uncoated prestressing tendons. In this manner the low strength steel would be sacrificed if galvanic action occurred, with the prestressing steel being afforded protection from all types of corrosion attack. However, eventually under these conditions the pressure created by the corrosion products of the galvanized mild reinforcing steel would crack the concrete thus allowing ingress of corrosive agents to the prestressing steel.

The above discussion presupposes conditions where chlorides occur in the concrete or have access to the concrete. Under conditions of relatively dry and salt-free concrete, however, it is considered that the bi-metallic corrosion between zinc and steel would be insignificant.

Item No. 5: Alternative means of deterring corrosion.

Other considered methods of deterring corrosion other than galvanizing are: the applications of various organic or inorganic coatings, cathodic protection, and the use of corrosion inhibitors. With the exception of coatings which provide sacrificial protection such as inorganic zinc silicate paints, coatings per se may not afford 100% protection as they are susceptible to mechanical abrasion. Any discontinuity of the coating film can allow corrosive attack, which, under certain conditions, may be more rapid than without the coating. Some coatings also may not offer sufficient bond to the surrounding concrete or grout. Water soluble oils may serve as effective corrosion inhibitors if protected from any flushing action of water. As water soluble oils must be of such solubility as to be removed prior to grouting so as not to affect bond, their practicality is questionable. Cathodic protection would not be practical due to the interconnection of the various steels occurring in a prestressed member and is not recommended at this time.

Corrosion inhibitors appear to offer the most practical means of protecting prestressing steel. Volatile corrosion inhibitors are commercially available and have been very satisfactorily used for the protection of aircraft engines and machinery during periods of storage and shipment. One of the more common ones which has been used with success is a vapor phase inhibitor known as V.P.I. and produced by the Shell Oil Company. These materials form a vapor which adheres to the metal in the form of a thin film which inhibits corrosion. Volatile corrosion inhibitor powders, referred to hereafter as V.C.I. powders, are widely used as an inhibitor component in packaging materials. Prestressing steel can be successfully protected during shipping and storage by the use of V.C.I. packaging or by the inclusion of V.C.I. powders within a packaging. Packaging must be reasonably airtight to retain the V.C.I. vapor, protected from physical damage, and be reasonably watertight as the V.C.I. crystals -- by nature being water soluble -- may be readily removed from the steel by the flushing action of water.

Prestressing steel stored in conduits awaiting final encasement in concrete can be successfully protected from corrosion by the induction of V.C.I. powders into the conduits or by the sprinkling of the powder onto the steel as it is fed into the conduits.

The quantity of V.C.I. powder required will vary, depending on the type used and the manufacturer and the conditions of usage, but in typical commercial containers will be in the neighborhood of 3 grams per cubic foot of air space surrounding the steel to be protected. The absolute quantity of V.C.I. powder to be used for prestressing steel corrosion inhibition has not been established due to the many variables involved.

The action of the corrosion inhibitor can be nullified by the following conditions:

a. Excessive ambient temperature greater than 160° F.

b. Free water running over the surface of the steel.

c. Water that has a pH of less than 6.5 (acidic).

d. Free circulation of fresh air.

e. Barriers that prevent the vapor from contacting the surface of the steel.

f. Water containing a high quantity of chlorides.

V.C.I. powders can be used and will protect the steel in an aqueous solution. The concentration required will vary with the type but typically may be about 2% by weight of the solution. Other inhibitors for use in a solution are available and may be more economical than solutions formed from V.C.I. powders. Some of these inhibitor compounds are: sodium nitrite, sodium benzoate, sodium dichromate and sodium cinnamate. There are other compounds which would be equally effective.

Other means of protecting prestressing steel are by spraying or otherwise applying a saturated solution of V.C.I. to the steel which will leave a crystalline residue of V.C.I. on the surface of the steel. To be effective, however, the steel requires protection from direct contact of water. If this method of corrosion protection is used, the ducts used in post-tensioned construction or pretensioned steel tendons may require flushing with water prior to grouting or casting in concrete as a heavy crystalline coating of the V.C.I. material will reduce bond as previously indicated in the tests on bond. A light film of the vapor on the steel, however, will not affect the bond strength.

The above discussion on the use of corrosion inhibitors concerns the protection of steel previous to its encasement in concrete or grout. Further research is needed to determine methods

of protecting prestressing steel from corrosive attack after encasement. Research is presently being conducted to improve grouting techniques and grout mix design. The feasibility of adding corrosion inhibitors to grout and to concrete will be investigated. With respect to post-tensioned construction, it is recommended that any flushing of the ducts prior to grouting or flushing to clear the ducts be performed with an alkaline water to preclude the possibility of an acidic water being introduced into the ducts.

As part of this investigation a number of pretensioned members which were unacceptable for use for various reasons and therefore of no value were made available to the Division of Highways by the Prestressed Concrete Manufacturers' Assn. of California. These members were broken into and sections of 7-wire prestressing strand removed and examined for corrosion. These members were stored in different environments in California and were of varying age. Generally speaking, the corrosion noted on the outer surface of the strands which were in contact with the concrete was minor. In some cases, however, the interior of the strands was quite severely attacked by corrosion. Some degree of corrosion on the interior of the strands was evident in all cases. This indicates a need to develop some means of protecting the interior of strands either by coatings or inhibitors. Further research is needed in this area.

TABLE I

Average Bond Stress (psi) for 1/4-inch Wire Grouted 6 Inches in Neat Cement Paste and Steam Cured 16 hours at 147-153° F.

(Average of Three Specimens)

	Average Bond Stress (psi) at:					
	Initial Slip (0.00005-in.) Unloaded End		Slip of 0.010-in. Loaded End		Ultimate Load	
Surface Condition of 1/4-inch Wire	psi	% of Control	psi	% of Control	psi	% of Control
Test Series 1						
Bare	105	= 100	280	= 100	280	= 100
Galvanized	20	19	345	123	460	164
Galvanized (white rust)	70	67	130	46	130	46
Sandblasted and coated with 1.0 mils vinyl wash	340	324	775	277	795	284
Sandblasted and coated with 4.0 mils Rust Ban 191	275	262	795	284	1050	375
Test Series 2						
Bare	105	= 100	250	100	250	100
Bare wire coated with 1-2 mils Vapor Phase Inhibitor (V.P.I.) crystals	105	100	130	52	130	52

TABLE II

Average Bond Stress (psi) for 1/2-inch, 7-wire Strand Embedded 6 inches in 7-sack Concrete and Steam Cured 40 hours at 147-153° F.

(Average of Three Specimens)

Surface Condition 1/2-in., 7-wire Strand	Average Bond Stress (psi) at: Initial Slip (0.00005-in.) Unloaded End			Slip of 0.0002-in. Unloaded End			Pullout Load		
	psi		% of Control	psi		% of Control	psi		% of Control
Test Series 1									
Bare	340	=	100	635	=	100	860	=	100
Galvanized	200		59	330		52	480		56
Galvanized (white rust)	165		49	275		43	385		45
Vinyl Wash (1.0 mil)	330		97	530		84	770		90
Sandblasted and coated with 2.5 mils Rust Ban 191	345		102	585		92	1135		132
Test Series 2									
Bare	365	=	100	580	=	100	635	=	100
Bare Strand coated with 1-2 mils Vapor Phase Inhibitor (V.P.I.) Crystals	285		78	475		82	535		84

Figure I

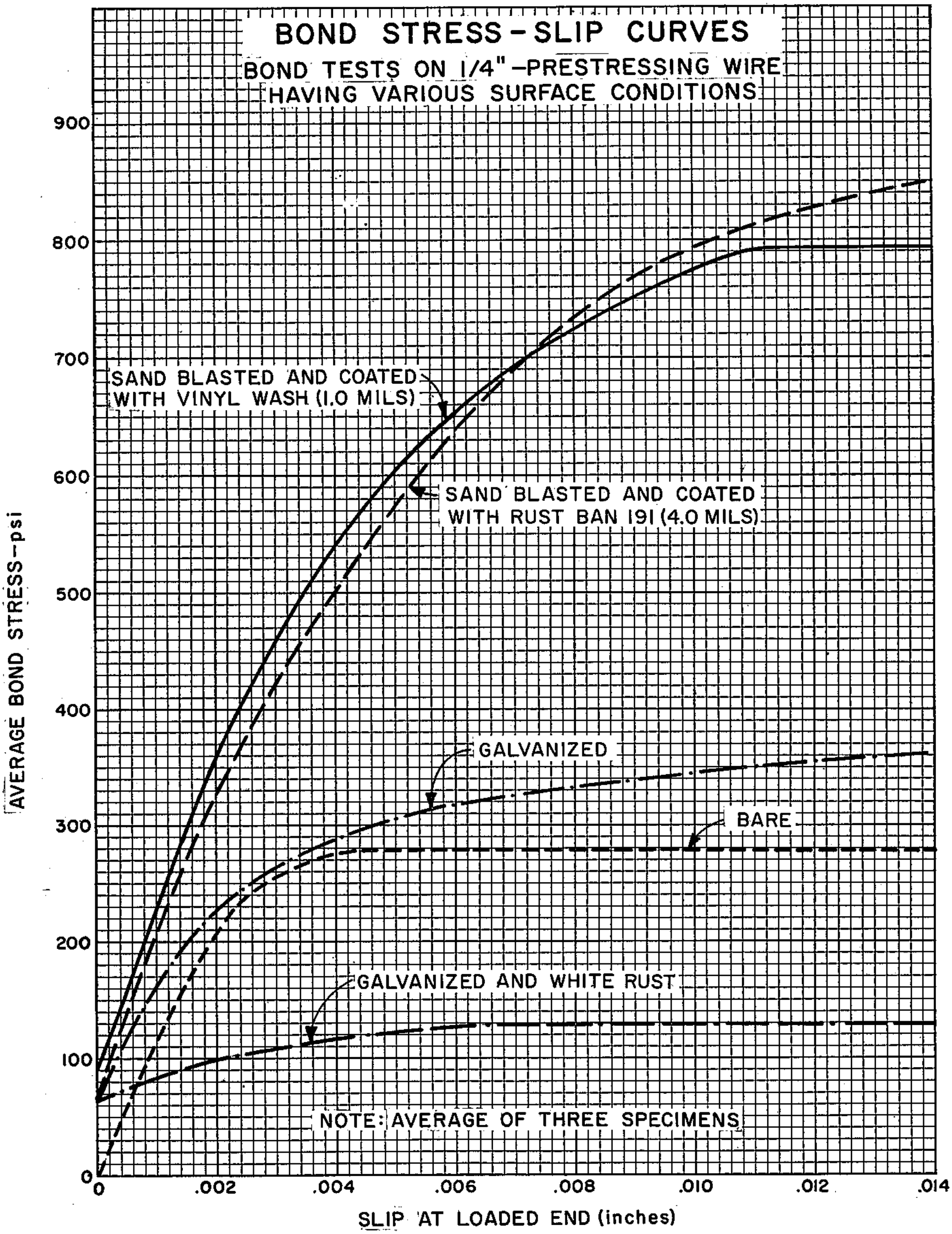

BOND STRESS - SLIP CURVES
BOND TESTS ON 1/4" - PRESTRESSING WIRE
HAVING VARIOUS SURFACE CONDITIONS
SAND BLASTED AND COATED WITH VINYL WASH (1.0 MILS)
SAND BLASTED AND COATED WITH RUST BAN 191 (4.0 MILS)
GALVANIZED
BARE
GALVANIZED AND WHITE RUST
NOTE: AVERAGE OF THREE SPECIMENS
AVERAGE BOND STRESS - psi
0
100
200
300
400
500
600
700
800
900
0
.002
.004
.006
.008
.010
.012
.014
SLIP AT LOADED END (inches)

Figure 2

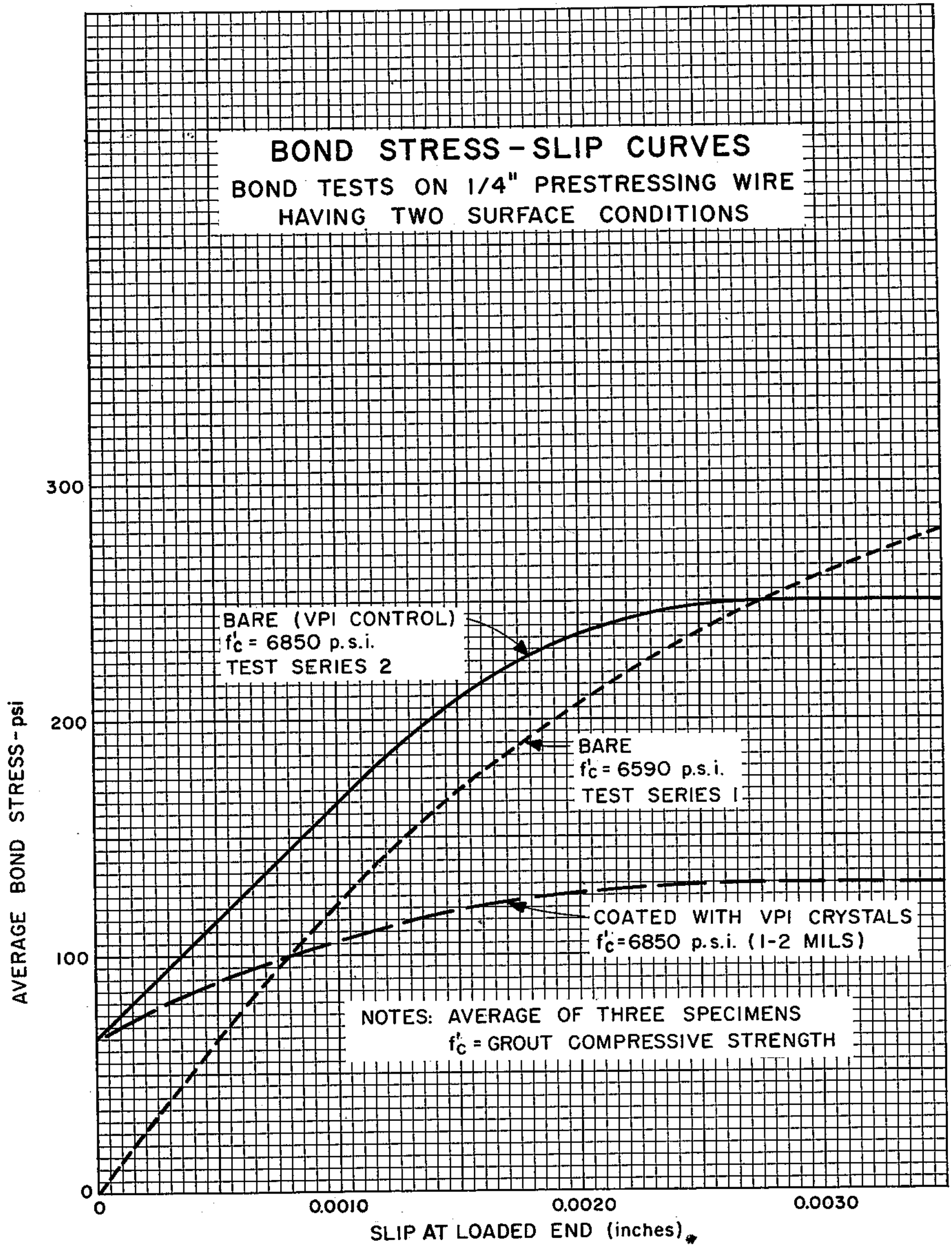

BOND STRESS-SLIP CURVES
BOND TESTS ON 1/4" PRESTRESSING WIRE HAVING TWO SURFACE CONDITIONS
BARE (VPI CONTROL)
f'c = 6850 p.s.i.
TEST SERIES 2
BARE
f'c = 6590 p.s.i.
TEST SERIES 1
COATED WITH VPI CRYSTALS
f'c = 6850 p.s.i. (1-2 MILS)
NOTES: AVERAGE OF THREE SPECIMENS
f'c = GROUT COMPRESSIVE STRENGTH
AVERAGE BOND STRESS - psi
0
100
200
300
0
0.0010
0.0020
0.0030
SLIP AT LOADED END (inches)

Figure 3

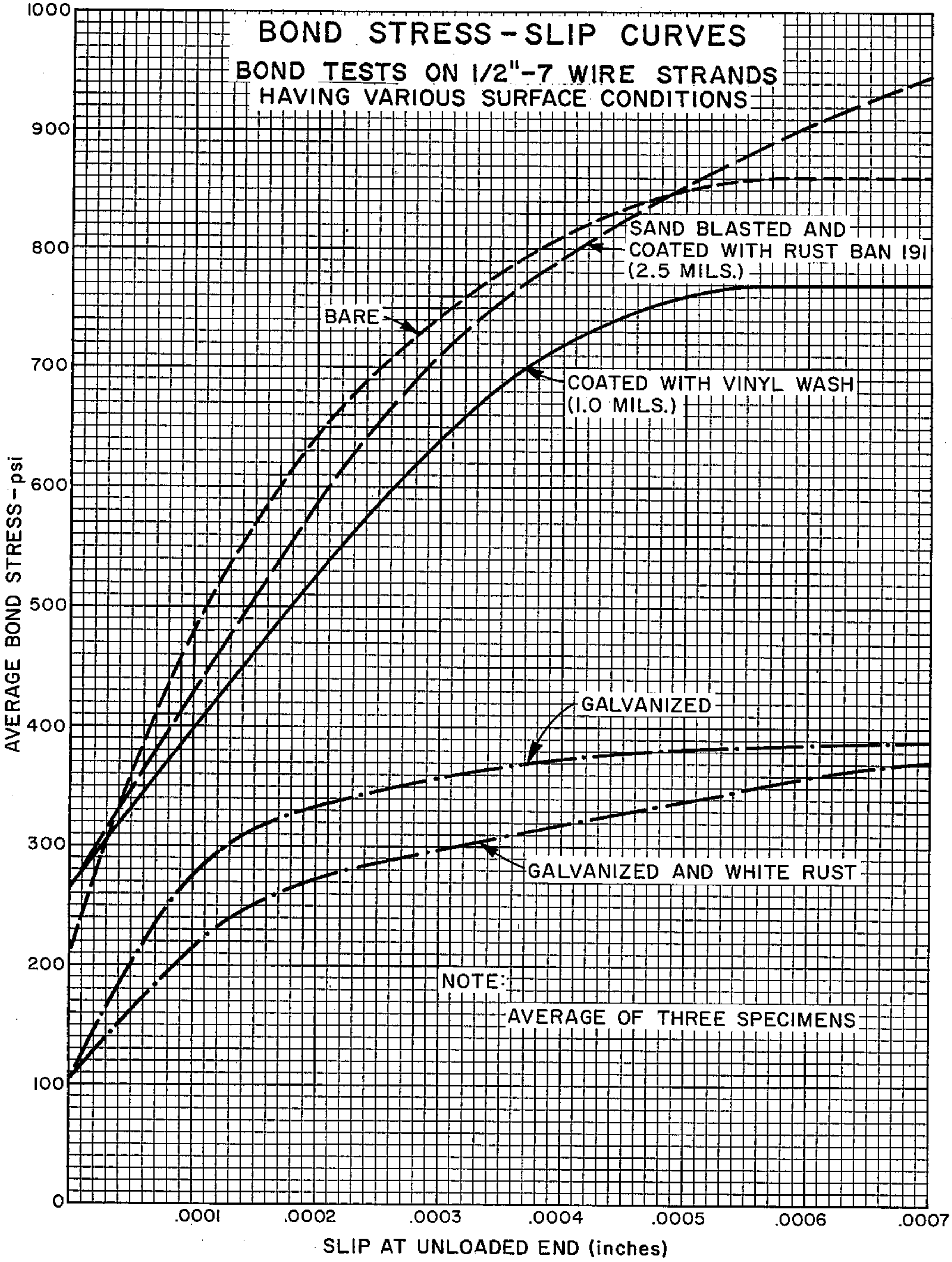
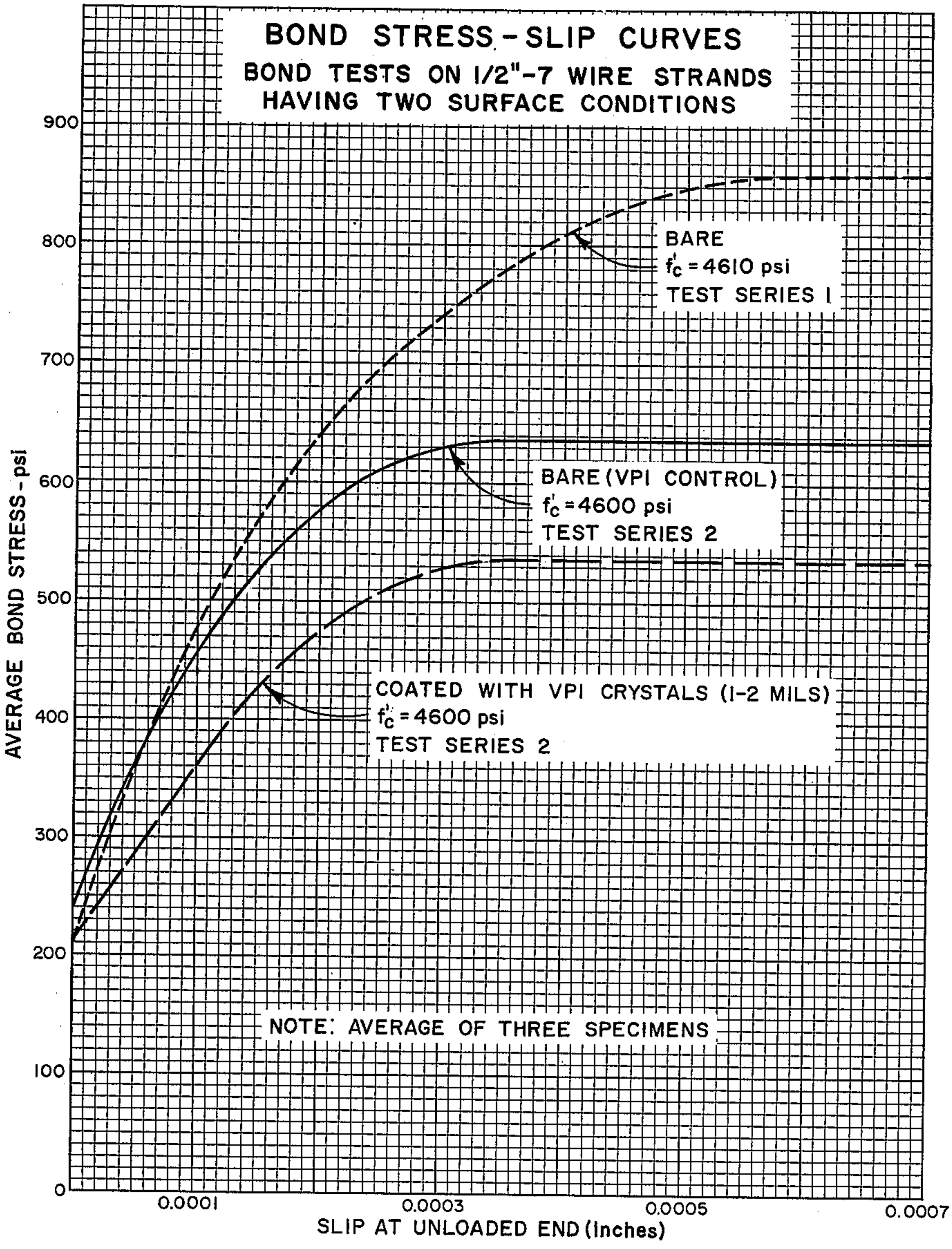

BOND STRESS - SLIP CURVES
BOND TESTS ON 1/2"-7 WIRE STRANDS
HAVING VARIOUS SURFACE CONDITIONS
SAND BLASTED AND
COATED WITH RUST BAN 191
(2.5 MILS.)
BARE
COATED WITH VINYL WASH
(1.0 MILS.)
GALVANIZED
GALVANIZED AND WHITE RUST
NOTE:
AVERAGE OF THREE SPECIMENS
AVERAGE BOND STRESS - psi
1000
900
800
700
600
500
400
300
200
100
0
.0001
.0002
.0003
.0004
.0005
.0006
.0007
SLIP AT UNLOADED END (inches)

Figure 4


BOND STRESS - SLIP CURVES
BOND TESTS ON 1/2"-7 WIRE STRANDS
HAVING TWO SURFACE CONDITIONS
BARE
f'_c = 4610 psi
TEST SERIES 1
BARE (VPI CONTROL)
f'_c = 4600 psi
TEST SERIES 2
COATED WITH VPI CRYSTALS (1-2 MILS)
f'_c = 4600 psi
TEST SERIES 2
NOTE: AVERAGE OF THREE SPECIMENS
AVERAGE BOND STRESS - psi
0
100
200
300
400
500
600
700
800
900
0.0001
0.0003
0.0005
0.0007
SLIP AT UNLOADED END (Inches)

TESTING APPARATUS FOR BOND TESTS

ASTM (C234-57T)

Figure 5

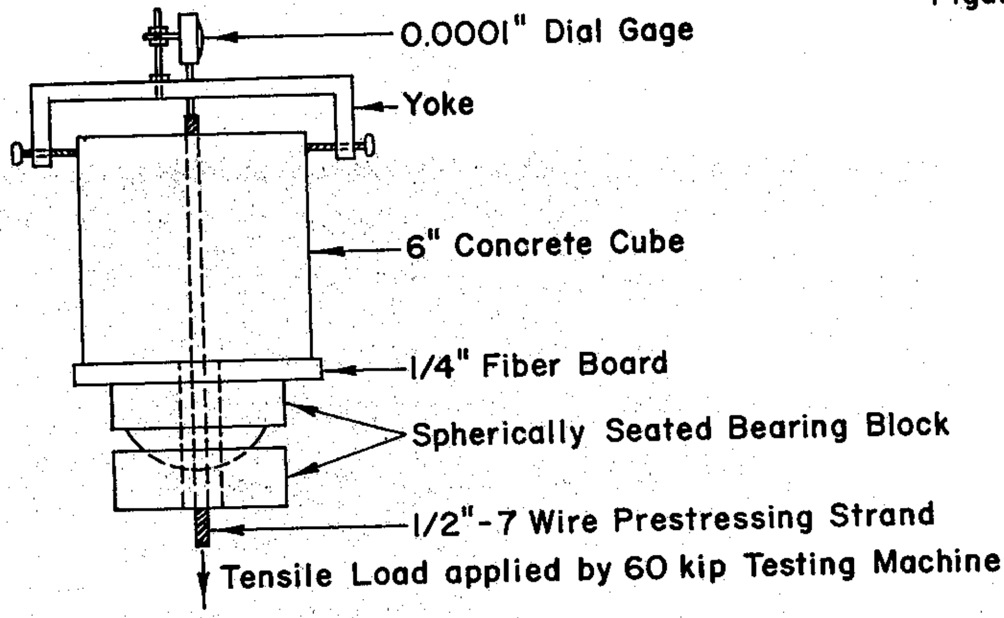
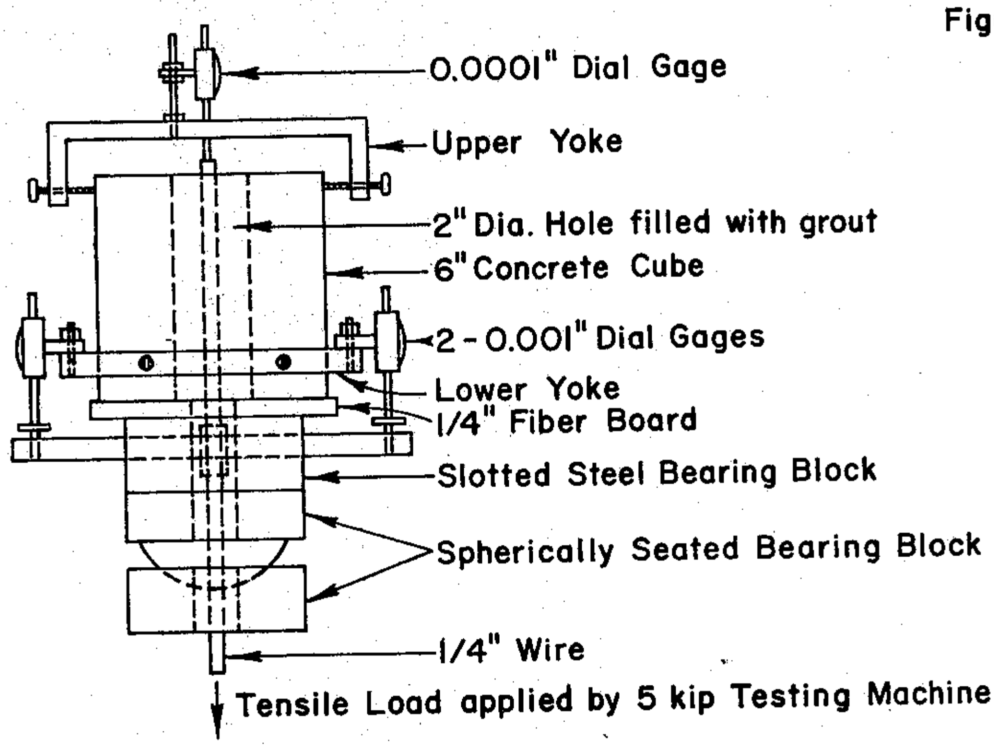


Figure 6



V. COMMITTEE RECOMMENDATIONS

November 16, 1964

Mr. A. L. Elliott:

The Committee on Corrosion of Prestressing Steel offer the following recommendations.

For consideration of the Specification Section:

1. Galvanizing

The considered opinion of the committee is that galvanizing is not a panacea for the protection of prestressing tendons against corrosion. Its use as corrosion protection should be limited to specific types of design where encasement of the tendons is not feasible or desirable. Also in highly corrosive environments galvanizing may be the most practical solution if steel in a prestressed member is subject to corrosion after casting of the concrete. Further research is required to verify this possibility.

For the majority of our structures galvanizing does not appear to yield the best engineering solution for various reasons. From limited testing there is evidence that the bond resistance of galvanized steel may not be equivalent to that of bare steel. There are indications that galvanizing coated with "white rust"--oxidized zinc--will develop practically no bond. Therefore, considerable care would be required to maintain a galvanized surface free from oxidation until final encasement in concrete.

There is serious concern regarding slippage of galvanized tendons in certain anchorage systems. Further testing and research would have to be performed in this area.

Another serious objection to galvanizing is the phenomenon of galvanic action between zinc and bare steel. Extreme care would be required to prevent any interconnection of the two dissimilar materials, such as galvanized prestressing strand and mild reinforcing steel, or corrosion could in fact be accelerated.

Economically galvanizing would be quite expensive. Industry has quoted increases of from 10 to 25 percent in cost for furnishing galvanized tendons. There would be an additional increase of a minimum of 10% to make up for a loss in strength inherent in galvanizing prestressing steel.

2. Protective Coatings

We recommend the specifications be revised to give additional assurance of corrosion protection as it applies to post tensioned systems by requiring that prestressing steel shall be

further protected after placement in enclosures or conduit by a corrosion inhibitor approved by the Engineer. Such an inhibitor should be maintained in the enclosure to the satisfaction of the Engineer up until the time the prestressing steel is grouted. If the enclosures are back flushed after pouring concrete, the corrosion inhibitor shall be replaced.

Such corrosion inhibitors would be a vapor phase inhibitor--V.P.I. as produced by the Shell Oil Company, or solutions containing inhibitors such as sodium nitrite, sodium benzoate, sodium dichromate, or sodium cinnamate. There are no doubt others which would be equally effective. V.P.I. could be introduced in a saturated aqueous solution, by sprinkling on the tendon as it is introduced into the duct, by blowing it through the duct, by dissolving it in a highly soluble liquid such as an ethyl alcohol and introducing it as a mist by spraying through an atomizer.

3. Transporting, Handling and Storage

Specifications dealing with transporting, handling and storage should be amplified in the following areas. It should be clearly stated that the factory treatment or process include complete protective measures from mill origin until final encasement in grout or concrete. We should require that the treatment include some type of corrosion inhibitor. At present the treatment in most cases is simply to wrap the steel in paper or plastic. We should require that any damaged wrapping be replaced at once. The package should state the type, date and amount of corrosion inhibitor so that it can be replaced if necessary.

4. Time Limit for Pretensioning

For pretensioned concrete members, the time between placing the strand in the forms or stressing bed and placing concrete shall not exceed 3 days unless methods acceptable to the Engineer are employed to protect the prestressing steel.

5. Inspection of Tendons

For post tensioned members, the Engineer should be allowed, at no cost to the State, to remove prestressing steel tendons to inspect for corrosion whenever, in the opinion of the Engineer, adequate protective measures are not being used.

6. Grouting

Grouting specifications should be expanded to include control of water content, additives, strength of grout, and plastic volume change. See "Tentative Recommended Practices for Grouting Post-tensioned Prestressed Concrete", P.C.I. Journal, June 1960.

Other Measures to Insure Uniform and Proper Protection of Prestressing Steel:

1. Training Program

It is recommended that a training program be developed to assist BDR's in handling construction problems peculiar to post-tensioned construction.

2. Continued Research

There is a very definite need for continued research in this field of corrosion of prestressing steel. Further work should be done in the field of galvanizing to explore various unknowns such as the potential danger of galvanic action, the long term effect of galvanizing on bond as well as further research into the initial effect, the effect of galvanizing on the physical properties of the steel, and the effect on anchorages. Such research should be directed to also include the possibility of using galvanized reinforcing steel.

Further research into the permeability of prestressed concrete is needed. The possibility and degree of intrusion of chlorides, sulfates, and other harmful salts into the concrete from its environment need be studied. Parameters which influence the permeability of concrete are the amount of cover, cement factor, water-cement ratio, various additives, etc. The possibility of using coatings to render the concrete impermeable and the possible addition of a substance to the grout which would inhibit corrosion also need be considered.

Further investigation is required to determine the availability of effective protective coatings other than what has already been mentioned. Limited research on the use of vinyl wash and inorganic zinc silicate paint indicates excellent initial bond resistance. Over-all effectiveness is presently unknown.

To determine the existence and degree of corrosive attack of prestressed tendons, prestressed members which are available for destruction either in the manufacturers' plants or due to structure obsolescence, etc. should be opened up and examined. Where feasible on existing structures, both post-tensioned and pretensioned, portions of the prestressing tendons should be exposed for inspection to determine if corrosion attack is occurring.

3. Special Designs

Designers should consider special treatment of structures in highly corrosive environments; for example, over or near the ocean. This treatment could include extra cover, extra cement, or even galvanizing all steel - re-bars as well as tendons.

An immediate proposal is to include additional cover for prestressing steel comparable to that required for conventional reinforcement, Vol. I 6-8.2.

4. Continue Committee

A permanent committee should be formed to continually review the problems associated with corrosion of prestressing steel. This committee should continue investigating the possibility of galvanizing and the use of various corrosion inhibitors. It is suggested that the committee consist of:

T. J. Bezouska - Chairman
R. C. Blake
J. R. Stoker
C. Stewart
R. Stratfull

Current Corrosion Committee

Eric Nordlin
L. Krueger
J. R. Stoker
T. J. Bezouska
R. C. Blake, Chairman

VI. SPECIFICATIONS

B 50-01 (Cont'd.)
4-12-65

All prestressing steel shall be protected against rust or other results of corrosion and physical damage at all times from manufacture to grouting or encasing in concrete. It shall be the responsibility of the Contractor that all prestressing steel shall be free from rust or other results of corrosion until grouted or encased in concrete.

Prestressing steel shall be packaged in containers or other shipping forms for the protection of the steel against physical damage and corrosion during shipping and storage. A corrosion inhibitor which prevents rust or other results of corrosion shall be placed in the package or form, or, when permitted by the Engineer, may be applied directly to the steel. The packaging or form shall effectively retain and prevent the loss of the corrosion inhibitor. Packaging or forms damaged from any cause shall be immediately replaced or restored to original condition.

The shipping package or form shall be clearly marked with the following information:

> A statement that the package contains high-strength prestressing steel, and the care to be used in handling. The type, kind and amount of corrosion inhibitor used, including the date when placed, safety orders and instructions for use.

The corrosion inhibitor shall have no deleterious effect on the steel or concrete or bond strength of steel to concrete. A sample of the corrosion inhibitor proposed for use, with instructions for use, shall be submitted to the Engineer for verification of claimed properties.

The Contractor shall submit evidence to the Engineer that the proposed corrosion inhibitor at its intended dosage can effectively inhibit the corrosion of the steel in those applications as defined by these specifications.

The Contractor shall also furnish to the Engineer a certification of the corrosion inhibitor in the following form signed by the manufacturer:

> This is to certify that the product (trade name) as manufactured by the (company) is a corrosion inhibitor to be used for prestressing steel and contains (list the chemical(s) and their proportion (s) in the corrosion inhibitor).

Prestressing steel for post-tensioning which is installed in members prior to placing and curing of the concrete, shall be continuously protected against rust or other corrosion until grouted by means of a corrosion inhibitor placed in the enclosure or applied to the steel in the enclosure. The corrosion inhibitor shall conform to the requirements specified herein.

Enclosures for prestressing steel shall be securely fastened in place to prevent movement.

All water used for flushing enclosures shall be saturated with either quick lime (calcium oxide) or slaked lime (calcium hydroxide).

Grout shall be mixed in mechanical mixing equipment of a type that will produce uniform and thoroughly mixed grout. Approved admixtures may be used in the grout. Water shall be first added to the mixer, followed by portland cement and any admixtures.

Mixing shall be of such duration as to obtain a uniform and thoroughly mixed grout without excessive temperature increase. The water content of the grout shall be kept as low as possible and shall be less than 5 gallons per sack of cement. Retempering of grout will not be permitted.

All grout shall be screened prior to being introduced into the grout pump and the grout shall be agitated as required to maintain uniformity. Injection of the grout into the enclosures shall be continuous until grout of a consistency equivalent to that being injected flows from each vent opening. Standby flushing equipment with sufficient capacity to flush out any partially grouted enclosures shall be provided.

VII. A GUIDE FOR THE USE OF SHELL VPI

Current Special Provisions for prestressing steel will require the use of a corrosion inhibitor to insure that the steel will be rust-free from the time it is manufactured until it is grouted or cast into the concrete. One of the more common commercial products is "VPI" as manufactured by the Shell Oil Co.

1. General Properties

"VPI" is a registered trade-mark for "vapor phase inhibitor". The product is a fine grained white powder (like flour) and is described as a nitrogen containing organic compound. This compound will vaporize and redeposit on the surface of metal. When a sufficient quantity of the vapor comes in contact with the metal, it will chemically prevent rusting. However, the action of the corrosion or rusting inhibitor can be nullified by the following:

a. Temperatures greater than 160° F. for more than a few hours.

b. Free water running over the surface of the steel.

c. Water that has a pH of less than 6.5 (acidic).

d. Free circulation of fresh air.

e. Barriers that prevent the vapor from contacting the surface.

f. The powder not being within 12 inches of the metal surface.

g. Water containing a high quantity of chlorides.

2. Available Types of Shell VPI

a. VPI 220 - gives rapid initial protection.

b. VPI 260 - gives long-term protection.

c. VPI 250 - is a mixture of VPI 260 and 220 which gives both rapid initial and long-term protection, most commonly used.

d. VPI 270 - used in acidic conditions, probably not applicable for use with prestressing steel.

3. Water Solubility of VPI

a. 5.4 pounds of VPI 220 will dissolve in 10 pounds of water.

b. 0.39 pounds of VPI 260 will dissolve in 10 pounds of water.

4. General Notes about Using VPI

a. The vapors are heavier than air.

b. Will protect steel under water and also above the water line if the concentration of the VPI is greater than 2% by weight of the water. However, for under water corrosion protection, it is more economical to use other types of inhibitors such as sodium benzoate, or sodium nitrite.

c. Some packaging materials are acidic, such as green wood. VPI 220, 250, and 260 will gradually deteriorate on these surfaces. Use neutral materials for packaging.

d. VPI vapors will not effectively penetrate cardboard or paper dividers.

e. VPI can be coated on wrapping paper, and protection is afforded prestressing steel when it is wrapped in this paper. In using VPI paper, the "coated" side must be on the inside toward the steel.

f. VPI is intended to be used for the prevention of the atmospheric corrosion of steel caused by oxygen and water vapor.

g. VPI is not poisonous when used in the amounts recommended and in accordance with the manufacturer's instructions. Like any chemical, excessive handling or inhalation may cause some reaction, and should be avoided.

5. VPI and Bond Strength

A heavy coating of VPI powder on the surface of the steel will significantly reduce the bond strength of the steel to the concrete. However, during normal construction operations where the ducts are flushed with water and grout is wasted through the duct during grouting, it is unlikely that a harmful amount of the VPI powder will remain on the steel.

To further reduce any concern that a coating of VPI powder can remain on the steel, the highly water soluble, and thus more easily removable, VPI 220 is recommended for use in the field.

The corrosion inhibiting vapor film on the surface of the steel will not affect the bond strength.

6. Protecting Prestressing Steel in a Dry Duct - Not in Member

Method 1. Sprinkle VPI 250 on the steel as it is fed into the duct. The amount will vary somewhat depending on the size and type of prestressing steel. A light uniform application of a few ounces per 100 feet is usually sufficient, keeping in mind that it will eventually be flushed out.

Method 2. Prior to the insertion of the steel, blow into the duct by means of air pressure approximately 2 ounces of VPI 250 per 100 feet of duct.

7. Protecting Prestressing Steel in a Wet Duct - Concrete Curing by Steam

At the conclusion of the steam curing, and within one day prior to the insertion of the prestressing steel, blow the accumulated concrete bleeding water out of the duct. Then blow approximately 4 ounces of VPI 220 per 100 feet of duct prior to the insertion of the steel. Plug the ends to provide reasonable air tightness.

8. Protecting Prestressing Steel in a Wet Duct - Water Curing of Concrete

If VPI was sprinkled on the steel as it was introduced into the duct, it is believed that corrosion protection will be afforded even after concrete is cast and water leaks into the duct. A monitor wire (see Sec. 10) should be used to check this assumption. If corrosion begins, VPI 250 should be blown into the duct in the amount of 4 ounces per 100 ft. Blow half this amount into each end.

9. Protecting Prestressing Steel in Pretensioned Concrete

During rainy, foggy or highly humid weather, if concrete placement is not completed on the same day as when the steel is placed in the bed, the following protective measures may be taken.

Sprinkle VPI 220 or water saturated with VPI 220 on the surface of the steel, and by means of a tarpaulin or other water shedding material cover the forms so that free water will not wash over the steel.

(At present, pretensioning is done in commercial plants where inspection is by the Materials and Research Department.)

10. Checking the Efficiency of the Corrosion Inhibitor - Field

a. Insert a length of oil-free and non-rusted steel strip or wire (not stainless) into each end of the duct as "monitors".

b. At time intervals of about 5 days, slide out the piece of corrosion monitoring steel and inspect for any trace of rust. If rust is observed on the steel, recharge the duct with VPI 220.

11. Repairing Packaging of Steel Wrapped with VPI Paper

a. Replace damaged areas with VPI paper, if available, or

b. Lightly sprinkle VPI 220 on exposed steel and seal torn area with water repellant paper or plastic.

12. General Cautions to be Observed when Using VPI

a. Any water entering a duct will wash the VPI from the surface of the steel and rusting can occur.

b. Immediately after the injection of the VPI into the ducts, cover the ends of the ducts to prevent the free access of atmospheric air to the interior. The cover on the duct need not be positively air-tight but should be reasonably tight.

c. High temperatures (160° F) can chemically destroy the inhibitor. Prolonged exposure to sunshine should be avoided.

d. Protect the duct during storage from direct exposure to rainfall or other sources of moisture as the water can dissolve the VPI and rusting of the steel can occur.

e. When injecting the VPI into the duct, good distributions will be evident when the powder is observed coming out the opposite end or an intermediate vent.

f. If possible, insert the steel into the duct at the end opposite from where the VPI was last introduced.

g. Immediately prior to grouting, thoroughly flush the duct.

h. When the duct is of such length so as to contain intermediate vents, inject the powder at each vent and also at each end of the duct.

i. VPI should be mixed with potable water only, and the pH of the water must be within 7 to 9.