DESIGN OF SYSTEMS FOR TIME DELAYED ACTIVATED INTERNAL RELEASE OF CHEMICALS IN CONCRETE FROM POROUS FIBERS, AGGREGATES OR PRILLS, TO IMPROVE DURABILITY

by

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(ABSTRACT)

Incorporation of chemicals into the internal matrix of cement or concrete, with later release occurring upon stimulation, alters the matrix parameters from those at the initial set. Permeability is reduced, for example, and therefore durability enhanced. The advantages of these designs would be the ability to reduce maintenance and repair costs in the initial building configuration and to delay the time of eventual repair. The components and the structure could take greater environmental abuse also.

Permeability is significantly reduced by release of a polymer from wax-coated porous fibers upon heating to temperature of polymerization. Freeze/thaw damage is somewhat reduced by the timed release of linseed oil or antifreeze from porous aggregates due to the freezing action itself. These example designs using timed release mostly gave improved durability performance when compared to

conventional treatments for durability or environmental distress. Concerns that significant strength reduction would occur due to heating or fiber loading were shown to be unfounded by our test results; indeed, heating and fiber inclusion increased strength. An adequate amount of wetting of the samples could be obtained with 2.75% volume of fibers; however, above a 2.75% volume of fibers, fibers do reduce the strength. Results were analyzed by the method of comparing results in the samples with factors varied to results in samples without variable factors, that is, by comparing to the controls.

This research shows that timed internal release of chemicals into cement can be accomplished; it appears feasible and is potentially useful.

Long-term tests need to be performed on such factors as chloride ion intrusion/ corrosion tests. Filled fiber, aggregate or prill manufacture, storage, and placement need to be researched and assessed for cost. Design of components using only targeted areas for release in the component and the use of time released fibers in reinforced cement laminates should be evaluated.

DEDICATION

To Paul, my new husband; to Minnetta, the mother who always believed in me; and to God, with whom all creative things are possible.

ACKNOWLEDGMENTS

I would like to thank Dr. Francis T. Ventre, Chairman, and my committee members Dr. Halbert Brinson, Dr. Richard Walker, Professor Robert Schubert, and Dr. Jerry Householder for their unfailing assistance and support throughout the study.

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CHAPTER I

INTRODUCTION: BACKGROUND OF THE PROBLEM

In the United States, where concrete is the most widely-used building material (Hobbs, 1988, preface), it has become clear in recent decades that the costs for maintenance, repair, and replacement for structures and infrastructures is much higher than initial costs. As a result, durability has become one of the important cost issues for design.

In the American Concrete Institute conventional designs for components and structural systems, the durability issue is addressed mainly by the depth of the concrete: to prevent corrosion, a thicker cover is needed; to reduce microcracking, fibers are included, for example. However, durability is not a function of the concrete material by itself. It is the relationship of aggressive environmental agents intruding and ingressing into the material as related to the material properties, especially the permeability, which controls the rate of ingression and the rate of penetration of destructive environmental agents which deteriorate material properties such as modulus of elasticity. The deterioration of concrete is closely related to the way in which aggressive environmental agents penetrate and attack. Because permeability controls this rate and the associated pore structure, size, distribution, and cracking, it is then a most significant measure of the ability of environmental agents to intrude. Durability is not a property of concrete by itself. It must be evaluated as a function of performance versus time, it is influenced by the environment in which the concrete structure serves as well as the properties of the concrete itself. Durability problems specific to concrete in an environment must be addressed by changing the adaptable properties over time and, hence, controlling durability.

The hypothesis of this study is that by incorporating physical or chemical means into the matrix of the material for later release, the material matrix can evolve or adapt to changing environmental and material circumstances over time; certain parameters such as matrix permeability, pore, and crack structure can be altered. This in turn can alter the potential for environmental degradation such as freeze/thaw damage and corrosion damage.

Design of Systems for Activated Internal Release

The release of chemicals into the matrix to adapt the material to changing circumstances over time can be in direct response to the intrusion of the environment. The intrusion of chloride ions, the intrusion of water, which can freeze, or loading which can cause cracking are examples of this. A planned response to changes known to occur at specific times in the life of the concrete can also enhance durability. Examples of release in direct response to the naturally timed intrusion of the environment are (see Figure 1) (a) crack sealants may be released from porous fibers flexed due to loading, (b) calcium nitrite may be released from porous polypropylene fibers near the rebars due to degradation of a pH sensitive

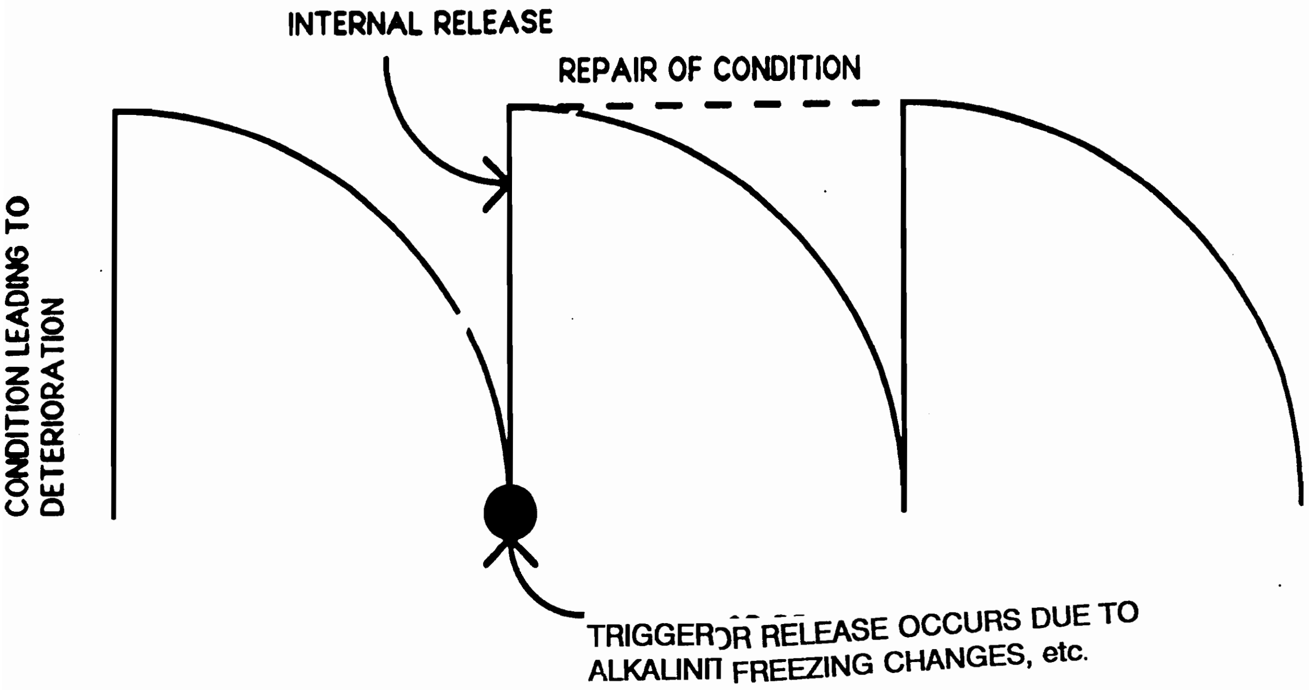


Figure 1. Release in direct response to naturally timed intrusion of the environment.

fiber coating which degrades at pH 11.5 (the level at which corrosion starts, thus reducing the corrosion on the rebars); (c) porous aggregates saturated with propylene glycol may release these chemicals into the matrix when freezing/thawing pressures occur, thus the freeze/thaw damage may be reduced; and (d) Xypex, a catalytic crystallizing agent, may release from prills, after the matrix is set. A prill is a mixture of the Xypex and wax or polyol made into capsule form. When heat is applied the wax melts (or it releases the Xypex due to polyol degradation in alkalinity), releasing the Xypex to crystallize in the matrix. This reduces matrix permeability.

An example of release timed in response to a stimuli caused by human intervention is (see Figure 2) (e) methyl methacrylate which may release from porous fibers coated with wax when heat is applied. This occurs after matrix is set and heat is applied. The matrix would dry out as preparation to draw in the methyl methacrylate. The polymerization of the methyl methacrylate is also caused by the heat. The polymerization in the matrix pores reduces permeability. All of these designs are illustrated in Figure 3.

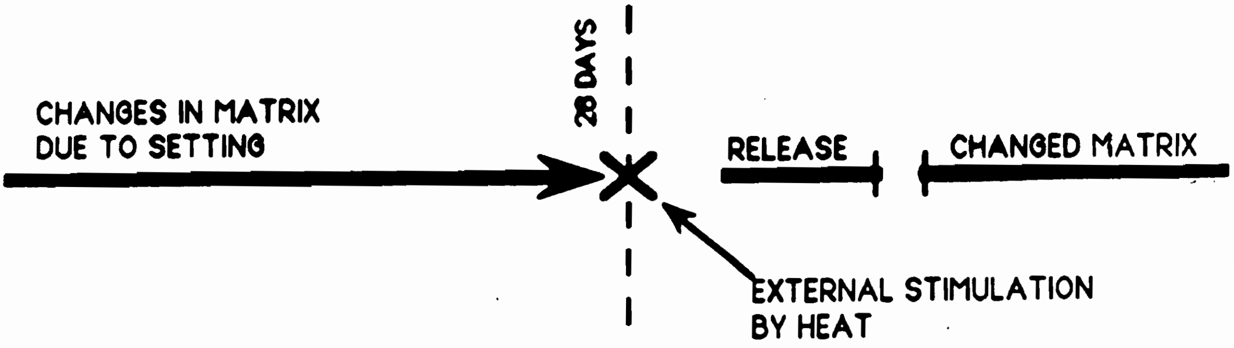
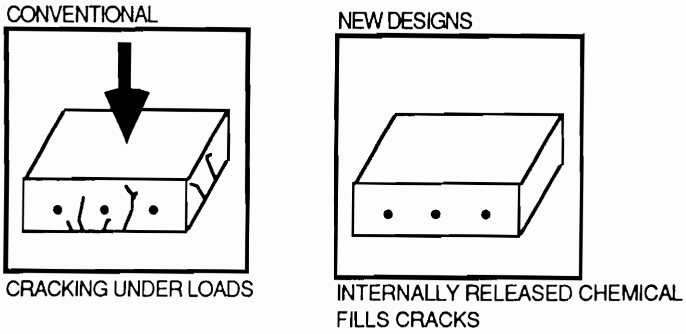


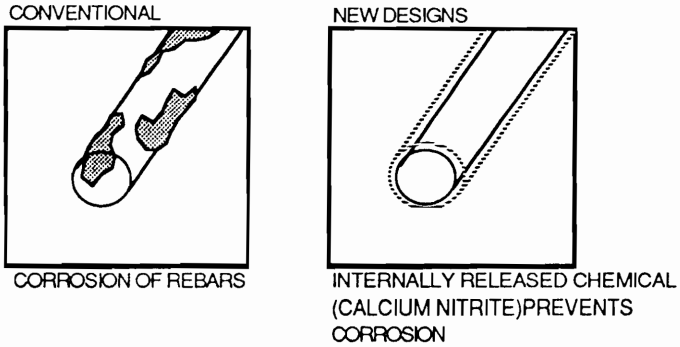
Figure 2. Timed release in response to a stimuli caused by human intervention.

Timed release of internal chemicals were also tested using two nonconventional cementitious materials: dense silica fume cement and phosphate bonded sintered bottom, and fly ash. In the first design: (a) after the matrix is set, water

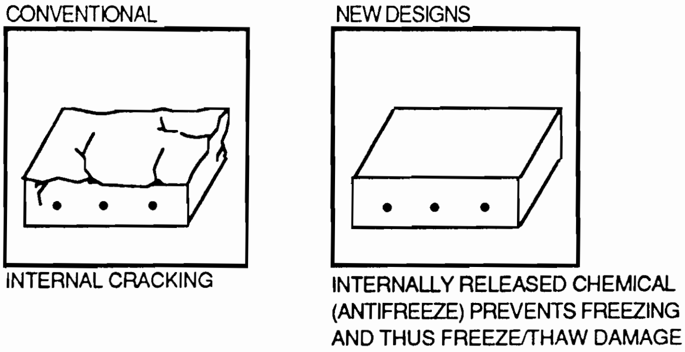
a) Cracking due to loading



b) Corrosion of rebars



c) Freeze/thaw damage



d) Permeability

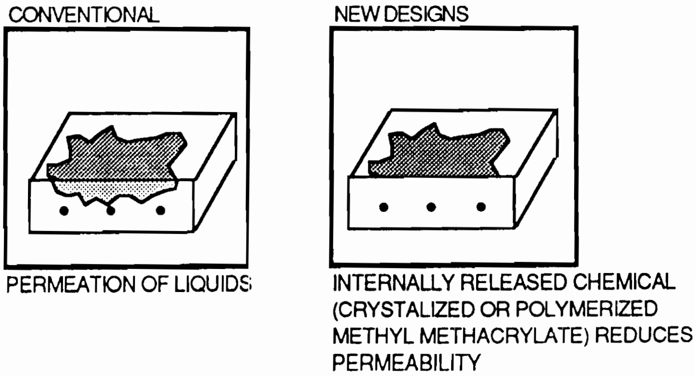


Figure 3. Alleviating environmental distress.

will release from porous aggregates into very dry, dense silica fume concrete. Usually, this material self-desiccates and causes cracking. We expect the time release of water from the aggregates due to water demand from the matrix to reduce the microcracking. This is in the category of release in response to a natural change. (b) Polyimides would release after the matrix is set from porous fibers coated with wax when heat is applied. It is in the category of one-time human-caused release. The matrix of phosphate bonded and sintered bottom ash composed of phosphoric acid and bottom ash is very permeable. The methyl polyimide would act as a polymer impregnating agent. It is one of the few materials known to reduce permeability and not carbonize at the 600° C used in sintering.

These materials are designed then to address the general durability issues of (a) permeability (porosity, structure, size), (b) cracking due to loading and self-desiccation and the specific penetration and attack of (c) chloride ion intrusion (causing corrosion), and (d) water and ion intrusion subjected to osmotic pressure causing damage such as freeze/thaw damage.

Conventional Designs for Durability and Potential Impact of Activated Internal Release Designs on Them

American Concrete Institute (ACI) designs treat durability of concrete as a property of the concrete to be embodied in the concrete from its first mix. New research sponsored by various organizations, however, investigates the problems introduced by some of those conventional designs. Some of these conventional design strategies are:

1. The conventional design strategy for permeability is to make the concrete cover thicker. The design of a system for activated internal release to reduce permeability would release the crystallizing agent or the polymer impregnator after the matrix has been set up to fill in the pores after hydration has taken place.
2. One conventional design to prevent loading cracking is the addition of fibers which interrupt the energy of cracking. The cement/fiber bond is weak, thus causing a reduction in compressive strength. The activated internal release of chemicals from fibers to reduce cracking would increase the bond between fiber and matrix. The crack sealant would flow out of the fiber, bonding the fiber well to the matrix.
3. Cracking is usually due to self-desiccation if a low water/cement ratio is used such as in dense silica fume cement. It would be alleviated by the activated internal release of water from porous aggregates in the systems designed in this report.
4. Freeze/thaw damage is conventionally prevented by the use of air entraining additives in the initial mix. This weakens the compressive strength due to the inclusion of small air bubbles, especially in high

strength concretes. The activated internal release of anti-freeze agents from porous aggregates could eliminate the problem of reduced compressive strength due to air entraining agents.

5. Conventional design strategies to reduce corrosion damage involve increased concrete cover and coating of steel reinforcing bars. The increased cover depth increases weight and cost. The anti-corrosion coating on steel reduces the bond between matrix and reinforcing bar. Internal release of calcium nitrite to protect the steel reinforcing bars against corrosion would eliminate the need for coating the reinforcing bars, thus increasing the bond between steel and concrete. The depth of concrete cover required to prevent ion intrusion would also be reduced.

The following are basic assumptions underlying the idea of timed, internal release:

1. If a chemical is released internally, then it could move more easily and quickly throughout the concrete matrix giving better coverage, or bonding with the cement;

2. If a chemical is released over time in response to environmental events, then it would reduce the time-dependent degradation factors such as freeze/thaw damage, corrosion damage, and so forth, by responding to each event as it occurs;

3. If a chemical such as a polymer or adhesive is released from inside the fiber into the matrix, the bond between fiber and matrix could be improved;

4. If a specific environmental event triggers the remedial action required to prevent damage from that event within the concrete, then the performance parameter could be increased and the cost of the material designed for protection from that environmental event reduced.

Some factors which influenced the material designs are as follows: fibers give added flexural strength to the cement matrix but can reduce compressive strength above 2.75%, whereas microcapsules reduce the overall compressive strength by adding defects yet add no other strengths. Viscosity of the fluid to be contained in the fibers, aspect ratio, and the porosity of the fiber walls all determine the rate of release from the fiber. The porosity and the moisture in the cement matrix are important factors in determining the rate of flow of the chemicals in the cement. In general, one must determine the conditions of the cement matrix at any given time, the desired time and amount of release into the cement matrix, and use those chemicals and physical attributes present or added by the environment or human intervention as mechanisms to open the fibers, draw off the chemicals, and cause the chemicals to penetrate into the matrix. Thermodynamic factors affecting flow of fluids across a permeable matrix govern the design of the systems. Yet the quantitative description of all the pertinent factors is not available in the literature.

The objectives of the research are to assess (a) if the timed internal release of chemicals in cementious matrix can be accomplished, (b) if it apperas feasible, and (c) if it is potentially useful. In order to do these first two assessments, the following research questions will be answered for seven specific designs for timed internal release of chemicals:

Research Question 1--Does the design for timed release of internal chemicals work? Relative parts to the question, on the workability of the release sequence for the designs for timed release, are:

1. Is the chemical taken up in the fibers or aggregate?
2. Can the carrier be coated?
3. Is the chemical retained in the coated carrier?
4. Will a stimuli release the chemical?
5. Is the chemical released into the matrix?
6. Will the chemical move into the matrix?
7. Visual or chemical analysis to see success of release.

Research Question 2--Does the successful release alleviate the particular environmental distress or reduce cracking or permeability?

Research Question 3--Do the fibers and stimuli degrade the strength or permeability properties; what are the strength and permeability contributions of the various separate factors of wax, chemical, fiber?

Research Question 4--Are these designs an improvement over conventional treatments for impermeability or crack reduction and environmental distresses?

Research Question 5--What are the effects of manufacture, storage, and in-the-field problems?

Potential usefulness will be assessed by answering the following questions on design and cost implications:

1. What would be the design implications of activated internal release in regard to the conventional designs for durability?
2. If durability is improved, how would costs for maintenance and repair be changed?
3. In a specific example, corrosion, what would be the design improvements and cost reductions by the use of internal timed release of chemicals?
    a. If a release is to be accomplished from a particular volume of fibers or aggregate located in one part of a component, what would be the cost and design implications of that?
    b. What would be the cost and design advantages in this example?
4. What would be the overall costs and design values of these design changes?
5. What new kinds of structural and/or component designs would benefit most from these internal release mechanisms?
6. What would be the specific impacts of these systems for internal release on (a) different building types, (b) for use in different environments, (c)

different building details, (d) on repair regimes, and (e) on different structural systems?

7. Of what value would timed internal release be to the historic development of plastic expression in reinforced concrete?

(Note. A glossary of terms is provided in Appendix A.)

CHAPTER II

RECENT RESEARCH; REVIEW OF THE LITERATURE

Recent concrete and cement research attempts to address the major performance problems of cement materials; namely, permeability/cracking, as well as brittleness. Developments in cement research on permeability either attempt to fill the pore structure or reduce the number, size, and structure of the pores. For instance, dense silica fume cements attempt to fill up the pore structure with close packing of small particles, the micro silica. Polymer impregnation which occurs at initial mixing, attempts to deposit polymers in the pore structure. Latex modified cements leave a rubbery deposit throughout the paste to "form a continuous polymer film" (Mindess and Young, 1981, p. 624). Macro defect-free concrete is designed to reduce the macro defect size and close up the pore structure. These last three materials, all of which are designed to reduce the pore size, are subject to the microstructure of the cement as it is set at the initial mix. In reality, the matrices are not perfectly packed nor are free of pores and are therefore subject to the effects of the environment on the material over time; that is, they have durability problems over time. Dense silica fume cement (DSP) cement is prone to self-desiccation which causes internal cracking (Paillere, Buil, and Serramo, 1989). In macro defect-free concrete, there is moisture sensitivity which is due to shrinkage at the initial set (Weiss, Gertner, and Tresouthwick, 1984, p. 22). Polymer impregnated cement is rarely completely waterproof because it can rarely be impregnated to more than 70-80% of the volume, leaving the rest vulnerable to the environment. Macro defect-free concrete has also been found to be partially water soluble.

Recent research also addresses the other main issue in cement/concrete performance, that is, brittleness. The prevalent method proposed is the addition of fiber reinforcement to increase toughness strength. The disadvantages to this approach are (a) the fibers deteriorate in the cement environment over time, despite much research on new alkali resistant fibers, and in less alkaline cements, (b) they are expensive, (c) they are difficult to place, and (d) the bond between fiber and matrix is a site of structural weakness. Fibers toughen brittle cement materials by acting as crack arrestors or dissipators of crack energy. Considerable energy is consumed by this.

Integration by Proposed Designs of Trends in Recent Research in Cement/Concrete

These systems designed with activated internal release are attempts to solve the most important research problems of (a) brittleness and (b) permeability/cracking and integrate them in a new way. The approach is to combine the increased toughness from the fibers with the reduced permeability/cracking or reduced freeze/thaw damage and corrosion damage by the internal release of chemicals to reduce permeability/cracking or attendant freezing or corrosion.

In addition to attempting to address a combination of the most important research goals of reducing permeability and brittleness, the systems designed with activated internal release, release their chemicals inside the concrete as a result of an environmental trigger or human intervention after matrix, set giving them huge potential advantages. These are:

1. The internal release of the chemical could change the microstructure of the cement set and therefore change the permeability/cracking and associated effects, and related freeze/thaw damage and chloride intrusion damage;
2. If the chemical is released internally, it could penetrate thoroughly throughout the matrix;
3. In the cases where environmental events trigger the remedial action, the effectiveness of the treatment could be increased and the cost of the construction material reduced.

The potential disadvantages would be that these systems are novel; therefore, workmen must be trained. Field conditions may be such that it will not work well in some unforeseen way. These must be investigated further.

Related Research on Internal Release in Building Materials

Research on timed release of chemicals is mainly done in the field of biology, botany, medicine, or in chemical separation science. Nevertheless, the Federal Highway Administration (FHWA) sponsored a study on the use of internally sealed concrete containing Montan-paraffin wax beads. The conclusion was that specimens of 2 cu. ft. heated on the top surface only released the wax to a maximum depth of 1/16" heated at the maximum allowable of 425° F and that it was too costly and difficult to heat the slabs in the field to obtain matrix dry out and wax melting (Geishauser and Cady, 1977, pp. 85-94). They therefore funded the Battelle Research Laboratory program to develop degradable microcapsules in which the sealant is gradually released with time in order to stop chloride ion and water ingress without the application of heat for melting or removal of free moisture.

The concept of internal timed release to reduce corrosion and freeze/thaw damage was investigated by Battelle Research Laboratories (Kistler and Benton, 1983). That work established that the use of encapsulated sealers in bead form can significantly reduce the permeability and the problems of corrosion and freeze/thaw. The study was limited to the use of degradable beads which release their sealants into the concrete. The problems encountered were (a) the incorporation of the beads produced significant defects in the cement, sometimes causing a reduction in the compressive strength of the concrete; (b) some of the chemicals used interfered with the set of the concrete; and (c) some chemicals would not release into the matrix of the concrete. Linseed oil and silane liquid sealants were made into prills with ammonium stearate and degradable polymer carriers. Some types of beads reduced the compression strength depending upon the total volume of beads used plus entrained air. Freeze/thaw resistance depended only on entrained air, whereas lab tests showed the chloride penetration was reduced twofold by the addition of a 4% volume of beads. The degradable polymer linseed oil beads were optimized for bead formulation, size, loading, and other factors before conducting field tests. Field tests for chloride penetration, however, showed marginal benefit from the beads and gave a higher permeability. Production costs would raise the price of concrete mix about 2.5 fold, well within the range of a feasible material. Simulated storage revealed they could be stored up to 90° F but agglomerated at 105° F. The polymer materials degrade over time but the prill provides mechanical integrity for the beads (Kistler and Benton, 1983).

Solutions to Problems of Internal Release Materials by the Systems Designed for This Report

The systems designed herein use fibers or porous aggregate to give mechanical integrity for the encapsulation system. The fibers do not degrade the other mechanical properties. This is an improvement over the Battelle work. The coating, wax in most cases, also acts to seal the concrete. The filled fibers can be stored at room temperature or temperatures at which paraffin wax will not melt.

Durability in Concrete

Theoretical Basis for Understanding Durability and the Deterioration Processes

Builders, owners, and tenants need durability data in order to obtain the most building for their money, and make necessary repairs in a planned way. The question is, will the buildings deteriorate to an unacceptable level within their designed service life? (Browne, 1986, p. 102). When that stage is approached, demolition or upgrading repair are the only choices.

"Durability of the particular building material, cement, or concrete is not a property of the material but an attribute which can be evaluated by function of performance versus time" (Cabrera, 1986, p. 154). The attack by the environment has two stages: the time required to penetrate and the time for deterioration (Browne, 1986, p. 104). The performance life function is schematically shown in Figure 4 (Cabrera, 1986, p. 29). The resistance to deterioration of the particular material under a number of ingressive environmental conditions is represented in the figure. Rather than accept the assumptions of Figure 5 that "the crucial question is when will a building deteriorate to an unacceptable level" (Browne, 1986, p. 102), the preferred vision of deterioration is that of the Figure 6 (after Browne) in which deteriorating structures are restored. Figure 7 shows that variations occur within a structure, usually due to the quality of the concrete cover in the area and the ability of the environment to access that part of the structure (Browne, 1986, p. 102).

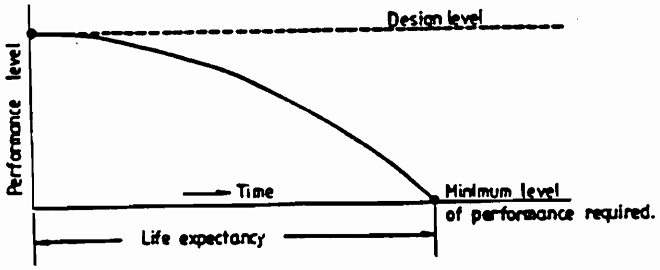


Figure 4. Durability schematically represented by the performance-life function (from Cabrera, 1986, p. 29).

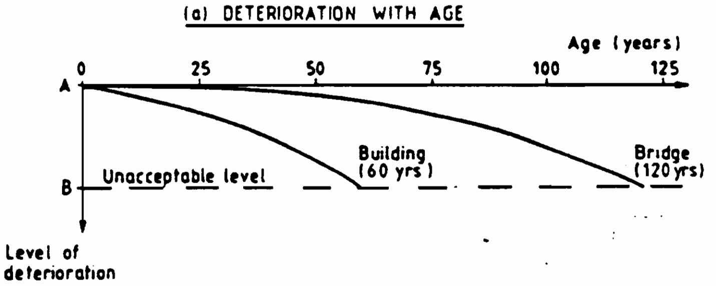


Figure 5. Deterioration with age of concrete durability (from Browne 1986, p. 103).

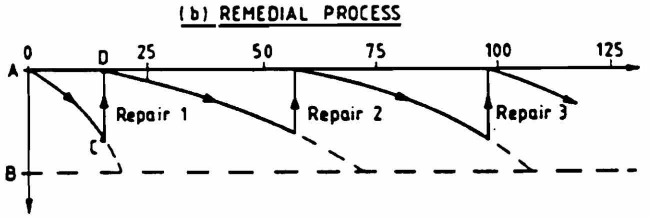


Figure 6. Remedial process of concrete durability (from Browne 1986, p. 103).

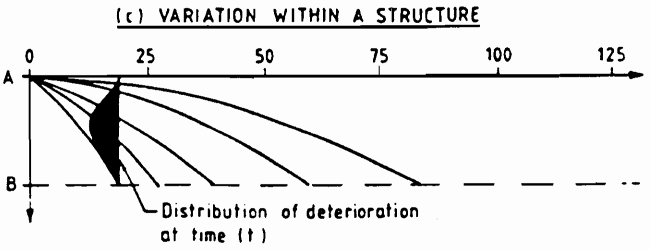


Figure 7. Distribution of deterioration (from Browne 1986, p. 103).

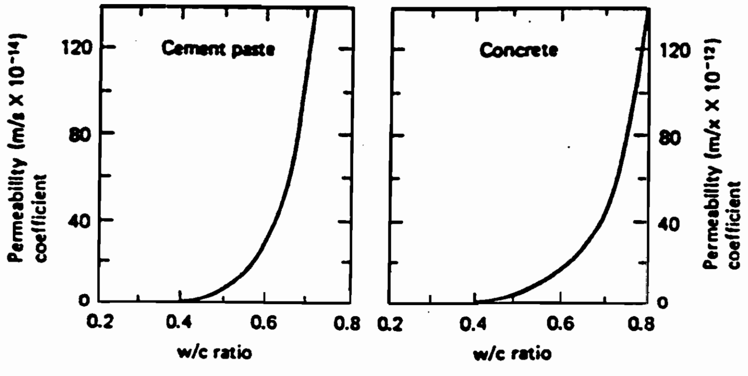
Permeability

Permeability controls the rate at which aggressive agents will penetrate and attack the concrete. Cements of similar total porosity may have very different permeabilities because of the pore structure and size (Peacock, 1986, p. 154). They may have different strengths for the same reasons (Peacock, 1986, p. 154). Penetrants can be gas, liquid, or ions. Permeability is the property most indicative of likely durability (Peacock, 1986, p. 154). Permeability represents the ease with which water or other fluids can move through concrete, transporting aggressive agents and thus it is of critical importance for many types of distress experienced by concrete (Young, 1988, p. 2). Permeability is comprised of the factors of porosity, pore size, pore structure, and cracking. The major determinant of durability is in most cases the water/cement ratio because this determines the permeability (Mindess and Young, 1981, p. 544). Lower water/cement ratio causes the concrete to have greater strength and less porosity (see Figure 8).

The permeability of concrete is measured by determining the rate of flow of a fluid through a concrete slab; that is, it obeys D'Arcy's law for flow through a porous medium:

$$V = K_p \frac{h}{x}$$

V = rate of flow of water, h = the head of water, x = thickness of the specimen, and K_p = permeability coefficient (Mindess and Young, 1981, p. 546).



(a) (b)

Figure 8. Influence of w/c ratio on the permeability of: (a) cement paste (from T. C. Powers, L. E. Copeland, J. C. Hayes, and H. M. Mann, Journal of the American Concrete Institute, Vol. 51, No. 3, 1954, pp. 285-298); (b) concrete (adapted from Concrete Manual, 8th ed., U.S. Bureau of Reclamation, Denver, Colorado, 1975) (Mindess and Young, 1981, p. 545).

The usual treatments to reduce permeability are: (a) application of sealants from the surface, (b) reduction of water/cement ratio, and (c) close packing of particles. The related problems are that sealants penetrate imperfectly and only to a certain distance and can trap water below, preventing its evaporation. Close packed materials with low water/cement ratio such as dense silica fume cements (DSP) tend to self-desiccate, causing cracking or, like MDF cements, are susceptible to swelling in wet conditions and loss of strength (Weiss et al., 1984, p. 22). Replacing the water in the pores with a solid material, thereby eliminating the void space, is the theory of polymer impregnated concrete.

Solutions to Permeability Problems in Concrete by the Use of Internal Release Chemical

The two remedies for permeability presented in the systems designed herein are the release of a crystalizing powder Xypex or a polymer which would fill the pores, reduce the size of the pores and change the pore structure by disrupting their continuity, and thus would reduce permeability.

Polymer Impregnated Concrete

"The problem of incorporating a solid into the pore system is solved by using a liquid monomer to impregnate the concrete and subsequently polymerizing the monomer to form the solid polymer in situ within the pores" (Mindess and Young, 1981, p. 616). The typical properties of plain concrete and polymer impregnated concrete are shown in Tables 1 and 2. Methyl methacrylate is

Table 1

Typical Properties of Plain Concrete and PIC

Properties	*Plain*	*PIC (Methyl methacrylate)*	*PIC (Styrene)*
Compressive strength (28 days), MPa (lb/in.^{2})	37 (5300)	140 (20,300)	70 (10,000)
Tensile strength (28 days), MPa (lb/in.^{2})	2.8 (400)	11 (1600)	5.8 (840)
Flexural strength (28 days), MPa (lb/in.^{2})	5.2 (750)	18 (2600)	—
Modulus of elasticity, GPa (lb/in.^{2})	24 (3.5×10^6)	44 (6.3×10^6)	44 (6.3×10^6)
Permeability of water, m/s (ft/yr)	5.3×10^{-4} (5.3×10^4)	1.4×10^{-8} (1.4×10^4)	1.5×10^{-8} (1.5×10^4)
Water absorption (%)	6.4	0.3	0.7
Thermal coefficient of expansion, 10^{-6}/°C (10^{-6}/°F)	10.0 (5.5)	9.5 (5.3)	9.0 (5.0)
Bond to steel, MPa (lb/in.^{2})	1.7 (250)	3.8 (550)	4.1 (600)

Note. From Mindess and Young, 1981, p. 616.

Table 2

Durability of PIC

	Plain	*PIC (MMA)*	*PIC (Styrene)*
Freeze–thaw			
Number of cycles	740	2650	5440
Weight loss (%)	25	2	21
Sulfate attack			
Number of days	48	720	630
Expansion (%)	0.488	0.006	0.003
Acid resistance (15% HCl)			
Number of days	105	805	805
Weight loss (%)	27	9	12
Abrasion resistance[a]			
Abrasion depth, mm (in.) per 1000g of shot	1.25 (0.050)	0.38 (0.015)	0.93 (0.037)
Total weight loss (g) of specimens	14	4	9

[a] Shot blast test, using a Ruemelin abrasion machine. (Based on data from "Polymers in Concrete: First Topical Report," Dept. BNL S0134, Brookhaven National Laboratory, 1968.)

Note. From Mindess and Young, 1981, p. 622.

commonly used because it has a low viscosity, low toxicity, can be easily polymerized, is inexpensive, and available (see Figure 9) (Mindess and Young, 1981, p. 617). The cementitious material must be first dried using approximately 150° C (Mindess and Young, 1981, p. 617).

> Saturation of the concrete pore system depends upon the viscosity of the monomer, the porosity and pore size distribution of the concrete, the hydrostatic pressure, and time. Overnight soaking with gravity gives 70-80% total impregnation by soaking in it overnight. Depth of penetration is proportional to the square root of time, indicating a diffusion process. (Mindess and Young, 1981, p. 618).

A problem of surface sealants is that they can plug the pores that exist in the concrete, thus trapping water which is migrated from another area beneath the surface treatment material. This water cannot escape and can be frozen in place, causing freeze/thaw damage (Bean, 1988, p. 7, 8).

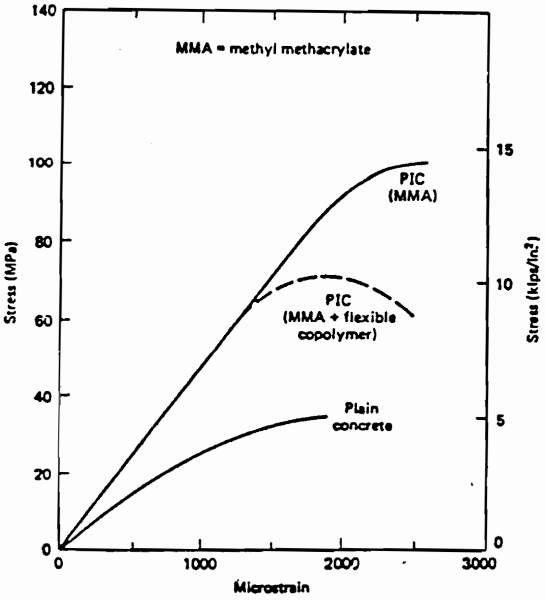


Figure 9. Stress-strain curves for PIC compared to plain concrete (Mindess and Young, 1981, p. 620).

Catalytic Waterproofing Agent

Xypex is a sodium silicate which crystallizes in the matrix (Xypex Company promotional literature, 1989). In the presence of water, Xypex, a crystal forming barrier, will grow deep into the concrete. They observed Xypex crystalline growth at 50mm within three weeks. Their literature cites the following information. It is a reactivation of the cement curing process that eventually blocks the capillary systems from passage of water but allows the passage of vapor for evaporation. In a normal setting, up to 25% of the cement will not become hydrated due to the protection against water which the chemistry of the concrete offers. Due to the addition of Xypex, this resistance changes, allowing water to reach the unhydrated cement. Crystals can grow and the reactions spread as a result of osmosis, dry particle reactions, and Brownonian movement. Normally, this material has been applied to the surface, and in such cases the crystals grow until they reach a point deep in the product where water is not available or all the cement has been hydrated. Construction joints can be made water tight and to withstand osmotic pressure in excess of six bar atmospheric pressure. If the Xypex is used with freshly mixed concrete, the effect is to retard setting, and other strength properties will be deteriorated. Independent companies (as presented in the Xypex literature) suggest that permeability in samples is nonexistent, there is no damage due to freeze/thaw cycling, and in the presence of many commonly damaging chemicals such as chlorine, ethylene glycol, mineral oil, acid, and the cylinders averaged between 14% and 24% increase in compressive strength compared to untreated cylinders (Xypex Company promotional literature, 1989).

The Advantages of Xypex Applied Internally

The advantages of Xypex applied internally protected from water as proposed herein would be (a) cutting the time for crystalline growth from weeks to days because the crystals would grow from points all throughout the specimen rather than the surface, and (b) the Xypex would not reduce strength properties as occurs if applied to wet concrete. The addition of internal release agents to concrete to reduce permeability by adding Xypex or methyl methacrylate as a polymer impregnator would affect design principles, in that high loads could be placed on the structures due to increased compressive strength, fewer reinforcing bars could be used due to increased tensile strength, and less concrete cover would be needed to protect the reinforcing bars from environmental factors. Also designs to prevent water buildup on the surface of the structure could be eliminated, air entraining would not be used due to increased freeze/thaw resistance, and the resistance to various chemicals such as acid would be increased, and expansion due to moisture intrusion would be less.

Cracking

Cracking, along with pore structure, size, and number of pores, contribute to overall permeability. Cracking begins during the hydration process usually due to drying and shrinkage but when the concrete structure is loaded, the stresses at the tips of the crack can become quite large and grow under repeated cycles of loading, thus a cyclic loading of concrete produces a hysteresis loop as seen in Figure 10 (Mindess and Young, 1981, p. 378).

Figure 10 shows that the area within the loop, the energy, becomes available to propagate cracks, eventually leading to failure. The relationship between the stress range and the fatigue life is expressed by the modified Goodman Law:

$$\sigma_{an}=\sigma_n(1-\frac{\sigma_m}{\sigma_\mu})$$

where σ_{an} is the stress amplitude for a given fatigue life, σ_n is the median fatigue strength for pure alternating stress as well as the mean stress and the ultimate stress (Mindess and Young, 1981, p. 373). Fatigue of concrete is well defined. If a single load will fail, the concrete at 4000 psi, then it should be able to handle an infinite number (10^6) of load cycles at 2000 psi (Richard Walker personal communication, July 1990). The Goodman Diagram is shown in Figure 11.

Figure 11 illustrates the determination of the maximum stress that concrete can withstand with 10^6 load cycles for given minimum stress; for zero minimum stress the conservative estimate is that the maximum load for 10^6 cycles of 50% of the static strength (Mindess and Young, 1981, p. 374).

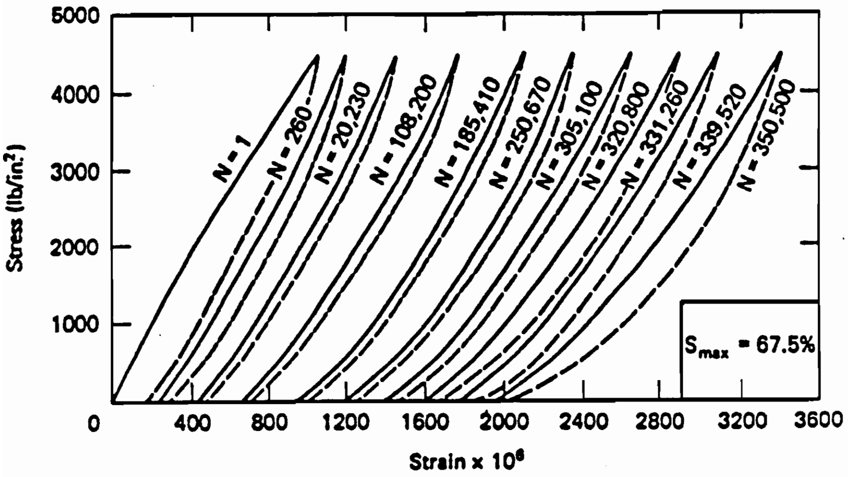


Figure 10. Variation of stress-strain curve with number of cycles (Mindess and Young, 1981, p. 377).

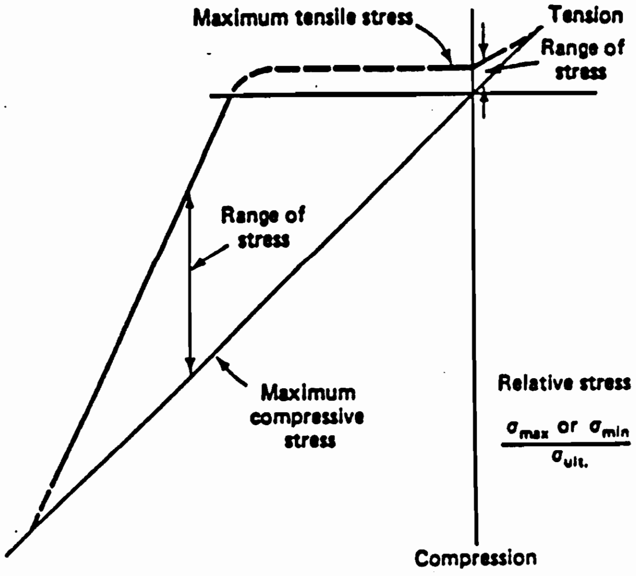


Figure 11. Modified Goodman diagram for concrete (schematic) (from Mindess and Young, 1981, p. 375).

The Miner hypothesis suggests that failure will occur when:

$$\sum_{1} \frac{n_1}{N_1} = 1$$

where n_1 is the number of cycles of load at some stress condition and N_1 is the number of cycles required to cause failure at that condition; the assumption is that there is a linear accumulation of damage due to each loading cycle (Mindess and Young, 1981, p. 376). These numbers are important because they can be used to determine the amount of chemical to be released over the life of the structure in the designs herein developed.

The conventional treatments for cracking are (a) surface application of materials such as paints; (b) application of materials which penetrate into the surface and block the pores, such as epoxy resins, asphalts, polymers; (c) injection of polymers and epoxies into the body of the concrete; and (d) very rapid setting cements applied as overlays (Mindess and Young, 1981, p. 575). Surface treatments tend to concentrate the cracking stresses into areas not treated and trap moisture inside the concrete due to the surface treatment (Bean, 1988, pp. 7-8). The latter can cause freeze/thaw damage to occur.

Solution to Cracking Problems Suggested by Design for Internal Release

In the system contained herein, the introduction of fibers into concrete will interrupt the energy build-up needed to cause cracking. The release of sealants or impregnators from the fibers will reduce permeability by filling in cracks as well as pores with chemical plugs.

Fiber Reinforcement

Low tensile strength of concrete can result in cracking. Fiber reinforced concrete is intended to reduce crack development by absorbing cracking energy. The most widely used fiber, fiberglass, is attacked by the alkaline environment of cement which degrades the strength of the fibers. Some glass fibers have been produced which are alkaline resistant, although the long-term durability issue is still open to question. The book on concrete by Mindess and Young (1981, p. 630) differentiates the other fibers as follows: Polymeric fibers, such as polypropylene, have lower elastic moduli in concrete, and therefore may even reduce the strength, but are effective in increasing impact resistance of the concrete. Kevlar and polyimides have high tensile strength and high modulus of elasticity but are expensive. Carbon fibers have high elastic modulus tensile strength and are costly. Organic fibers, based on cellulose, have low tensile strength and elastic modulus and tend to deteriorate in damp or alkaline environments (Mindess and Young, 1981, p. 630).

> The parameters which affect the mechanics of fiber reinforcement are the aspect ratio, i.e. diameter to length, the length of the fiber, the orientation, and the spacing between fibers. Most fiber reinforced concrete failure occurs at a bond failure or fiber pull-out. (Mindess and Young, 1981, p. 632)

A comparison of the various reinforcing fibers are presented in Tables 3 and 4. Typical fiber-matrix pull-out strength is a very important parameter (see Table 5). The fabrication of fiber-reinforced concrete is difficult because of the balling up of the fibers in the mixing equipment. The typical mix is shown in Table 6.

"The addition of fibers has little effect on compressive strength or the elastic modulus although tensile strength can be increased by high modulus fibers" (Mindess and Young, 1981, pp. 637-639). For the effects of fiber additions on flexural strength some investigators have found an increase of three times (Mindess and Young, 1981, p. 637). Toughness or the area under the stress strain curve is increased by the addition of fibers. This is important because toughness determines the rate of crack propagation (see Figure 12). The related factor, fatigue resistance, increases with increasing fiber content also (Mindess and Young, 1981, p. 641).

Solution to Problems by Use of Fibers in Designs Included in This Report

Nearly all fibers degrade in the cement environment and have poor bond with cement. The fibers in these designs are coated, even after release, leading to better durability of the fiber itself. The bond would be improved due to release from the fiber. The design of release of the polymer impregnator from a bundle of fibers would reduce cracking in two ways. Firstly, the fibers themselves would dissipate the cracking energy, and secondly, cracks extant would be healed by the

Table 3

Typical Properties of Fibers and Cement Matrix

Fiber	Diameter (μm)	Specific Gravity	Modulus of Elasticity (GPa)[a]	Tensile Strength (GPa)[a]	Elongation at Break (%)
Asbestos	0.02–20	2.55	165	3–4.5	2–3
Glass	9–15	2.60	70–80	2–4	2–3.5
Graphite	8–9	1.90	240–415	1.5–2.6	0.5–1.0
Steel	5–500	7.84	200	0.5–2.0	0.5–3.5
Polypropylene	20–200	0.91	5–77	0.5–0.75	20
Kevlar	10	1.45	65–133	3.6	2.1–4.0
Sisal	10–50	1.50	—	0.8	3.0
Cement matrix	—	2.50	10–45	3–7 × 10^{-3}	0.02

[a] GPa × 0.145 = 10^6 lb/in.^{2}.

Note. From Mindess and Young, 1981, p. 629.

Table 4

Typical Properties of Fibers

Type of fiber	Tensile strength, ksi	Young's modulus, 10^3 ksi	Ultimate elongation, percent	Specific gravity
Acrylic	30-60	0.3	25-45	1.1
Asbestos	80-140	12-20	~0.6	3.2
Cotton	60-100	0.7	3-10	1.5
Glass	150-550	10	1.5-3.5	2.5
Nylon (high tenacity)	110-120	0.6	16-20	1.1
Polyester (high tenacity)	105-125	1.2	11-13	1.4
Polyethylene	~100	0.02-0.06	~10	0.95
Polypropylene	80-110	0.5	~25	0.90
Rayon (high tenacity)	60-90	1.0	10-25	1.5
Rock Wool (Scandinavian)	70-110	10-17	~0.6	2.7
Steel	40-400	29	0.5-35	7.8

1 ksi = 6.9 MPa

Note. From "State of the Art Report on Fiber Reinforced Concrete," Report of ACI Committee, 544, Concrete International, May 1982, p. 11.

Table 5

Typical Fiber-Matrix Pull-Out Strengths

Matrix	*Fiber*	*Pull-out Strength, MPa (lb/in.²)*
Cement paste	**Asbestos**	**0.8–3.2 (115–460)**
	Glass	**6.4–10.0 (930–1450)**
	Polycrystalline alumina	**5.6–13.6 (810–1970)**
	Steel	**6.8–8.3 (990–1200)**
Mortar	**Steel**	**5.4 (780)**
Concrete	**Steel**	**3.6 (520) (first crack)** **4.2 (610) (failure)**
	Nylon	**0.14 (20)**
	Polypropylene	**1.0 (150)**

Note. From Mindess and Young, 1981, p. 333.

Table 6

Typical Proportions for Normal-Weight Fiber-Reinforced Concrete

Cement	**325–560 kg/m³ (550–950 lb/yd³)**[a]
***w/c* Ratio**	**0.4–0.6**
Fine aggregate/total aggregate	**0.5–1.0**
Maximum aggregate size	**10 mm (3/8 in.)**
Air content	**6–9%**
Fiber content	**0.5–2.5% by volume**[b]

[a] **Pozzolan is often used to replace some of the cement when high cement contents are needed.**

[b] **Steel fiber: 1% = 78 kg/m³ (132 lb/yd³); glass fiber: 1% = 25 kg/m³ (42 lb/yd³).**

Note. Mindess and Young, 1981, p. 634.

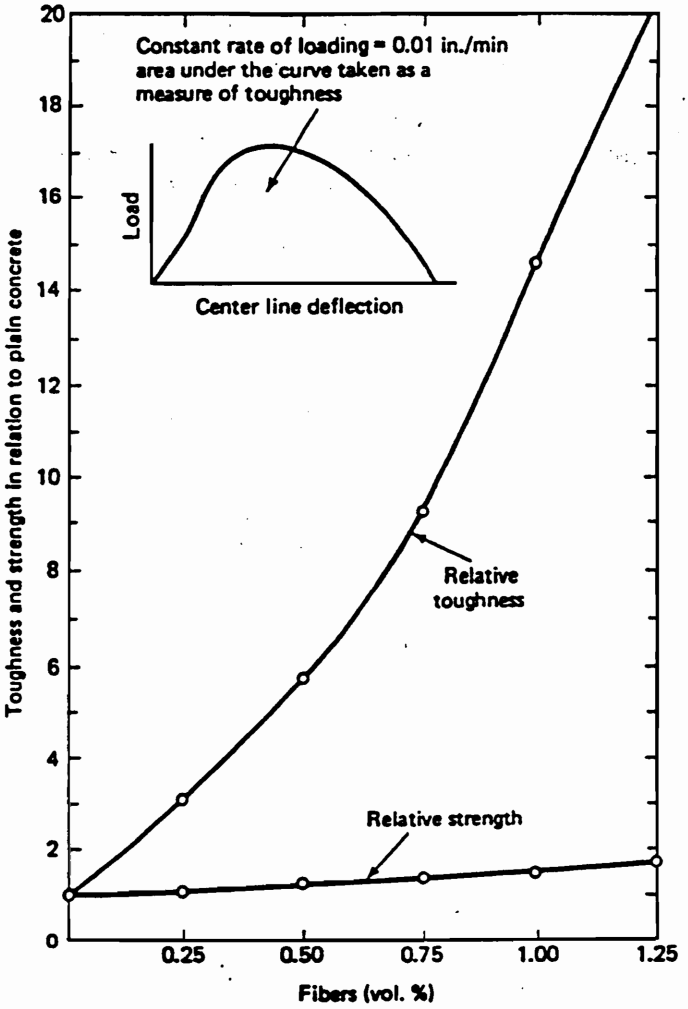


Figure 12. Effect of volume of fibers in flexure (from Mindess and Young, 1981, p. 640).

polymer impregnating substance. The design advantages for the system herein would be increased loading due to lower fatigue level, yield stress, and failure level; less freeze/thaw damage due to water intrusion; thinner cover needed to protect reinforcing bars from water intrusion; and fewer shrinkage and cracking joints would be needed, and thinner construction joints could be used.

Self-Dessication Cracking in Dense Silica Fume (DSP) Cements

Drying cracking due to self-desiccation is a problem in low water/cement ratio cements such as dense silica fume cements. Silica fume cements reduce the pore size by close packing of finer materials. Superplasticizers are necessary to attain this low water/cement ratio. The uniform distribution of hydration products and the elimination of larger pores results in a net increase in compressive strength of up to 43,000 psi (Young, 1985, p. 64). A model of the structure is shown in the Figures 13 and 14.

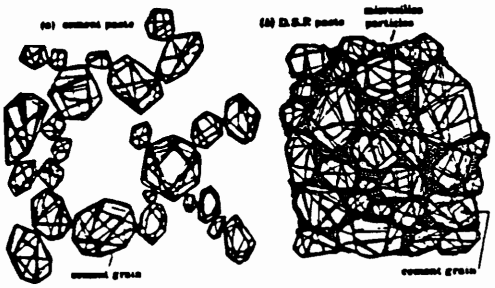


Figure 13. The structure of (a) cement paste and (b) D.S.P. paste (densified) systems containing homogeneously arranged ultrafine particles, after Hjorth (from Young, 1985, p. 64).

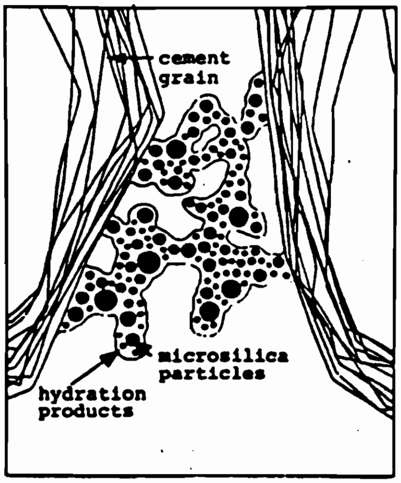


Figure 14. The effect of microsilica particles in "refining" the pore system, after Hjorth (from Young, 1985, p. 60).

Solution to Self-Dessication Cracking in DSP by Design In This Report

Slow release of water from porous aggregates as the DSP cures could reduce the self-desiccation drying cracking. Porous aggregates reduce cracking by interrupting the crack energy.

The porous aggregates, used herein, expanded vermiculite, porous limestone and expanded shale, all interact chemically with the cement and their increased water requirements, because of their high absorption, can present problems because strength depends on the water/cement ratio and related density (Mindess and Young, 1981, pp. 589-594). As seen in Figure 15, the denser the material, the more the compressive strength. Porous aggregates in DSP could serve to reduce the autogenous shrinkage and the requirement for more water because the pores of the aggregates would be filled initially. The main design

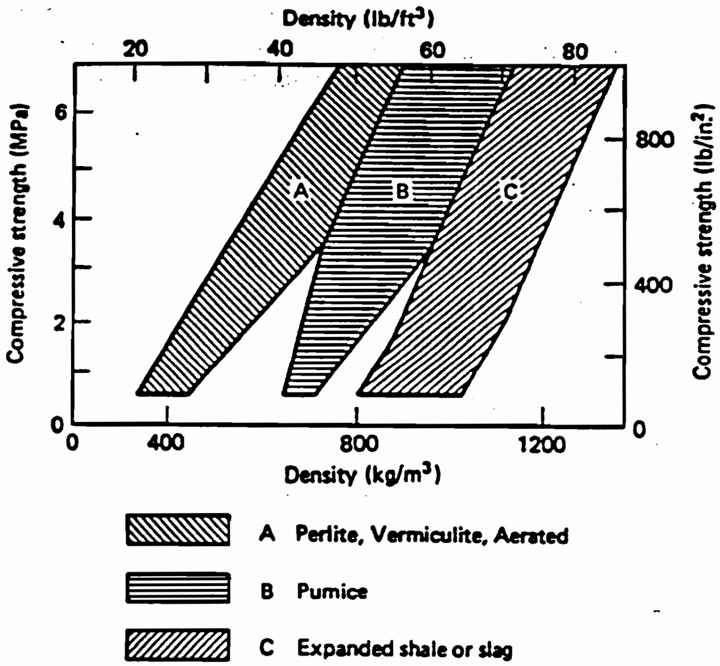


Figure 15. Influence of density on the strength of insulating concretes (Mindess and Young, 1981, p. 596).

implication from this system is that DSP cements, which have very high strength, could have enhanced with predictable durability due to reduced drying shrinkage.

Corrosion

"Corrosion, or rusting of metal, is an expansive reaction that causes cracking and damages concrete. It is an electrochemical process that requires the flow of electrical current in the presence of oxygen and moisture" (Mindess and Young, 1981, p. 557). The high alkalinity conditions in concrete usually cause an outside seal to form on the surface of iron bars, preventing corrosion. However, when the Ph is reduced to 11.0 or below due to carbonation or the entry of chloride ions, such as from de-icing salts, this oxide layer rusts (Mindess and Young, 1981, p. 558). The environmental factors causing corrosion are shown in Figure 16 (a) and (b).

The time it takes for the environment to penetrate the steel is easier to predict than the time for the corrosion to cause damage (Browne, 1986, pp. 110). The conventional strategies for fighting corrosion of reinforcing steel are reduction of the permeability of the concrete, protective coating of the concrete, protective coating of the steel reinforcing bar, and/or suppression of electrochemical processes (Mindess and Young, 1981, p. 560). The difficulty with the conventional means of fighting corrosion are that the reduction of the permeability of the concrete and the application of protective coatings tend to trap moisture and are not 100% effective as a preventative of chloride intrusion (Bean, 1988, pp. 7-8). The fact that carbonation is unlikely to permeate more than 25mm has a self-limiting effect (Mindess and Young, 1981, p. 558). However, chlorides will eventually penetrate the concrete completely.

Protective coatings of the reinforcing bar tend to reduce bond strength between bar and matrix. Suppression of electrochemical processes is expensive, and the results are somewhat unknown although promising. Side effects of the system proposed herein are that the cover of depth of concrete can be reduced because the protection is at the rebars. The permeability condition of the rest of the concrete has little impact.

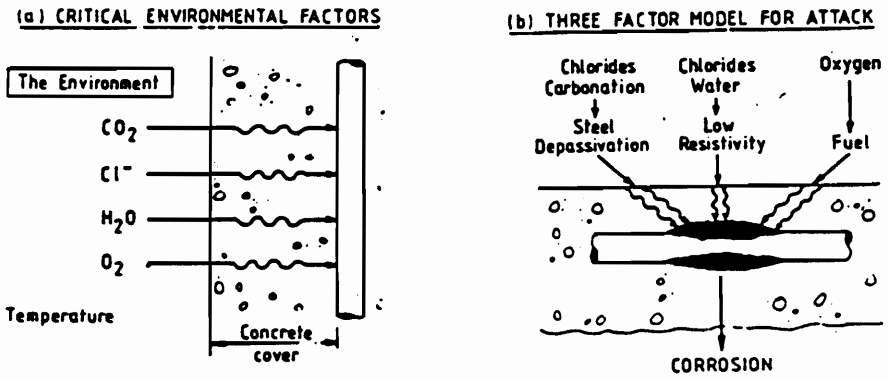


Figure 16. (a) Critical environmental factors; (b) Three factor model for attack (Browne, 1986, p. 105).

Calcium Nitrite Treatment for Corrosion Protection

Experimentation has concluded that the nitrite ion oxidizes ferrous iron to ferric and thus blocks the passage of ferrous ions from the steel (Rosenberg and Gaidis, 1979). Nitrite ions and chloride engage in competing reactions, one inhibiting and the other accelerating corrosion. The relative rates of these competing processes is not known. Rosenburg and Gaidis's (1979) experimentation has shown the result of the presence of the chloride ions is to bring more ferrous ions from the middle to the electrolyte. The effect of the nitrite enhances passivity and is connected with its ability to oxidize ferrous ions to ferric ions which are more insoluble (Rosenberg and Gaidis, 1979).

In a study done for Wiss, Janney, Elstner Associates, Inc., for the U.S. Department of Transportation (Pfeiffer, Langren and Zube, 1987), it was found that calcium nitrite corrosion inhibiting admixture does not significantly delay the initiation of corrosion compared to conventional concrete specimens during these studies. The severity of the subsequent corrosion process on gray bars and strands, however, was reduced significantly when compared to conventional concrete specimens. The amount of corrosion by-products on the gray bars was about one-tenth that measured on bars from conventional concrete specimens. Chloride permeability of the calcium nitrite concrete was similar to conventional concrete when moist cured but was greater when heat cured (Pfeiffer, Langren, and Zube, 1987).

Solution to Corrosion Problem by Internal Release of Calcium Nitrite

Calcium nitrite, when mixed freely with the concrete, retards the set and is expensive. The advantages of the addition of calcium nitrite, released over time just at the reinforcing bars, would be a reduction in the amount of calcium nitrite used, and no reduction in set time due to initial encapsulation of the calcium nitrite.

Freeze/Thaw Damage

The cause of damage in repeated freezing and thawing of porous materials containing moisture was thought by Powers to be hydraulic and osmotic pressure. "The resistance to freezing and thawing depends on the permeability of the concrete, the degree of saturation at a paste, the amount of frozen water, the rate of freezing, and the average maximum distance from any point in the paste to a free surface where ice can form" (Mindess and Young, 1981, p. 565). They say that the same hydraulic pressures can develop in aggregates upon freezing and thawing, if water is present, and such factors as permeability, freezing rate, and degree of saturation apply to porous aggregates. Litvan (1978, pp. 455-463)) writes that the most important factors in freeze/thaw damage are (a) the water content of the porous solid, (b) physical size of the porous solids, (c) increasing cooling rates which increase mechanical damage, (d) solids with either very high or low porosity, and (e) mechanical damage is more severe if the porous solid contains a solution instead of a pure liquid.

Litvan suggests three ways to avoid mechanical damage due to frost action. "The moisture content should be such that the amount of excess water generated in unit time is less than the quantity lost by the pore solid to the exterior in the same period. This will exist if (a) the total moisture content is low or (b) permeability high and the cooling rate low or (c) permeability low but thickness of element small (space in between air voids)" (Litvan, 1978, p. 462). The conventional means to achieve this latter condition is air entraining.

Systems Designed Herein to Prevent Freeze/Thaw Damage

The design developed in this report herein uses the second case in which the permeability of both the matrix and the aggregate is high and cooling rate is low due to the antifreeze. In the case of the addition of linseed oil in porous aggregate, it reduces the total water content of the matrix.

The use of porous aggregates can be thought of as a substitute for air entraining:

> Solid particles having a large internal porosity in suitable pore size have been added to concrete and act in a manner similar to that of air voids. The optimum particle size should range between 290 and 850 microns, total porosity to particles should be at least 30% by volume, and pore size distribution should be in the range of .0523 microns. (ACI Committee 212, 1989, p. 304)

Porous solid particles in the proper proportion has produced concrete with excellent resistance to freezing and thawing in laboratory tests using ASTM C666. (ACI Committee 212, 1989, p. 304.) It has been shown elsewhere that voids caused by air entraining, as used in the conventional treatment, actually can reduce the compressive strength of the concrete, although not for normal strength concrete for a given strength.

The design implications for the system releasing antifreeze are that designers can avoid using air entraining, if they want to avoid the expense and potential strength reduction, and yet the concrete can be exposed to freezing temperatures.

CHAPTER III

METHODOLOGY AND THE RESEARCH QUESTIONS

Design of the Systems for Adaptation Over Time Using Delayed Activated Release of Chemicals From Encapsulation

The design of the systems for release of adaptive materials (see Appendix B for data on materials used) from encapsulants have common attributes shared among the various designs. After working on several examples of this idea, the author drew up the following list of attributes necessary for a successful design of such a system. Steps in the method of designing the attributes for such a system are:

1. The types of problems or distress that can be effectively treated by chemical release must be determined. The attributes of those types of distress are:
    a. There must be a time dependent problem of durability.
    b. It will, therefore, be a problem relating the exterior environment to the matrix interior conditions.
    c. The problem must be important in cost and a frequent cause of deterioration. Obvious choices here are permeability and cracking.
    d. The distress could be treated by chemical release which occurs at one time (such as polymer impregnation). It may be the kind of

distress which is treatable at intervals, as with chemical time release of anti-corrosion agents in response to alkalinity changes to prevent corrosion damage.

2. The cement matrix properties should be defined at intervals of chemical release as appropriate. This characterization should include alkanity, ion concentration, porosity, permeability, the degree of hydration.
3. The internal impetus must be chosen which will allow the cement matrix to accept the chemical to be released.
4. The release mechanism of the fiber, aggregate or prill should be designed for this specific application; i.e., slow diffusion, release only with a specific stimulus, rapid release with external (human) caused stimuli.
5. The types of chemicals to be released, or i.e., the encapsulant, must be effective in treating the specific type of distress such as salt water intrusion, cracking, etc.
    a. Chemicals must be effective within the cement matrix structure containing a particular pore size and structure; i.e., permeability factors.
    b. The chemicals must be the right viscosity and chemical size to enter the fiber or microcapsule before inclusion in the matrix.
    c. Chemicals added to the cement should be evaluated for their non-interference with the chemical set reaction nor should they cause

physical damage later such as release of liquids which could cause increased crack size.

6. The physical properties of the release agent or encapsulator, that is, material and shape should be tailored to the specific application of the stress being treated as well as the other needs of the design of the component.
    a. The shape of the release agent or encapsulator depends upon the building component for which the concrete is intended. Fibers as release agents are most appropriate for use in panels which require reinforcing and enhanced impact resistance. Where the concrete is used in horizontal applications or thicker components, quite small microcapsules could be used because cement is anisotropic; i.e., it has no preferred direction.
    b. The fiber, aggregate or prill volume and placement in the component must be appropriate to release the appropriate amount of chemical in the necessary location to prevent deterioration and preserve durability.
    c. The fiber must have a release mechanism tailored to this specific treatment or application, and appropriate rate of release.
    d. The fiber must have an appropriate release mechanism in the sense of releasing from all over the fiber, ends of the fiber, top of the

fiber, etc., in relation to the matrix characteristic at that particular time of treatment.

e. The fiber, aggregate or prills must be such that it does not degrade the strength or chemical characteristics of the cement. For instance, large microcapsules cause macro defects and are not used. Fibers, on the other hand, should not degrade in the cement over time; they must bond well to the cement matrix in order to have a composite action. If they are emptied, they must not create a macro defect. The walls must be strong enough and the fibers must have an overall appropriate aspect ratio so that when the material escapes, the Poisson's ratio should not be affected. Reinforcing fibers must have appropriate stiffness and material strength to give reinforcing, i.e., they must have an appropriate modulus of elasticity. The internal stimuli caused by external environmental or humanly caused events must cause the chemical to be released and make the cement matrix to accept the chemical which is released.

f. The method of encapsulating chemicals into the fiber or microcapsules must be an efficient and inexpensive process.

7. The stimuli or source of energy or change must be such that: (a) it can cause the chemical to be released and (b) cause the matrix to accept the chemical; (c) this energy or source of change must not damage the

overall structural or chemical integrity of the cement; and (d) the stimuli or source of energy for change must not be difficult to release or activate.

8. The matrix must be such that it can accept the encapsulant in form, chemistry and volume and accept the chemical as it is released and accept the stimuli action necessary to release the chemical.

9. Different aggressive agents such as salt water and freezing and thawing, for instance, have very different rates and cycles. The system must be designed for these. There are various aggressive agents such as gases, liquid, acid rain, water, fluoride ions, etc. Flow in capillary pores can be described by D'Arcy's law for laminar flow through porous media (Young, 1988) as:

> dq/dt = KA (H/*L) where dq/dt is the rate of flow, A is the cross sectional area of the specimen, and H/*L is the hydraulic gradient across the section. K is the measured proportionality constant which represents the ease with which water flows through the specimen. The permeability coefficient is the material constant independent of the fluid use. K' = Kn/pg where n is the viscosity of the fluid, p is the density and g is the gravitational constant. In practice, K is the permeability constant. (Young, 1988, pp. 3-4)

In its simplest form:

$$V = k\,i$$

where k is coefficient of permeability and i is hydraulic gradient. The complications of flow through micro pores can be eliminated from the analysis (Young, 1988, pp. 3-4). The use of D'Arcy's law for laminar flow through porous media is used. The descriptions for the treatments for the various types of distress are quite different. For instance:

a. The type of distress that can be quite effectively treated by one time chemical release such as occurs in polymer impregnation to reduce water and chloride intrusion would use D'Arcy's law for laminar flow through porous media to describe only the flow from the microcapsule fiber into the cement matrix.
b. The treatment for cracking in which the chemical is released internally only with the specific stimulus of loading would be described by the flow of the chemical release from the fiber into the matrix.
c. The description of the treatment for intrusion of water or chloride ions of the type in which release occurs only with the specific stimulus of intrusion of the chloride ion or water would include D'Arcy's law for laminar flow through porous media for the salt water or chloride ions or water and the flow as well as the description of the flow through the matrix of the chemical released from the fiber or microcapsule.

In order to apply D'Arcy's law, one must know the following:

1. The force and frequency of the intrusion of the aggressive agent.
2. The condition of the matrix for ion content, permeability, alkalinity at the time of intrusion of aggressive agent.

3. The force of the stimulus which releases the chemical from the fiber and the force of the stimulus which prepares the matrix for acceptance of the chemical in the fiber.
4. The temperature of the material and the permeability conditions of the matrix.
5. The viscosity and density of the aggressive agent.
6. The viscosity and density of the chemical released from the fiber
7. The hydraulic gradient of the specimen.
8. The cross-section area of the specimen:

> The continuous capillary pores system through which water flows relatively easily can become cut off by the deposition of hydration products. This is dependent upon the water to cement ratio of the paste. In discontinuous pore systems flow is limited by movement through very fine j pores so the D'Arcy flow is greatly modified by the absorption of water on the porous surfaces. . . . Powers developed a theoretical approach to this model using the Stokes law applied to a concentrated suspension. (Young, 1988, p. 3)

Design of Actual Systems to Reduce Environmental Damage and Deterioration

In actual practice, it is very complex to determine the conditions of the cement matrix at any given time and formulate predicted flow through the porous medium. The number of hollow or porous fibers and aggregates appropriate for use in the overall system were severely limited, thereby reducing the ability to choose among the factors associated with those, such as whether the fiber releases from the ends or the length, the porosity of the fibers. In practical terms one must first determine the environmental distress to be addressed and invent a system to address it which includes a carrier for the chemical, a chemical to be released, a coating for the carrier, a stimulus to release the chemicals from the carrier to prepare the matrix. In optimum cases, the stimuli for release is a property of the matrix when the environment attack occurs and can be used to release the remedy.

Description of the Systems Designed for Activated Internal Release

1. Cracking, due to loading, is a major problem in concrete materials because the cracks increase permeability. Loading over time has a cumulative effect which can lead finally to complete deterioration of the component or structure. The design to alleviate this problem consists of filling porous fibers with a crack-filling chemical. The chemical is released from the fibers when the fibers flex due to loading. The stimulus for release is thus loading. This is the ideal situation in which the agent of environmental degradation, namely loading, is the stimulus to release the repair chemical. The testing regime design relies heavily

on the release of chemicals from the fibers due to bending caused by loading, therefore the research or investigation will focus on that area.

2. Cracking due to shrinkage caused by self-desiccation is a major problem in a new type of concrete, dense silica fume concrete. The low water/cement ratio used causes this. The design to address self-desiccation includes porous aggregates filled with water should release slowly in response to the demand for water from hydration of the cement. The stimulus for release is this demand for water. The initial volume of the aggregates allow for containment and slow release upon hydration; therefore, no coating is used. In the design herein, the drying shrinkage could be reduced due to the slow release of water for hydration into the system.
3. The ability of water and chemicals to intrude because the matrix is permeable is the major problem in durability. In the design herein permeability is addressed by the release of sealants into the body of the matrix from hollow, porous fibers. The methyl methacrylate is contained in the fibers for later release by coating the fibers with wax. To be effective, the methyl methacrylate has to be released from the fibers after the matrix is set up and then has to be polymerized. Heat is the stimulus which not only releases the methyl methacrylate from the porous fibers, but it also dries out the matrix to receive the methyl

methacrylate and polymerizes the methyl methacrylate in place. The heat stimulus has that threefold effect of accomplishing release, matrix drying, and polymerization. The research investigation in this design not only will focus primarily on the increase in impermeability but also on increased compressive strength due to the polymer and increased bending strength added by fibers.

4. Permeability is the durability problem because that is the way in which environmental agents penetrate to attack. In this design, Xypex, a catalytic crystallizing agent which crystallizes in the presence of water and causes the 25% unhydrated cement to hydrate, is released from prills. These prills are paraffin wax in which the Xypex is mixed. The stimulus for release is heat. In another design herein using Xypex, the prills are made from a polyol which is alkaline sensitive and should degrade due to the stimulation of the alkalinity change in cement to more alkaline as a precursor to corrosion. The research will investige increased impermeability as well as any attendant increase in compressive strength.
5. A novel material developed by the author of this report is a phosphate-bonded sintered bottom ash. This material is very permeable and therefore open to environmental attack. This design consists of the inclusion of a sealant material in fibers which will be released during

heating. The sintering process goes to 550-600° C. Therefore, the chemical and fibers have to withstand this heat. Fiberglass fibers containing a polyimide should be the most heat resistant combination. The research will focus on impermeability.

6. The problem of corrosion can be approached by reducing the ability of the steel to corrode. Calcium nitrite added freely to cement protects the steel but also retards the concrete set time. In this design calcium nitrite is put into hollow, porous fibers coated with wax. They are placed near the rebars. The rebars are heated, thus releasing the chemical from the nearby fibers. Also, the fibers could be coated with polyol. The stimulus for that release is the change in alkalinity to 11 at which point corrosion starts. This stimuli has the advantage that the mechanism of attack, i.e., the reduction of alkalinity to 11 due to the ingress of chloride ions or other causes, is also the stimulus for activation of the prevention system. The research in this investigation will focus on reduction in corrosion as measured by reduction in differences in electrical potential across rebars.
7. The problem of freeze/thaw damage is important because it breaks up the concrete internally, causing cracking and increased permeability. The design in this case is to load porous aggregates with chemicals which reduce freeze/thaw damage. These chemicals should be released

due to the expansion of water and the changes in osmotic pressure in the specimens upon freezing. In this case the stimulus is the agent of environmental attack, i.e., freezing. The chemicals to be released are linseed oil, which is a hydrophobic agent and reduces the ability of water to penetrate internally, or an anti-freeze, propylene glycol. The anti-freeze should reduce freeze/thaw damage by decreasing the temperature at which freezing will occur. The research investigation will focus on the reduction of freeze/thaw damage.

General Procedures

Experimental work was first undertaken to determine the feasibility of various fiber/chemical combinations to be used as potential treatments for various types of distress in concrete. Evaluations were made of the successful combinations of 12 hollow, porous or adsorptive fibers, 5 porous aggregates, 2 capsule compositions, 5 coating agents, and 4 different chemicals to be contained for later release. Many more were tried. White cement was used. The chronology of the testing procedures were as follows: (a) determination of what chemicals could be used to respond to specific events over the design life of the concrete structure, (b) evaluation of each fiber/chemical combination for compatibility with the desired objectives, (c) sample preparation procedures were evaluated for each fiber/chemical combination, (d) samples were prepared based on these factors, (e) the samples were cured, (f) the fiber/cement interface was visually evaluated for chemical release for that particular type of release desired through use of red dye visible in the white cement.

Sample Preparation

To answer the research questions, the following sample preparation procedures were used for all tests done using a cement matrix (see abstract diagram in Figure 17):

1. The amount of fiber, aggregate, or prill to be used is determined primarily by the intended use of the sample (i.e., to evaluate the chemical release, compressive or flexural strength, and freeze/thaw resistance [F/T]), etc.
2. The fiber, aggregate or prill is weighed prior to the inclusion of the chemical.
3. The fiber configuration and material type dictate whether precutting to 1 inch, searing the ends, is necessary prior to the uptake of the chemical or if longer strands with sealed ends are used. The fluid can be made to flow toward the center when held in a catenary curve, thus producing fuller fibers if only the fuller center section is used. One inch was chosen as the standard fiber length for all tests. All aggregates used were sifted through a size 8 seive.

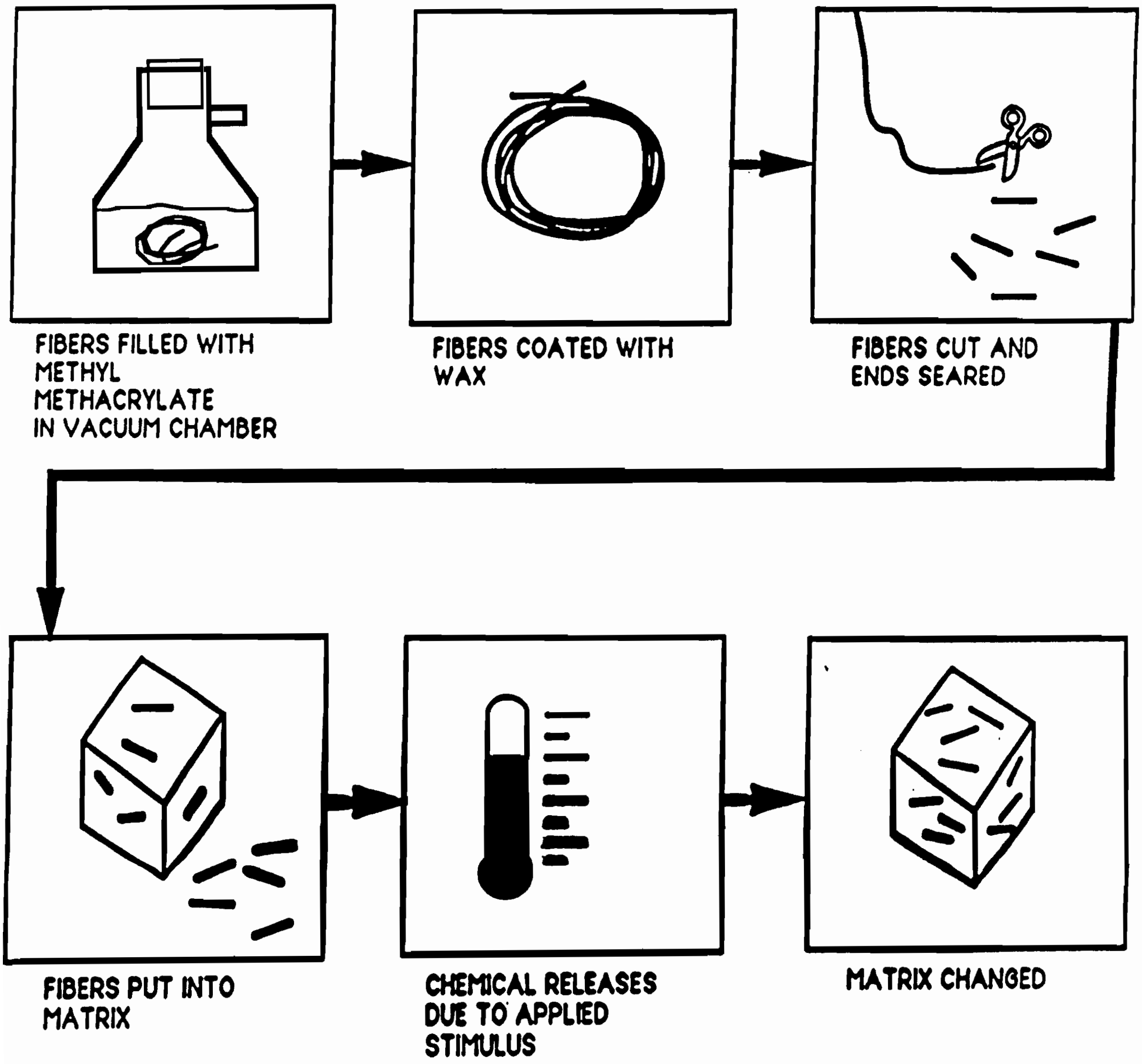


Figure 17. Abstract of the process of making samples with time delayed internal release of chemicals to a matrix.

4. The porous fibers or aggregates are placed in a vacuum flask, covered by the chemical and a dye, and evacuated to draw the chemical into the fibers or aggregates as in photos 1 and 2 (Photos can be found in Appendix C).
5. The time required for uptake of the chemical depends on various factors including: viscosity of the chemical, porosity of the fiber or aggregate, fiber or aggregate diamater, fiber or aggregate length, etc. The optimum time was determined by numerous trials; in most cases, it was one hour.
6. The fibers or aggregates are removed from the flask and weighed to determine the uptake of the chemical.
7. If the fibers or aggregates were to be coated with paraffin wax or polyol they were quickly transferred to a molten bath where a thin coat is applied as in photo 3. These were selected for the sealing materials because of the low melt temperature and inertness with the chemicals.
8. The precut fibers are then ready for placement in the sample. The fibers are now cut to 1" lengths using a heated, waxed blade to sear the ends and prevent loss of the chemical as in photo 4. They are then added to the matrix (see photo 5).
9. The samples are cast into molds with either random dispersion or ordered arrangement of the fibers. This differentiation is based on the

type of evaluation being performed (i.e., release of the chemical, strength, F/T resistance, etc.). Also, samples using a cement matrix were cast into 2 inch cube molds for compression tests, 1"x 1"x 6" prisms for bending evaluation (photo 6), 1-1/2" diameter by 3/4" thick cylinders for permeability evaluation, freeze/thaw samples were made into 3"x 6" cylinders, and corrosion samples were made into 12"x 12"x 6" cubes containing 6 rebars. If the matrix was bottom ash, closed molds were used for compression, 1-1/2" x 3" (see photo 7).

10. The curing of the samples is standardized and followed the appropriate ASTM standards.
    a. The samples (while in the mold) are placed in a curing chamber maintained at 100% relative humidity and 85° F for 24 hours (see photo 8).
    b. After 24 hours, the samples are removed from the mold and returned to the curing chamber for an additional 2 or 6 days (see photos 9, 10).
    c. The moist cure is followed by drying to 50% relative humidity at room temperature.
11. Following the curing procedures, the samples are appropriately treated for release stimulation. For instance, in the case of the methyl methacrylate samples, they are heated in an oven (see photo 11) at 120° F, or

220° F for 30 minutes or microwaved to initiate release of the filler material dry the matrix.

12. The samples were evaluated for release of the chemical, compressive strength (photo 12), flexural strength (photo 13), permeability (photos 14, 15), F/T resistance in a Logan (photos 16, 17) machine, and for changes in dynamic modules (photo 18), or corrosion resistance (photo 19), set time (photo 20), shrinkage (photo 21), and visual release of chemical (photos 22, 23), or evaluation using electro microscope (photos 24 to 26).

(Explanation of the testing and preparation procedures which are commonly used can be found in the appropriate ASTM standards).

Research Questions

The following questions were asked when designing the methodology for the present study: Does the design for timed release of internal chemicals work? What are the design and cost implications of internal timed release for building components and structures? Will the successful release alleviate the particular environmental damage such as freeze/thaw damage or corrosion damage or reduce cracking or permeability? Do the fiber and stimuli degrade strength or permeability properties; what are the strength and permeability contributions of the various separate factors such as coatings, chemicals, fibers, etc.? Are these improvements over conventional treatments for impermeability or crack reduction and other environmental damages? What are the effects of manufacture, storage, and in-the-field problems?

Research Question 1

Does the design for timed release of internal chemicals work?

Parts of the question, on the success of the release sequence for the designs for timed release, are:

1. Is the chemical taken up in the fibers or aggregate?
2. Can the carrier be coated?
3. Is the chemical retained in the coated carrier?
4. Will a stimuli release the chemical?
5. Is the chemical released into the matrix?
6. Will the chemical move into the matrix?
7. Can the release be seen by visual or chemical analysis?

The questions were framed so that the data necessary to answer them are comparative among controls and experimental results. The fact that numerous processing factors affect performance attributes of cement/concrete make it very difficult for to get results upon which meaningful comparisons can be made. Few comparisons to data in the literature are made because of this.

The encapsulation of chemical agents into hollow porous fibers is an area of research not addressed in the literature. Experimental work was first undertaken to determine the feasibility of various fiber/chemical combinations to be used as potential treatments for various types of distress in concrete. In this research study, those tests were done on some of these designs using methyl methacrylate, epoxies, silanes, oils, anti-freeze materials, anti-corrosion chemicals to be released from microcapsules, hollow fibers, porous fibers made of cellulose, polypropylene, polymers, porous polymer membranes, and fiberglass coated with waxes, a material which degrade in alkaline environments, etc.

Research Question 2

Does the successful release alleviate the particular environmental distress or reduce cracking or permeability? Samples were prepared from the fiber, aggregate, or prill and chemical combinations that appeared to be viable. These samples were tested in ways appropriate for the particular type of distress such as freeze/thaw resistance, corrosion resistance, or for permeability or cracking (see Table 7). Because there is a relatively small volume of encapsulated material contained in our samples, the question of the volume wetting and potential effectiveness of the chemical was researched. The assessment was made visually from the exterior samples and the interior of the samples.

Research Question 3

Do the fibers and stimuli degrade the strength properties; what are the strength and permeability contributions of the various separate factors of wax,

Table 7

Tests Used to Assess Success of Internal Release in Reducing Environmental Damages

Particular Environmental Distress Being Treated	Fiber, Aggregate Chemical Coating Matrix	Test	Test Standard Used
1. cracking caused by repeated loading	hollow, porous polypropylene fibers consolidec (a siloxane chemical) polyol or shellac coating white cement	bending loading to cause cracking	visual inspection using microscope
2. cracking caused by self-desiccation drying	porous haydite filled with shrinkage water dense silica fume cement	drying & shrinkage test: measurement of of length change:	ASTM C596-89 C596-89 C490-86
3. water/chemical intrusion; permeability	hollow, porous polypropylene fibers colored methyl methacrylate wax coating polyol or shellac coating white cement, portland cement	permeability	gravity flow permeability test[a]

Table 7 (continued)

Particular Environmental Distress Being Treated	Fiber, Aggregate Chemical Coating Matrix	Test	Test Standard Used
4. water/chemical intrusion; permeability	wax prills Xypex white cement, portland cement	permeability	gravity flow permeability test[a]
5. water/chemical intrusion; permeability	hollow, porous fiberglass fibers methyl polyimide wax coating sintered phosphate bottom ash	permeability	gravity flow permeability test[a]
6. corrosion of reinforcing bars in concrete	hollow, porous polypropylene fibers colored calcium nitrite chemical	long-term tests in progress for corrosion	W.R. Grace proposed ASTM test for corrosion[b];
	wax coating	permeability	gravity flow permeability test[a]
	polyol coating white cement, portland cement	set-time tests slump test	ASTM C191-82 or ASTM C403-88 ASTM 143-89

Table 7 (continued)

Particular Environmental Distress Being Treated	Fiber, Aggregate Chemical Coating Matrix	Test	Test Standard Used
7. freeze/thaw damage	aggregates; vermiculite, porous limestone, haydite	freeze/thaw test	ASTM C666-84
	polypropylene glycol linseed oil		
	no coating		
	white cement, portland cement		
		bending test:	ASTM C78-84
		making and curing specimens	C192-88
		flexural strength	ASTM C78-84
		compressive strength	ASTM C109-88

[a]Ludijdsa, Berger, and Young, 1989, pp. 433-437; [b]Engineering Bulletin DCI/no. 6, W. R. Grace & Co., 1989.

chemical, fiber? In this question, potential problems were addressed. Is the response to internal/external stimuli damaging to the strength properties of the concrete? This was assessed for heat. What is the effect of volume of fibers on strength properties? Various volumes of fibers were added and tested for strength. What is the contribution to strength or impermeability of the various factors such as wax, fiber, chemical, and heat? These factors were isolated for testing alone and in combinations. For instance, holes were drilled in which only an appropriate volume of methyl methacrylate was added, then similar tests were done with wax in holes. These holes were placed in the appropriate size, shape, and placement of the fiber additions. Fibers were added with wax coating only, chemical inside only, wax and chemical both.

1. Is the internal/external stimuli damaging to the strength properties of the concrete? This was assessed for heat and microwave stimulation by a series of tests in which the heat temperature and microwave were varied. Standard ASTM tests for strengths in bending and compression were carried out.
2. What is the effect of volume of fibers on strength properties? Various volumes of fibers or prills (see photo 27, 28, and 29) were added to samples which were later tested for bending strength, compressive strength. These tests were carried out on various volumes of fibers containing methyl methacrylate, calcium nitrate, and Xypex prills.
3. What is the contribution to bending strength, compression strength, or impermeability of the various factors such as coating (wax), fiber, and chemical contained? The coating, fiber, and chemical factors were isolated for testing alone or in combination. In the case of the design to alleviate the problem of water/chemical intrusion due to permeability, in which methyl methacrylate was added, holes were drilled and an appro-

priate volume of the chemical was added; in other samples, only an appropriate amount of wax was added, and so on, to isolate all the factors. These holes were placed in the appropriate size, shape, and placement of the fiber additions. Fibers were added with wax coating only, chemical inside only, wax and chemical both (see photo 30). The assessment of the impact of various factors was made by standard ASTM bending and compression tests and permeability tests. These tests were also done on the methyl methacrylate samples, and the Xypex prill samples.

Research Question 4

Are these designs an improvement over conventional treatments for impermeability or crack reduction and environmental distresses? Tests were done to compare the effectiveness of these designs to the conventional way of treating the particular environmental distress or to reducing cracking or permeability. For instance, the internal release of methyl methacrylate from hollow porous fibers was compared with the conventional polymer impregnation surface application of methyl methacrylate and inclusion of fibers (see photo 31). Xypex top application was compared to Xypex release from prills (see photo 32). Strength and impermeability properties were compared. In the design to address corrosion, the internal release of calcium nitrite was compared with the inclusion of calcium nitrite in the initial mix. The comparison was made for strength properties, permeability, and set retardation, not corrosion because of time factors. In the case of a catalytic sealant Xypex, the comparison was made between the sealant released from wax prills contained inside the samples with the sealant applied externally with and without wax particles in the cement (see photo 32). The comparisons were made for permeability and strength.

Research Question 5

What are the effects of manufacture, storage, and in-the-field problems?

Changes in the material during storage were assessed by the storage of fibers for three month-long periods both outside and inside at ambient temperatures and in a refrigerator (see photo 33) to discover whether the wax-coated fibers agglomerate or the chemicals evaporate. The simulation of infield stimuli are being studied; for instance, top heating for polymer impregnation was tested. Samples containing methyl methacylate in fibers were placed in a bed of insulation which only allowed top surface heating (see photos 34, 35). The method of placement of fibers into the cement matrix is yet to be studied. The effect of loading fiber volume in particular areas of a component is yet to be tested.

CHAPTER IV

RESULTS

Discussion

Research Question 1

Does the design for timed release of internal chemicals work?

Results. The experimental results are shown in Table 8. In all cases, except for the cracking under loading conditions, a release sequence was successful. The difficulties encountered in this phase with various combinations were: the uptake of the chemical into fibers (some chemicals are too viscous) and isolating the chemical in the fiber until the desired release. Also carbonization of the chemical at very high temperatures and stretching of the fibers were problems of specific systems. In the cases of linseed oil, propylene glycol (antifreeze) and pyralin (methyl polyimide) they were too viscous for fiber uptake. Therefore, we used porous aggregates from vermiculite, limestone, and expanded clay or coated the fiber outsides with pyralin because the bottom ash matrix was used and the direct application of pyralin should not cause loss of strength. Some chemicals stayed in a cloth weave in the voids between fibers. In the design for slow release of water into dense silica fume cement, the volume capacity of the aggregate presented the opportunity to have a chemical released over time without the need for a coating on the aggregate. In the case of the catalytic agent, Xypex, a powder, it would go into neither a porous fiber nor a porous aggregate in any significant amount;

Table 8

Testing of Chemical Release Sequence

Particular Environmental Distress	Fiber/ Aggregate Chemical Coating Matrix	Chemical Uptake in Fibers, Aggregate	Chemical Retention in Coated Fibers, Aggregate, Prill	Internal or External Stimuli	Release of Chemical into Matrix	Movement of Chemical into Matrix	Probable Explanation if Blocked	Success of Release to Date Treated
cracking caused by repeated loading	hollow, porous polypropylene fibers						polypropylene fibers stretch rather than forcing chemical out	
	consolidec (a siloxane chemical)	yes	no	loading (and bending)	no	no	siloxane evaporates from fibers during coating	poor
	fiberglass fiber						fibers broke upon stretching	
	polyol or shellac coating							poor
	white cement							
cracking caused by drying shrinkage due to self-desiccation	porous haydite aggregate	yes	yes has enough volume to give slow release					
	water	yes		hydration	yes	yes		moderate
	dense silica fume cement							

Table 8 (continued)

Particular Environmental Distress	Fiber/ Aggregate Chemical Coating Matrix	Chemical Uptake in Fibers, Aggregate	Chemical Retention in Coated Fibers, Aggregate, Prill	Internal or External Stimuli	Release of Chemical into Matrix	Movement of Chemical into Matrix	Probable Explanation if Blocked	Success of Release to Date Treated
water/chemical intrusion due to permeability	hollow, porous polypropylene fibers							
	colored methyl methacrylate chemical	yes	yes	heat	yes	yes		excellent ideal release sequence
	wax coating							
	white cement, portland cement							
water/chemical intrusion due to permeability	wax prill	NA	yes	heat	yes	yes	powder could not be drawn into porous fibers or aggregate, but prills worked	good
	Xypex							
	white cement, portland cement							

Table 8 (continued)

Particular Environmental Distress	Fiber/ Aggregate Chemical Coating Matrix	Chemical Uptake in Fibers, Aggregate	Chemical Retention in Coated Fibers, Aggregate, Prill	Internal or External Stimuli	Release of Chemical into Matrix	Movement of Chemical into Matrix	Probable Explanation if Blocked	Success of Release to Date Treated
water/chemical intrusion due to permeability	hollow porous fiberglass fibers		chemical				both fiber & pyralin withstand 500° C	
	methyl polyimides (pyralin) wax	no	yes	heat	yes	yes	potential chemical incompatibility with acid in matrix but is overcome	poor to moderate; somewhat unclear
	in sintered bottom ash/ phosphoric acid matrix						viscous so chemical stays in exterior pores of fibers; is believed to release from there	
	polyol coating			alkalinity changes	unknown	unknown		
corrosion of reinforcing bars in concrete	hollow, porous polypropylene fibers							
	colored calcium nitrite chemical	yes	yes				release due to polyol degradation in increased alkalinity	excellent (with heat)
	wax coating			heat	yes	yes	still needs more investigation	ideal release sequence

Table 8 (continued)

Particular Environmental Distress	Fiber/ Aggregate Chemical Coating Matrix	Chemical Uptake in Fibers, Aggregate	Chemical Retention in Coated Fibers, Aggregate, Prill	Internal or External Stimuli	Release of Chemical into Matrix	Movement of Chemical into Matrix	Probable Explanation if Blocked	Success of Release to Date Treated
freeze/thaw damage	hollow, porous polypropylene fibers							
	vermiculite	yes	no coating; retention in interior of aggregates	freezing action	yes	yes	propylene glycol is too viscous for fiber uptake so porous aggregates were used	good (with porous aggregate & fibercloth)
	porous limestone aggregate	yes			yes	yes		
	expanded clay (haydite)	yes	retention		yes	yes		
	fibercloth	yes	retention within weave of cloth		yes	yes		
	propylene glycol							good
	linseed oil							
	no coating due to volume capacity of aggregate							moderate
	white cement, portland cement							

therefore, we created a prill by mixing the Xypex with the wax. In both the encapsulation of methyl methacrylate and calcium nitrites in polyporous polypropolyene fibers coated with wax, the chemical release sequence worked perfectly. The polyol coating over the calcium nitrite filled fibers was untested for corrosion reduction due to the length of time required for testing.

In the case of methyl polyimid (pyralin) added to porous fiberglass fibers in a matrix of bottom ash/phosphoric acid sintered it 500° centigrade, the problem encountered was finding a chemical that would not degrade in acid nor carbonize at those high temperatures; pyralin will not. The fiberglass fibers would withstand that temperature and acid. However, time required us to use this pyralin in the exterior pores of the fibers for release due to its viscosity of 110 pois. A less viscous pyralin could be tried later.

In the design to release a chemical under loading conditions and bending, to fill in cracks, the polypropylene fibers were found to stretch rather than force the chemical out. Fiberglass fibers which are less flexible, broke upon loading and were therefore unsuccessful.

An environmental scanning electron microscope was used to produce a video of the successful release of calcium nitrite chemicals into the matrix. Scanning electron microscopy (SEM) was used to photograph the white cement matrix after release (see photo 24), the fiber as it releases the chemical (photo 25), and the bottom ash matrix with fibers (photo 26).

Research Question 2

Does the successful release alleviate the particular environmental distress or reduce cracking or permeability?

Results. These answers are different for the different systems.

1. Cracking caused by repeated loading was to be tested for cracking caused by loading with a test done in which a bending apparatus (a load cell) was applied. Preliminary test results pulling the filled fibers under a microscope showed that the polypropylene fibers stretched rather than forcing the chemical out. Porous fiberglass fibers broke before forcing the chemical out. The load cell tests were therefore unnecessary.
2. Cracking caused by self-desiccation drying in dense silica fume cement was tested by a comparator which measures shrinkage due to drying (ASTM Test C596-89). As seen in Figure 18, test results show that either putting in no haydite, a porous aggregate, or haydite with no water gives less shrinkage than the haydite saturated with water. Furthermore, in Figure 18, the DSP cement containing water saturated haydite not only shrunk more, but continued to shrink over a longer time, as seen in Figure 19. Therefore, the design to alleviate self-dessication shrinkage did not work, that is, the haydite saturated with water did not reduce self-desiccation shrinkage, it was increased. This is an unexplained phenomena.

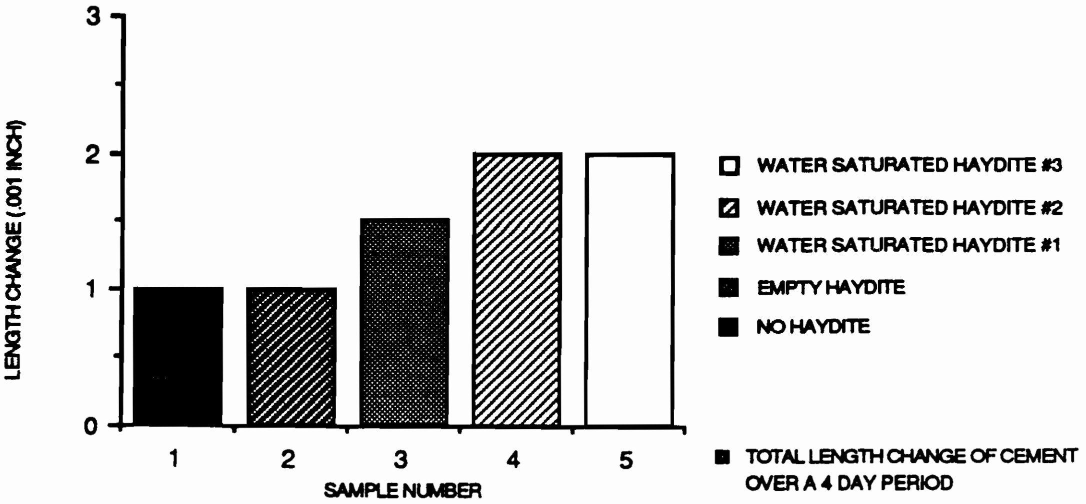


Figure 18. Shrinkage of dense silica fume cement using a water saturated, porous aggregate--haydite (expanded clay).

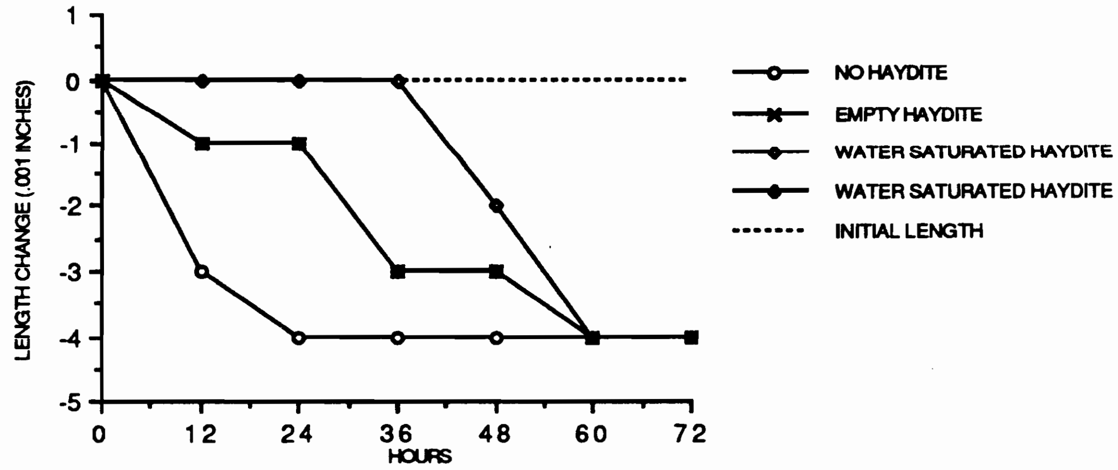


Figure 19. Duration of shrinkage phenomena of dense silica fume cement using a water saturated porous aggregate, haydite (expanded clay) vs. dense silica fume without water-soaked aggregate.

3. The design to resist chemical or water intrusion due to impermeability uses methyl methacrylate contained in polypropylene fibers coated with wax. It was tested by the gravity flow permeability apparatus (Ludijdsa, Berger, and Young, 1989). The results (Figure 20) show that methyl methacrylate in polyprophylene fibers, but not polymerized (heated only to 120°F), decreases the permeability. In Figure 21, it shows that the methyl methacrylate released and polymerized (heated to 212°F) reduces the permeability more and has lower permeability than the control.

4. The test for increased impermeability using Xypex prills was done with the gravity flow permeability test also. The results in Figure 22 show that the addition of Xypex/wax prills does not increase impermeability.

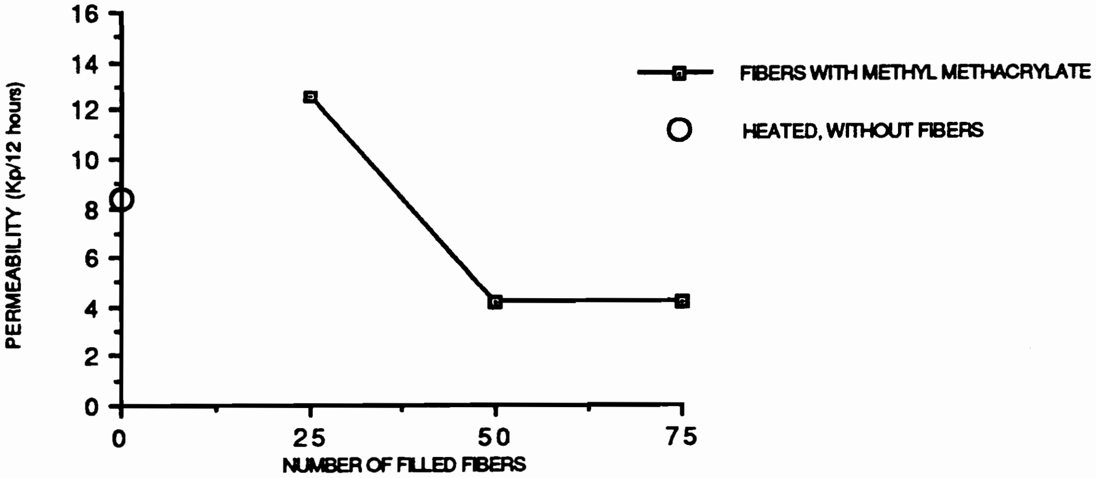


Figure 20. Permeability of white cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 3 days--heated to 120° F for 30 min).

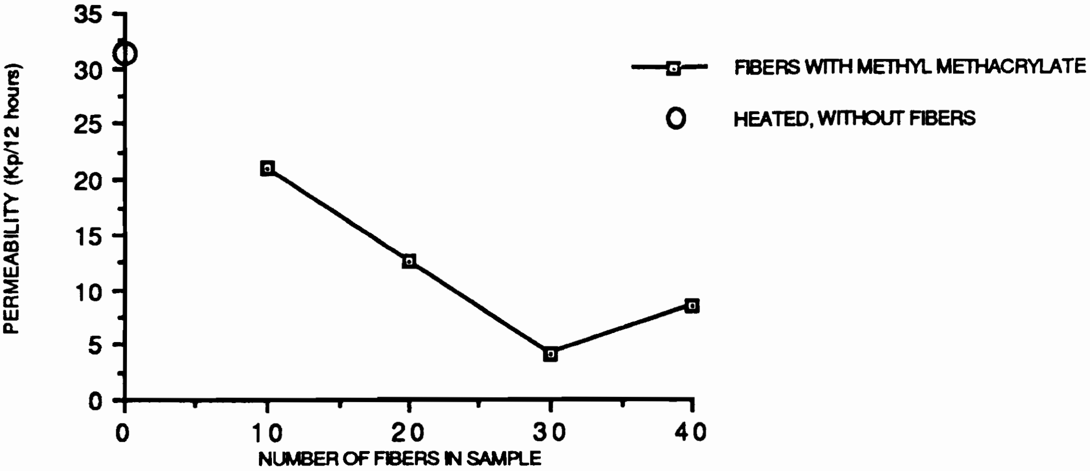


Figure 21. Permeability of portland cement containing methyl methacrylate and wax released from polypropylene fibers (samples cured for 7 days--heated for 212° F for 30 min).

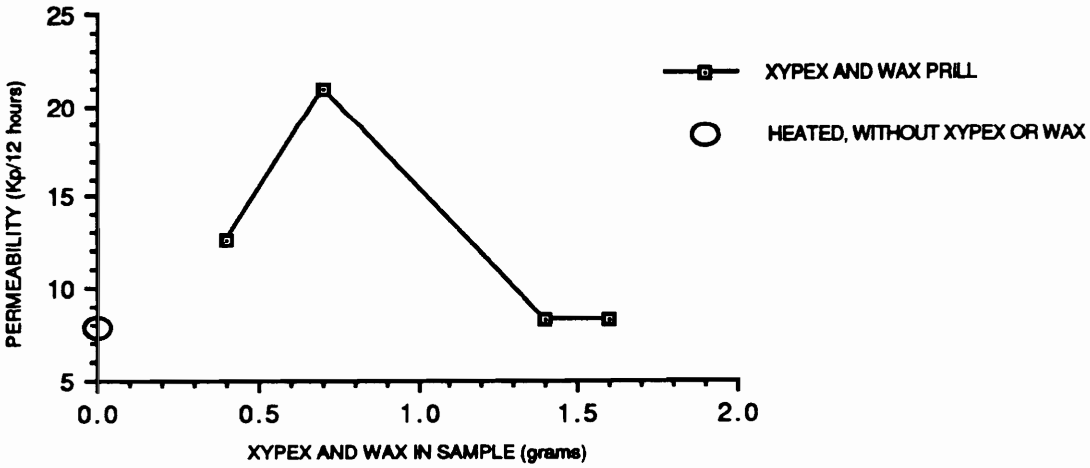


Figure 22. Permeability of portland cement containing Xypex and wax released from prills (samples cured for 7 days--heated to 120° F for 30 min).

5. In the design to relieve chemical intrusion, i.e., permeability, by the inclusion of hollow, porous fiberglass fibers containing methyl polyimides in their outside pores in a matrix of sintered phosphate bonded bottom ash, the tests were permeability tests using the gravity flow test. The results are shown in Figure 23. Permeability is reduced significantly.
6. The design to resist corrosion of reinforcing bars in concrete by release of calcium nitrite from polypropylene fibers coated with wax was tested by the time of setting of hydrated cement by Vicat or Gillmore needles ASTM C191-82. The results are shown in Figure 24. This design does not retard the set as much as the freely mixed calcium nitrite.
7. Freeze/thaw damage was assessed for 6"x 3" cylinders using the standard ASTM C 666 test using a Logan freeze thaw machine which cycles 300 times. Figures 25 and 26 show the dynamic modulus results. Figures 27 through 33 show the weight and length loss (photo 17) shows the results of freeze/thaw testing of the samples). The conclusion is that time release of antifreeze and linseed oil somewhat reduces freeze/thaw change in some cases.

The question of volume wetting. Because there is a relatively small volume of encapsulated material contained in our samples, the question of the volume of wetting predictability and the related issue of potential effectiveness of the

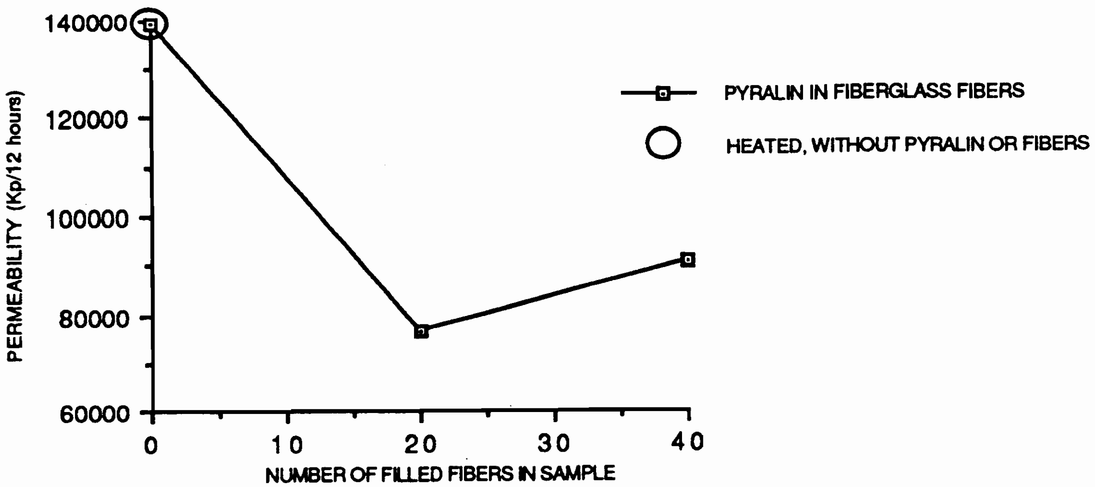


Figure 23. Permeability of bottom ash containing pyralin (methyl polyimides) released from porous hollow fiberglass fibers' exterior pores (wax coated) (samples heated to 500° F for 15 min).

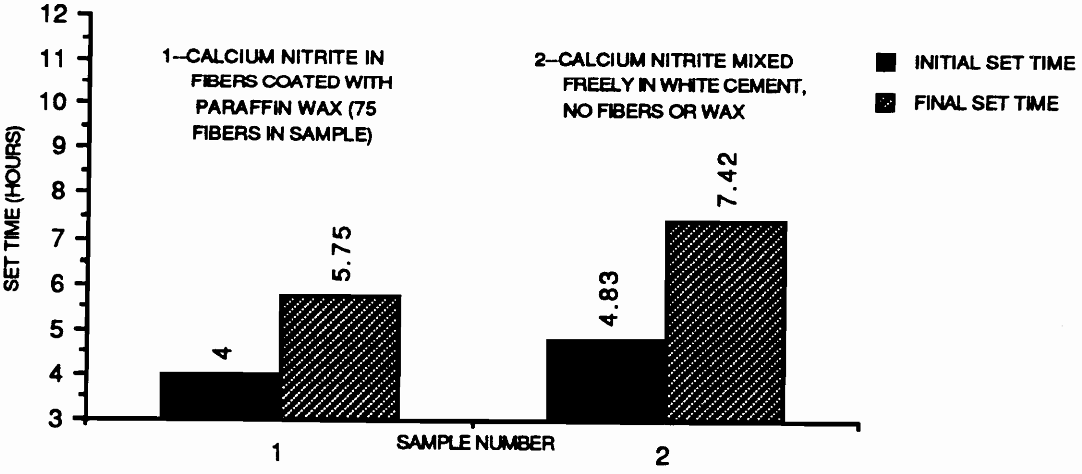


Figure 24. Time of setting of portland cement containing free calcium nitrite vs. portland cement containing calcium nitrite released from wax-coated porous polypropylene fibers.

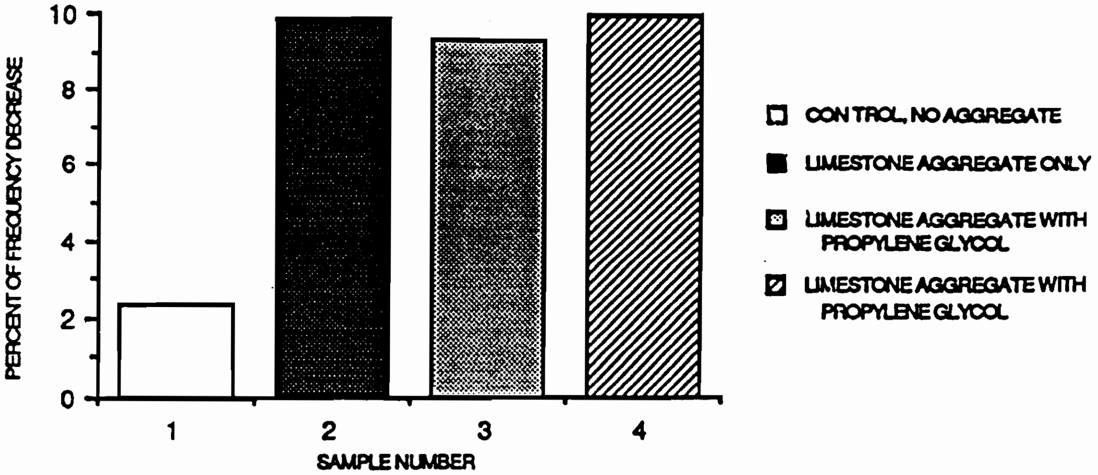


Figure 25. Freeze/thaw damage to white cement with porous aggregates containing propylene glycol vs. cement without as measured by dynamic modulus.

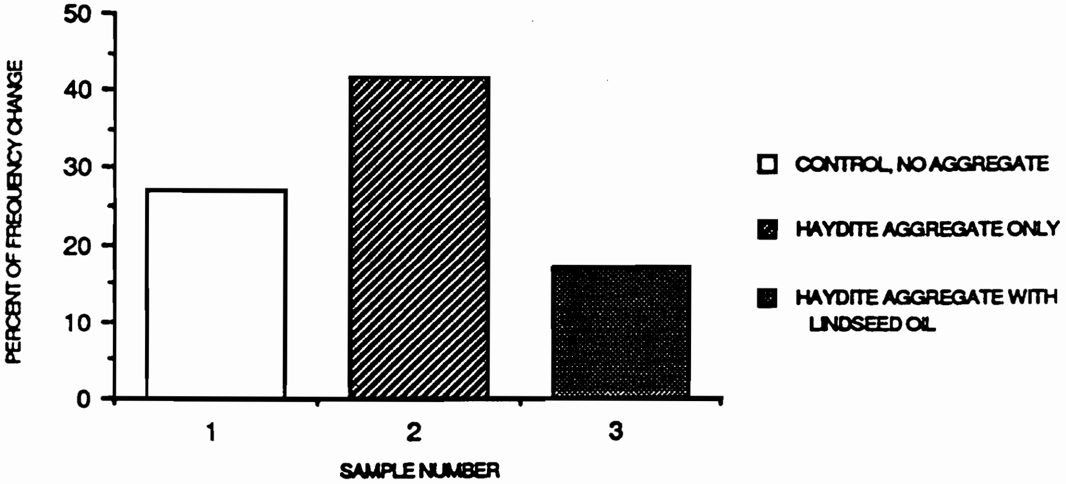


Figure 26. Freeze/thaw damage to white cement with porous aggregates containing linseed oil vs. cement without as measured by dynamic modulus.

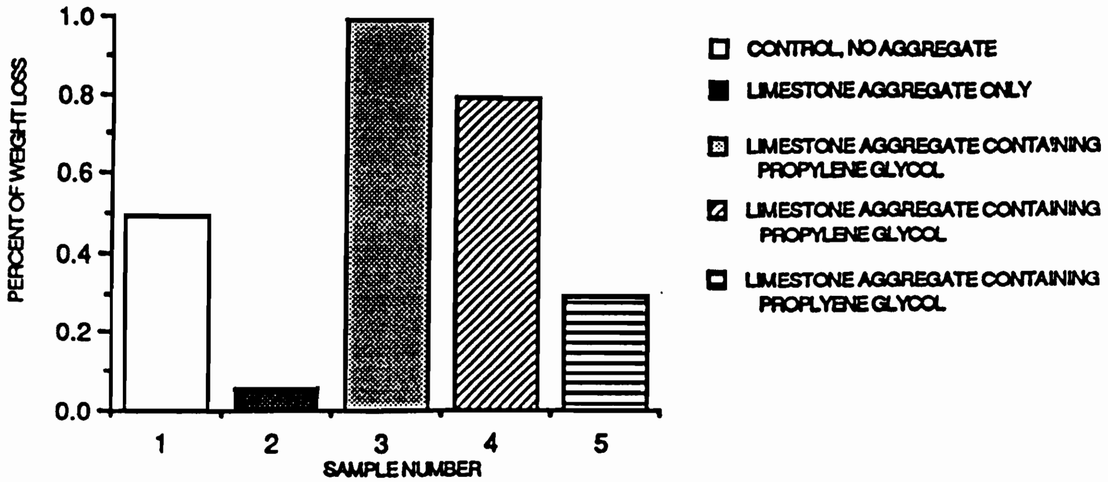


Figure 27. Freeze/thaw damage to white cement with porous aggregates containing propylene glycol vs. cement without as measured by weight loss.

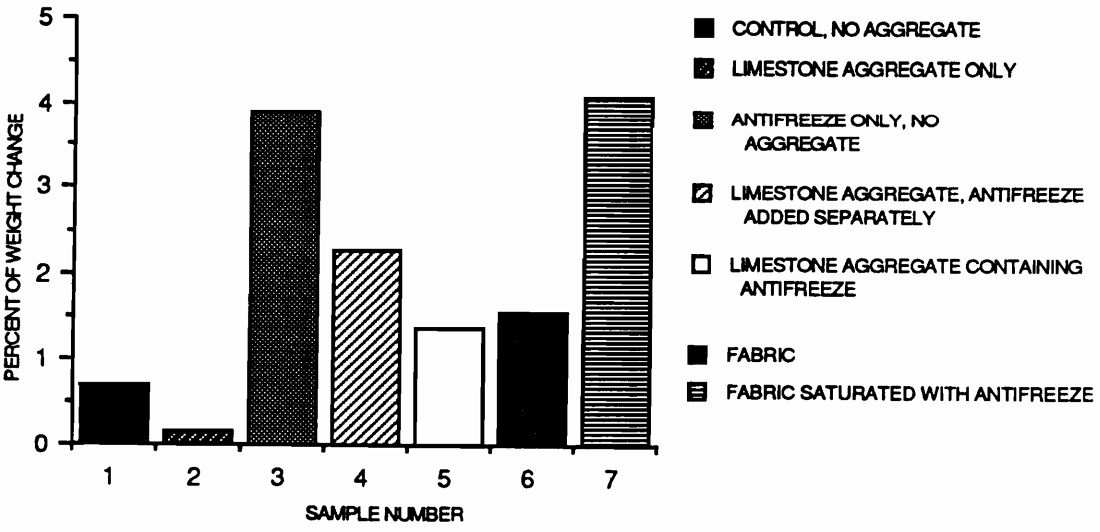


Figure 28. Freeze/thaw damage to portland cement with porous aggregates or fabric containing propylene glycol antifreeze as measured by weight loss.

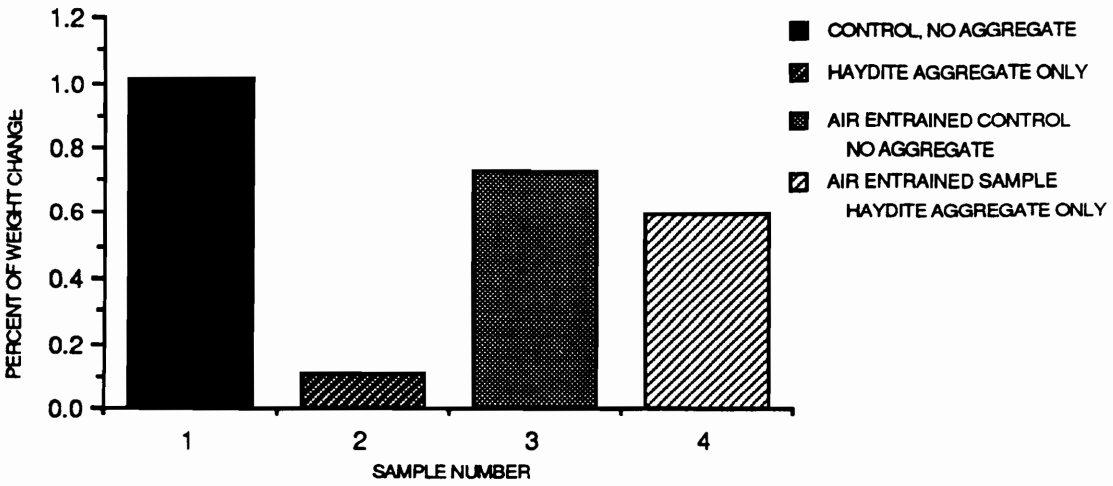


Figure 29. Freeze/thaw damage to white cement with porous aggregates containing antifreeze vs. cement without as measured by weight loss.

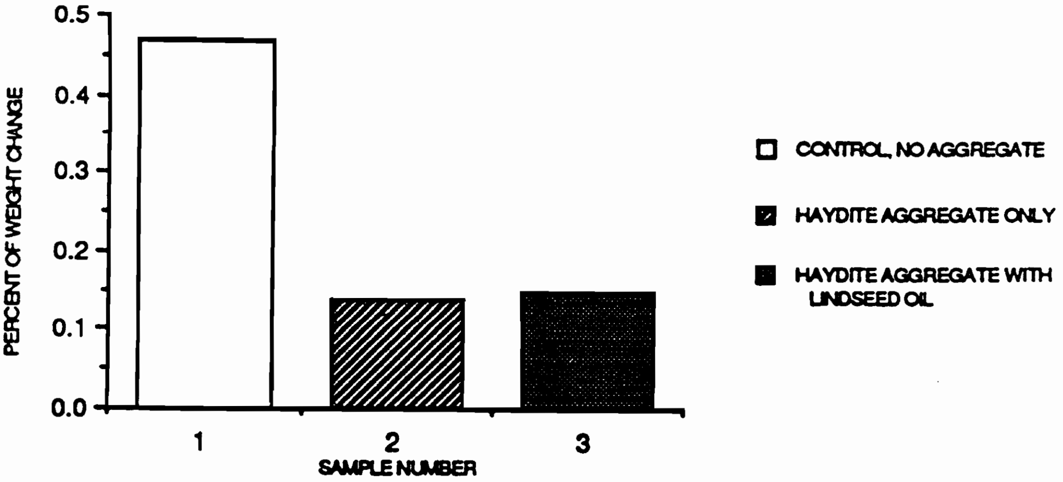


Figure 30. Freeze/thaw damage to white cement with porous aggregates containing linseed oil vs. cement without as measured by weight loss.

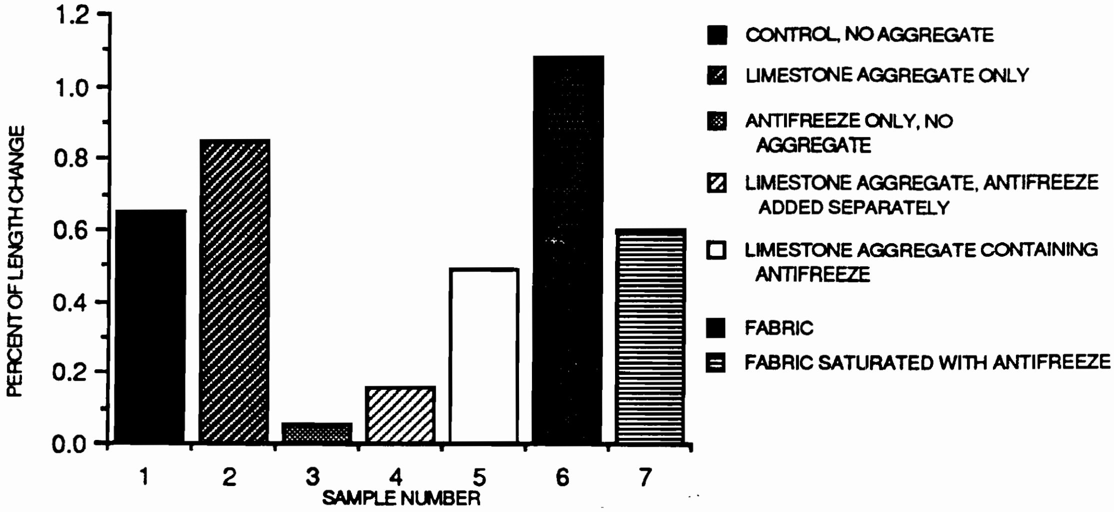


Figure 31. Freeze/thaw damage to portland cement with porous aggregates or fabric containing propylene glycol vs. cement without as measured by length loss.

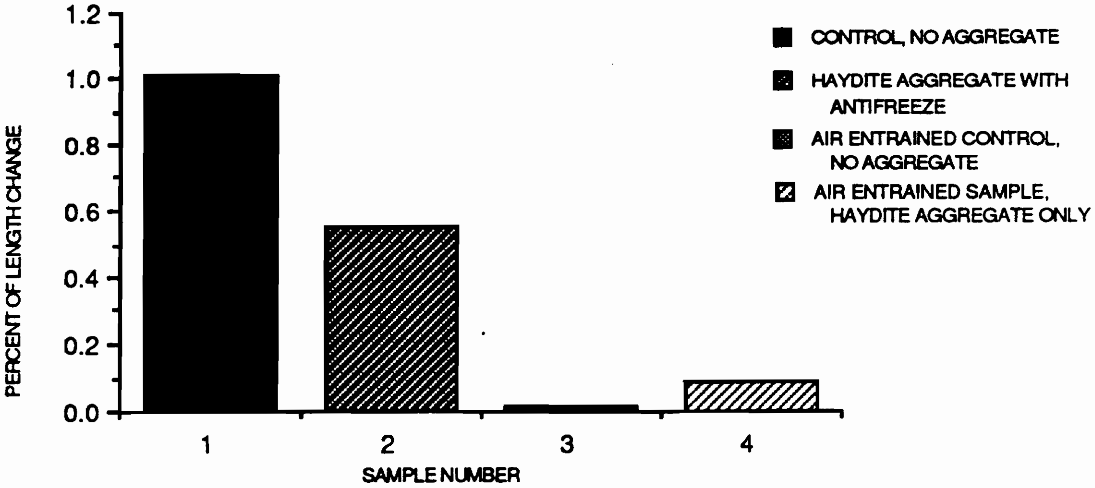


Figure 32. Freeze/thaw damage to white cement with porous aggregates containing propylene glycol vs. cement without as measured by length loss.

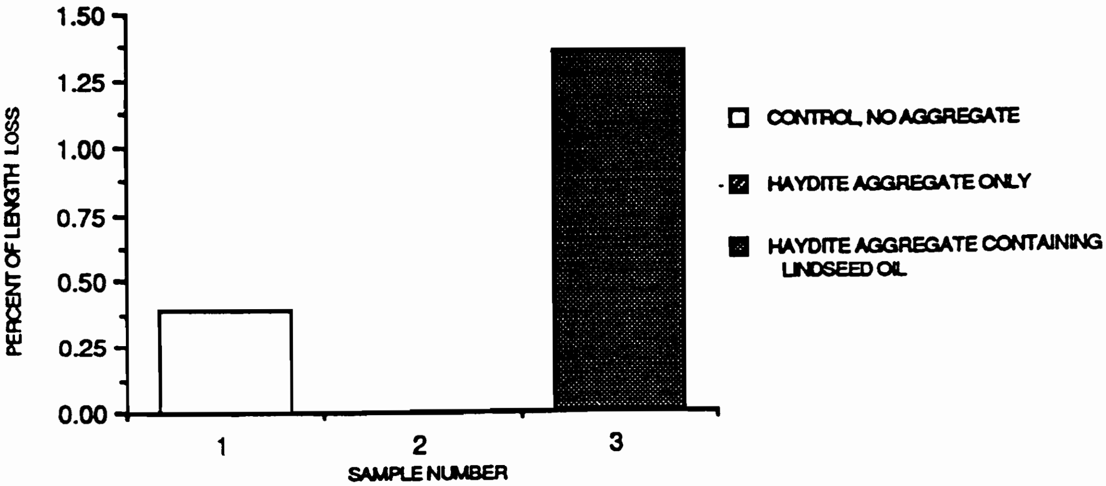


Figure 33. Freeze/thaw damage to white cement with porous aggregate containing linseed oil vs. cement without as measured by length loss.

chemical was researched. The assessment was made visually from the exterior samples, the interior of the samples, and with environmental SEM. The assessment for percent of volume wetted by release was made visually from the exteriors of the samples by the following procedure:

a. The fiber is weighed before inclusion of the chemical. The chemical is included and then weighed. Finally the fibers are coated with wax chemical and weighed so that the weight of the fiber in each chemical is ascertained. The percentage of volume of fiber, or prills filled is visually determined. The samples are then heated.

b. The percentage area wetted from the outside surfaces are visually determined and assessed as to correspond with volume of chemical put in samples.

c. Some samples containing calcium nitrite had environmental SEM done on them to ascertain the spread of the chemical. Environmental scanning electron microscopy was done to show the spread of the chemical. Also some samples were broken to visually ascertain the spread of the dye and the wax.

Results. These tests were done on samples containing calcium nitrite and methyl methacrylate only. Table 9 shows how much chemical could be seen on the exterior of surfaces of the samples. In both cases, in all the tests for bending and compression shaped samples heated either to 120°F, 212°F or microwaved, the results were consistent. The number of filled fibers proportionally increased the percentage of surface area wetted by the release. As seen in Figures 34 and 35 (for methyl methacrylate) and Figures 36 and 37 (for calcium nitrite), exterior inspection showed consistent results.

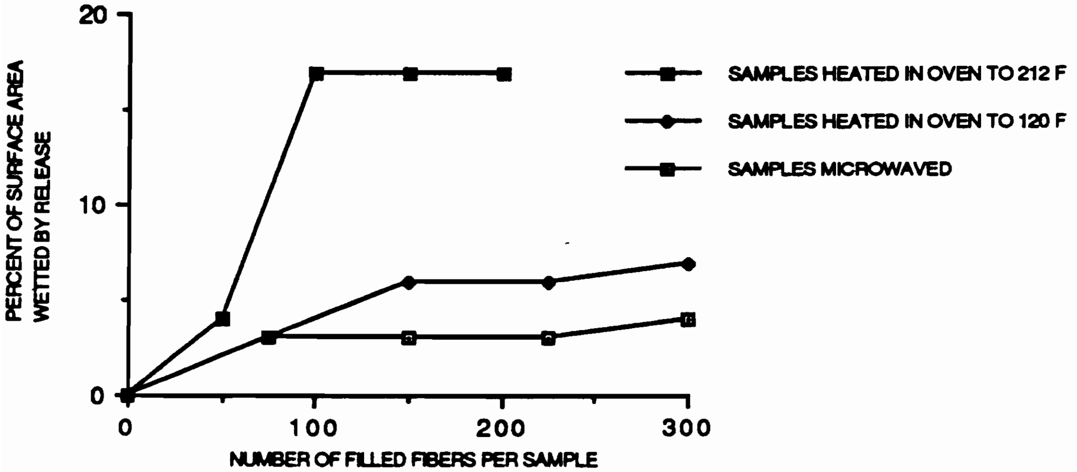


Figure 34. Release of methyl methacrylate and wax into matrix as visually assessed from surfaces (samples shaped for compression testing, 2" x 2" x 2").

Table 9

Tests to Assess Area Wetted by Internally Released Chemical

Treatment for Particular Environmental Distress	Fiber, Aggregate Chemical Coating	Fiber Type and Size	Volume of Cement Matrix	Number of Fibers Used	Volume of Chemical in Fiber if Filled	Percentage of Area Visibly Wetted by Release 100%
corrosion of reinforcing bars in concrete	hollow, porous, polyproylene colored calcium nitrite chemical wax coating	hollow, porous polypropylene fiber 1" long 400 micron inside diameter 40% porosity				see Figures 34-37 see photos 22,23
			samples to be tested for compression $8\ in^3$ volume of the cube	1x=75 fibers 2x=150 fibers 3x=225 fibers	$.0146\ in^3$ $.02925\ in^3$ $.04387\ in^3$	15% 25% 35%
			samples to be tested for bending $6\ in^3$ volume of the prism	1x=75 fibers 2x=150 fibers 3x=225 fibers	$.0146\ in^3$ .02925 in3 .04387 in3	10% 25% 30%
			samples to be tested for permeability $1.325\ in^3$ volume of cylinder	1x=25 fibers 2x=50 fibers 3x=75 fibers	$.0049\ in^3$ .0097 in3 $.0146\ in^3$	10% 35% 30%

Table 9 (continued)

Treatment for Particular Environmental Distress	Fiber, Aggregate Chemical Coating	Fiber Type and Size	Volume of Cement Matrix	Number of Fibers Used	Volume of Chemical in Fiber if Filled	Percentage of Area Visibly Wetted by Release 100%
water/chemical intrusion due to permeability	hollow, porous polypropylene fibers	hollow, porous, polypropylene fiber 1" long 400 micron inside diameter 40% porosity	samples to be tested for compression 8 in^3 volume of the cylinder	1x=75 fibers	.0146 in^3	see Figures 34-37 see photos 22,23
				2x=150 fibers	.02925 in^3	30%
				3x=225 fibers	.04387 in^3	40%
	color methyl methacrylate chemical		6 in3 volume of the prism	3x=225 fibers	.04387 in^3	15%
	wax coating		samples to be tested for permeability 1.325 in^3 volume of cylinder	1x=25 fibers	.0049 in^3	
				2x=50 fibers	.0097 in^3	
				3x=75 fibers	.0146 in^3	

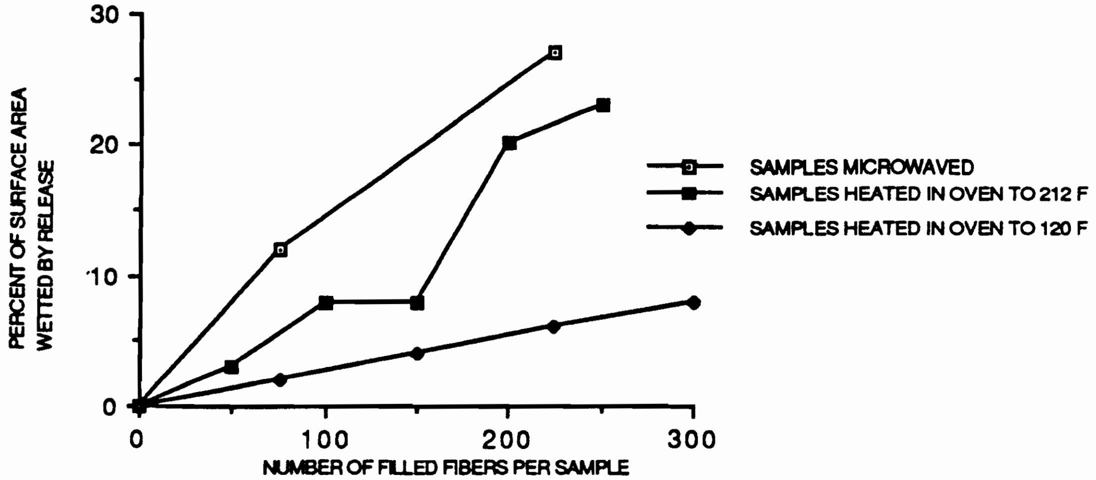


Figure 35. Release of methyl methacrylate and wax into matrix as visually assessed from surfaces (samples shaped for bending testing, 1" x 1" x 6").

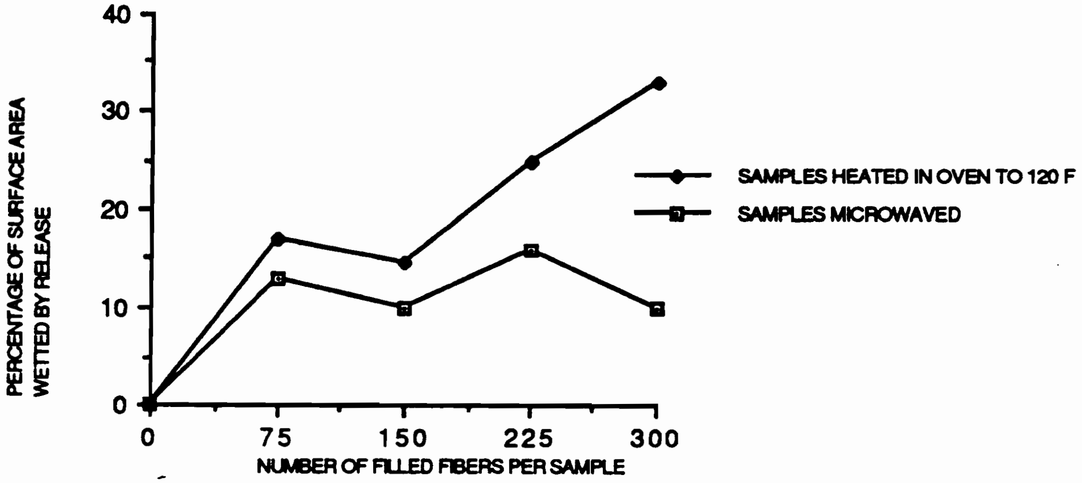


Figure 36. Release of calcium nitrite and wax into matrix as visually assessed from surfaces (samples shaped for compression testing, 2" x 2" x 2").

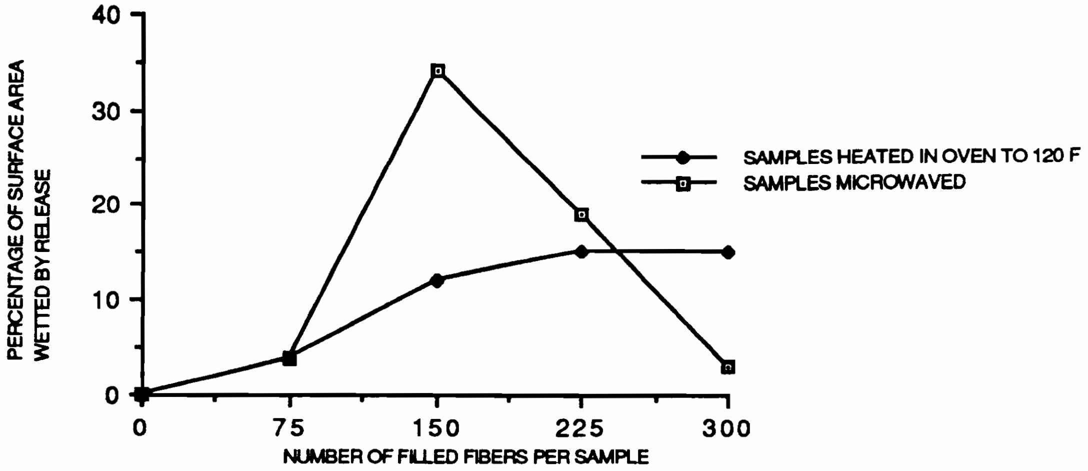


Figure 37. Release of calcium nitrite and wax into matrix as visually assessed from surfaces (samples shaped for bending testing, 1" x 1" x 6").

Research Question 3

Do the fibers and stimuli degrade the strength properties; what are the strength and permeability contributions of the various separate factors of wax, chemical, fiber?

1. Is the internal/external stimuli damaging to the strength properties of the concrete?

Results. In both bending and compression tests done on both calcium nitrate in polypropylene fibers and methyl methacrylate in wax-coated polypropylene fibers heated to different temperatures or microwaved, it is shown in Figures 38 and 39 for methyl methacrylate and in Figures 40 and 41 for calcium nitrate that heating most often increases the bending and compression strength and that higher temperatures increase it slightly more than moderate temperatures. Microwaving, however, gives unpredictable variable results, as seen in Figures 42 through 45.

2. <u>What is the effect of volume of fibers on strength properties</u>?

<u>Results</u>. As can be seen in Figures 46 and 47 (for 3 days), Figures 48 and 49 (for 7 days), and Figures 50 and 51 (for 14 days cure), in the case of methyl methacrylate in polypropylene fibers, the compressive strength is higher at the temperature of polymerization (212°F), but at both 212° and 120°; the compression strength is not degraded with fibers up to 2.75% volume of fibers. In the case of bending, the methyl methacrylate samples also maintained their strength; they also maintained their strength up to 2.75% volume of fibers or approximately 225 per sample. In the compression tests on calcium nitrite (as shown in Figure 52), the filled fibers have a higher compression strength and maintain that strength fairly well. In the bending results on that chemical (Figure 53), the filled fibers also have the highest bending strength.

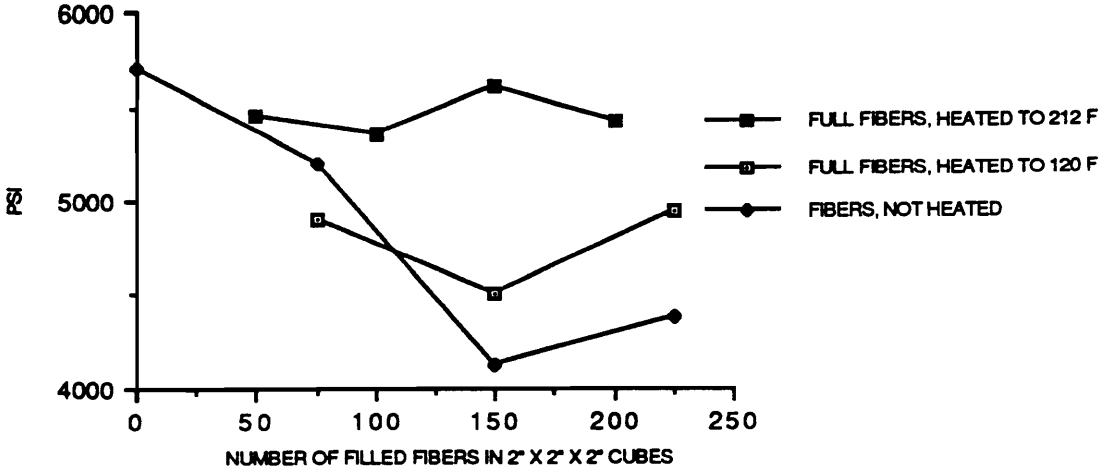


Figure 38. Effect of heating on compressive strength of white cement containing methyl methacrylate and wax in porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

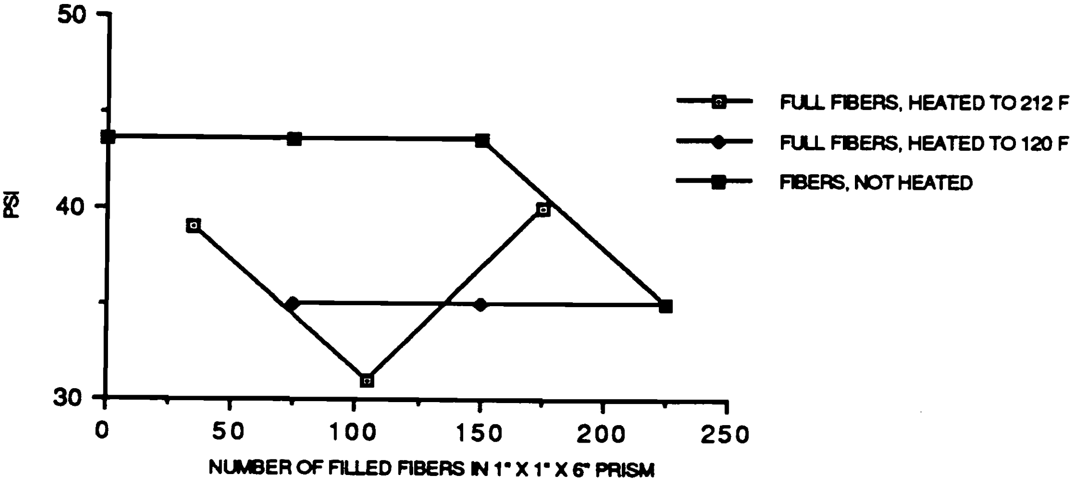


Figure 39. Effect of heating on bending strength of white cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

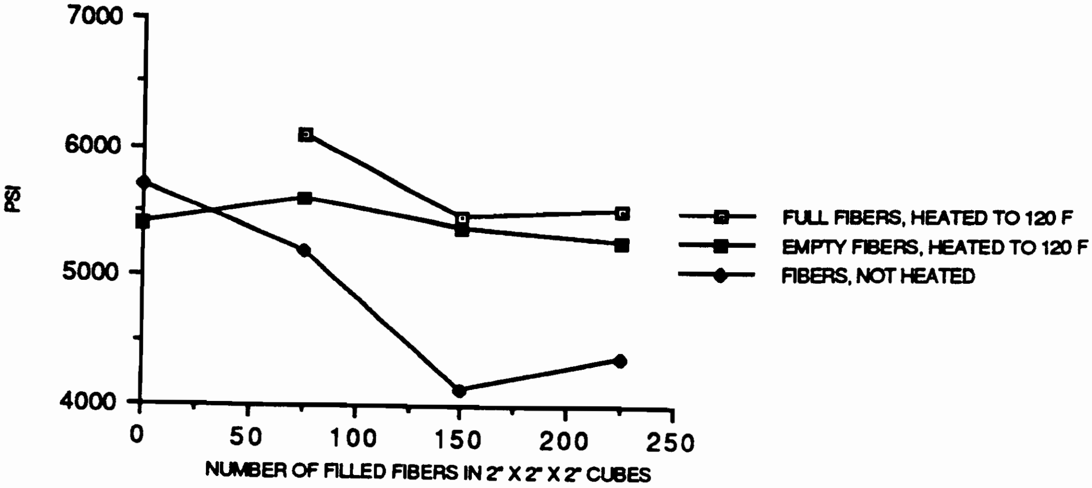


Figure 40. Effect of heating on compressive strength of white cement containing calcium nitrite and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

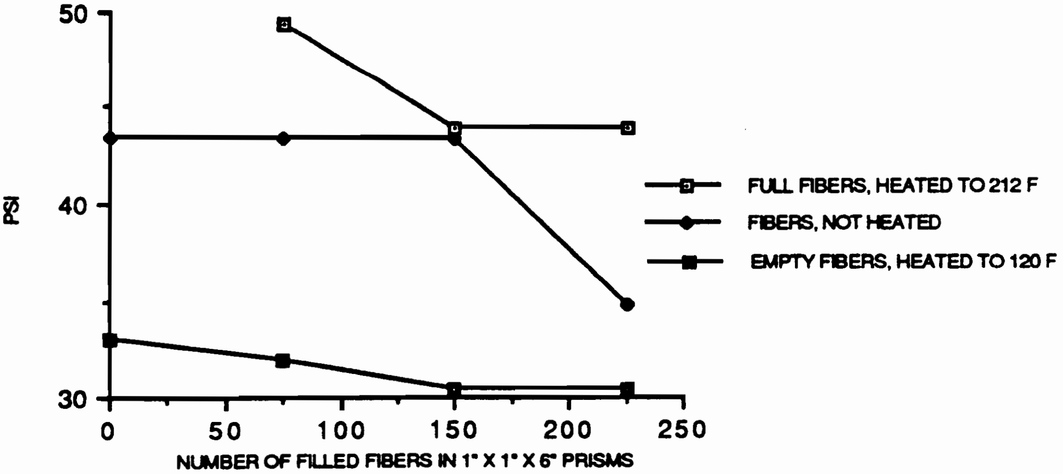


Figure 41. Effect of heating on bending strength of white cement containing calcium nitrite and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

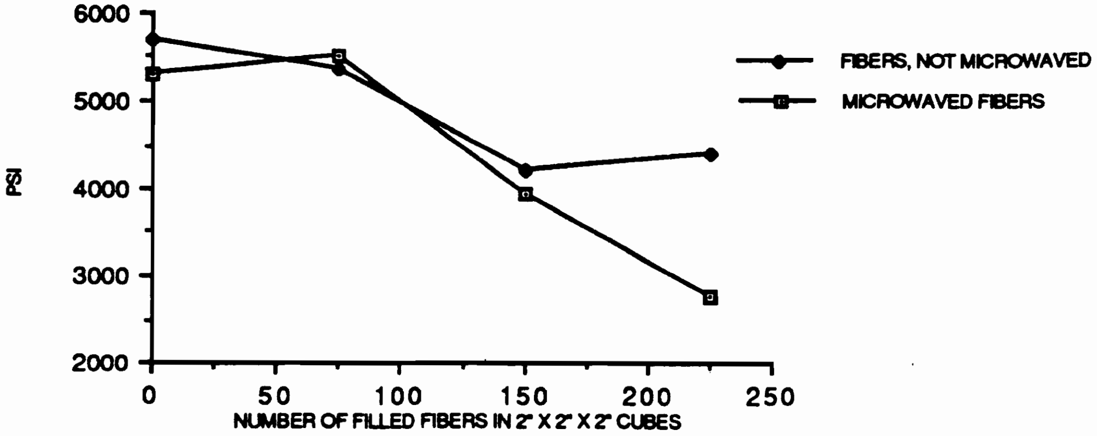


Figure 42. Effect of microwave heating on compressive strength of white cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 3 days--microwaved for 2 min, maximum power).

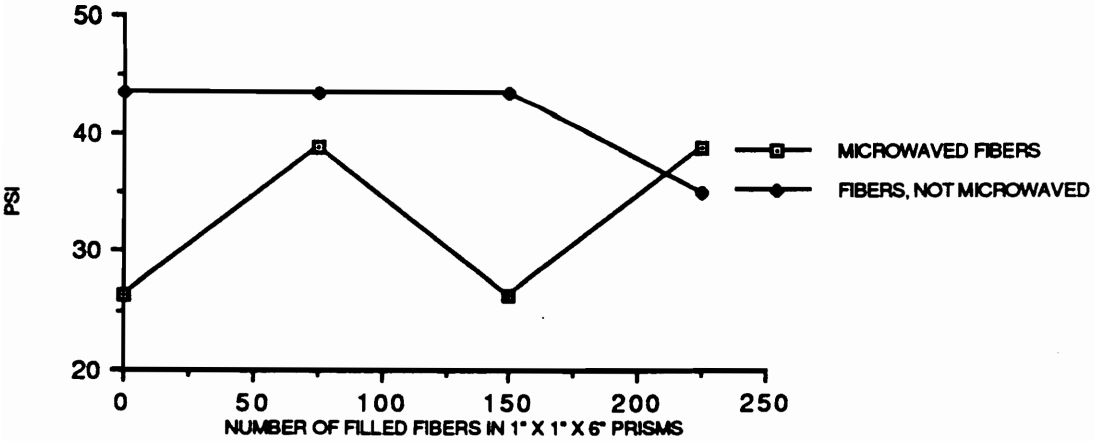


Figure 43. Effect of microwave heating on bending strength of white cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 3 days--microwaved for 2 min, maximum power).

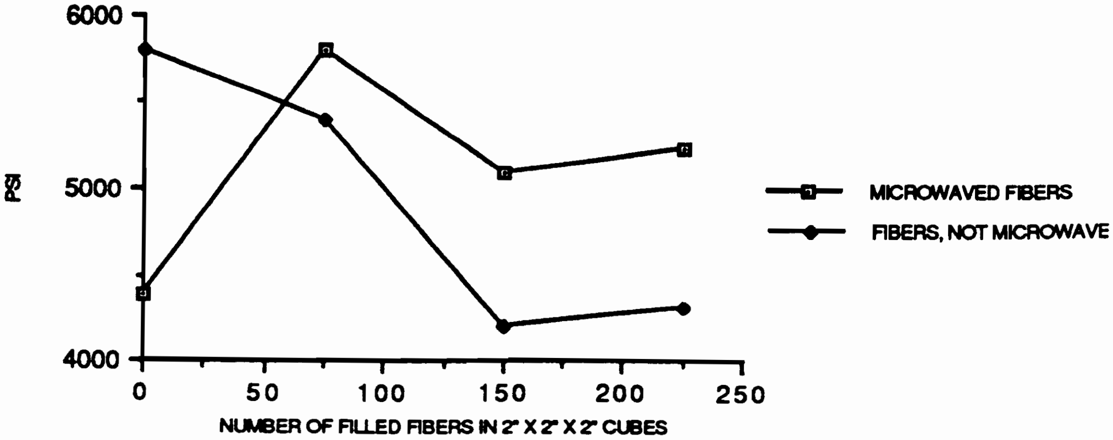


Figure 44. Effect of microwave heating on compression strength of white cement containing calcium nitrite and wax released from porous polypropylene fibers (samples cured for 3 days--microwaved for 2 min, maximum power).

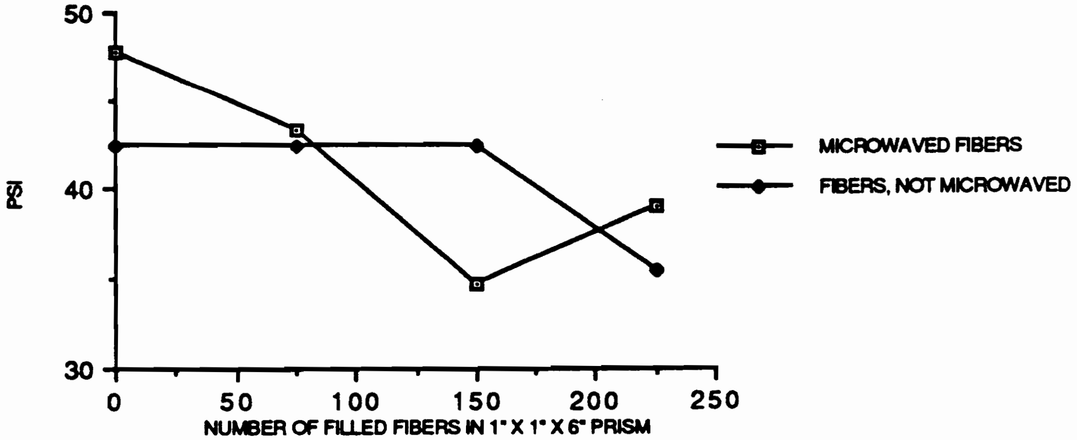


Figure 45. Effect of microwave heating on bending strength of white cement containing calcium nitrite and wax released from porous polypropylene fibers (samples cured for 3 days--microwaved for 2 min, maximum power).

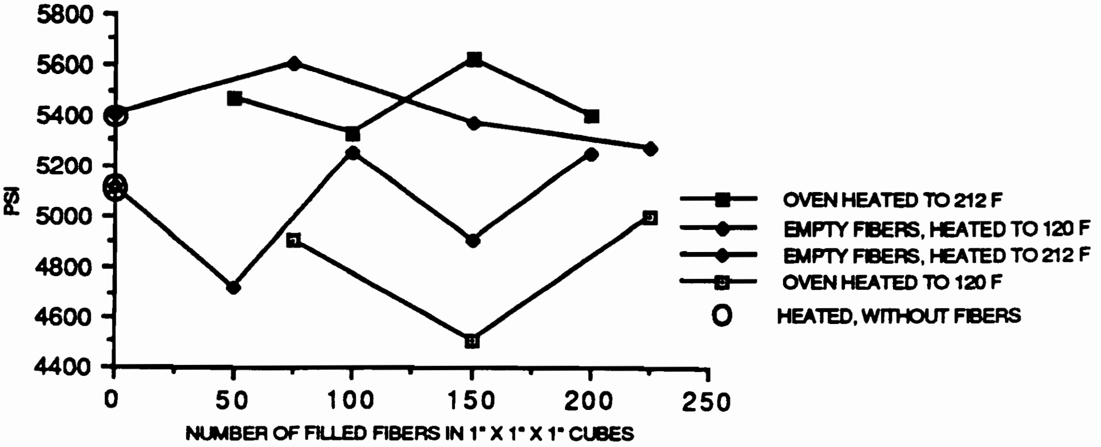


Figure 46. Effect of volume of fibers on compressive strength of white cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

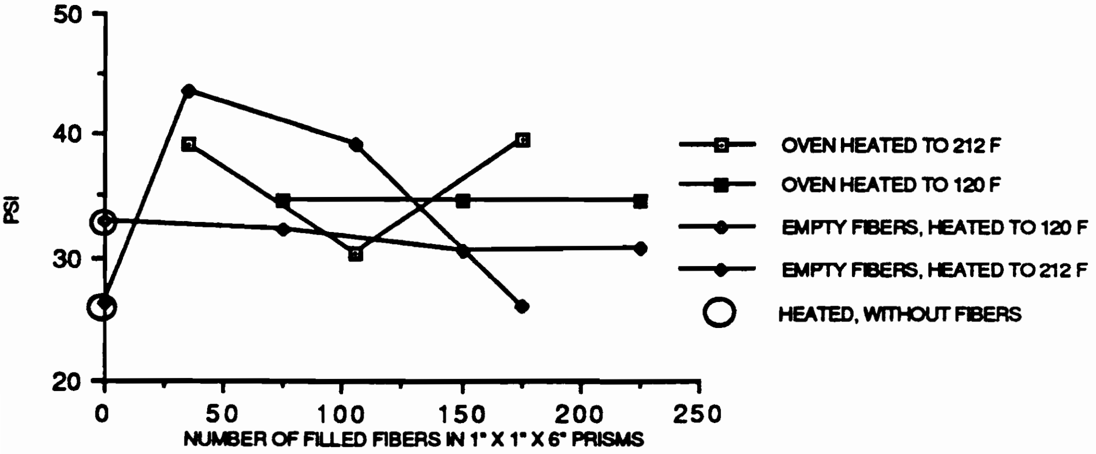


Figure 47. Effect of volume of fibers on bending strength of white cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

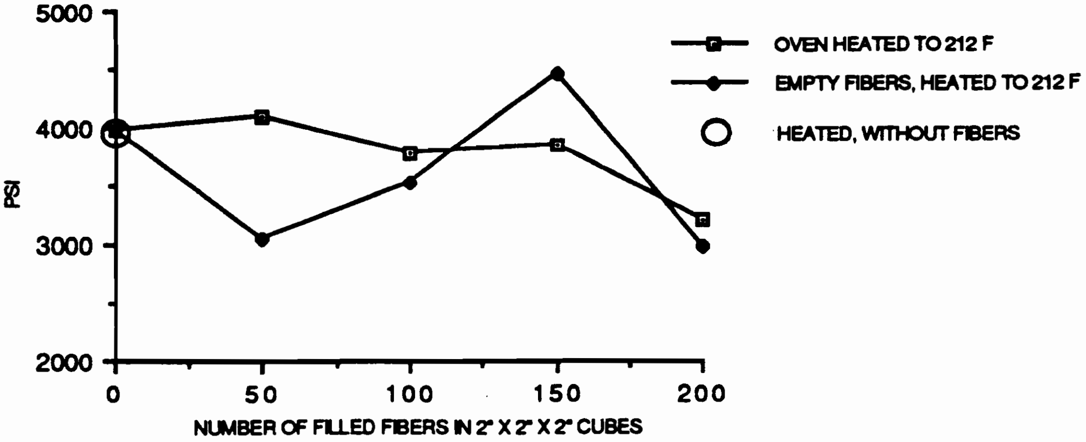


Figure 48. Effect of volume of fibers on compression strength of portland cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 7 days--heated to 212° F).

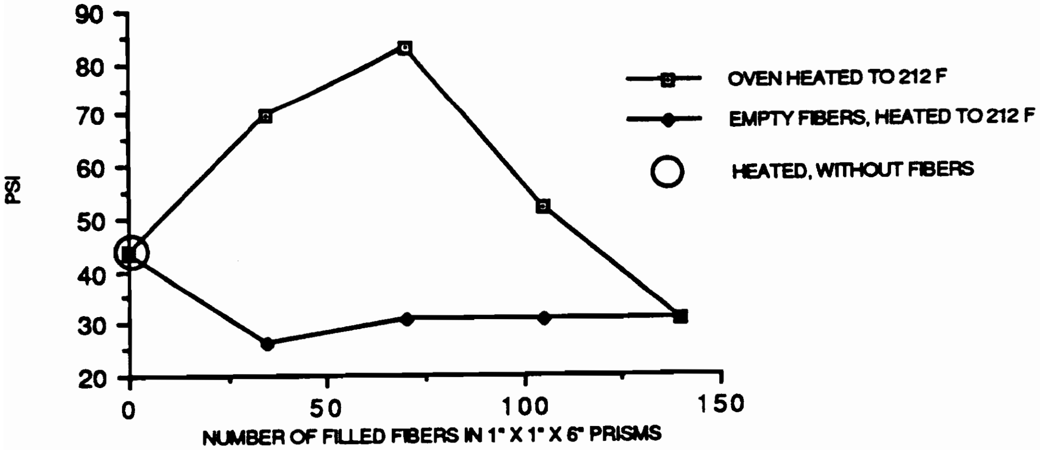


Figure 49. Effect of volume of fibers on bending strength of portland cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 7 days--heated for 30 min).

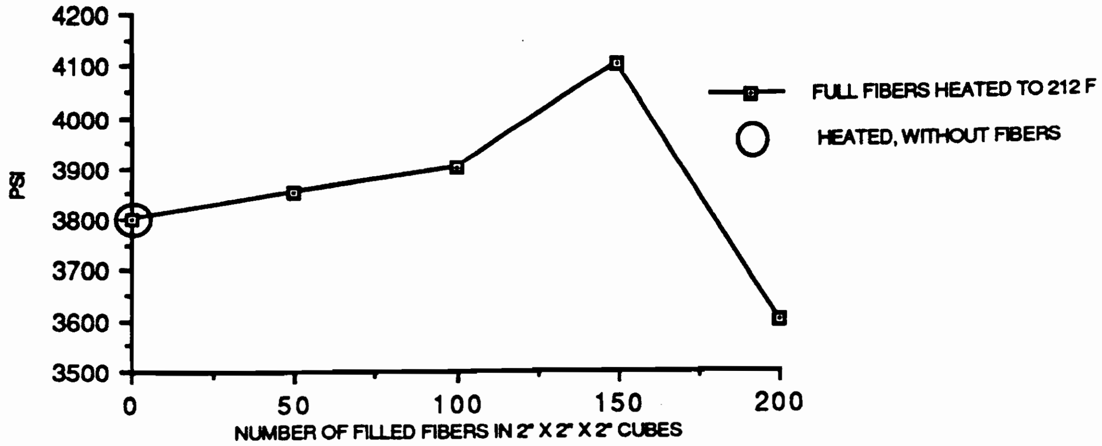


Figure 50. Effect of volume of fibers on compression strength of portland cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 14 days--heated to 212° F for 30 min).

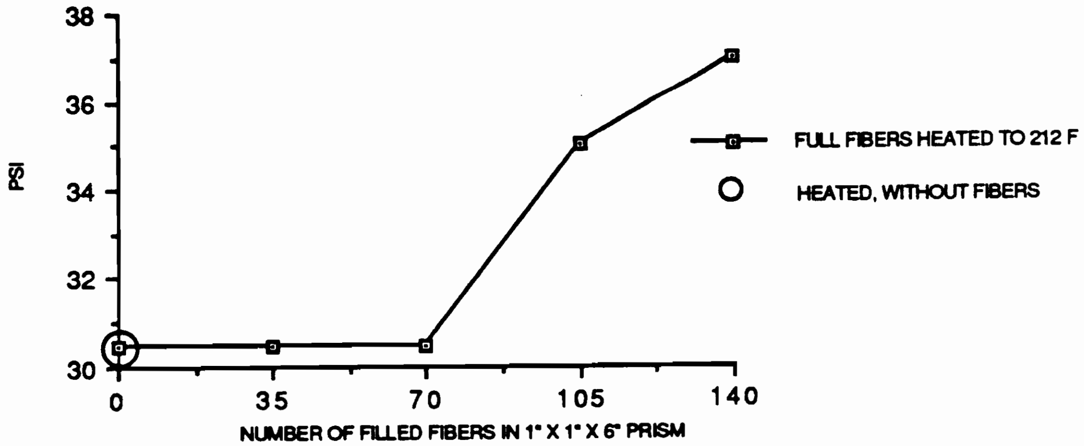


Figure 51. Effect of volume of fibers on bending strength of portland cement containing methyl methacrylate and wax released from porous polypropylene fibers (samples cured for 14 days--heated to 212° F for 30 min).

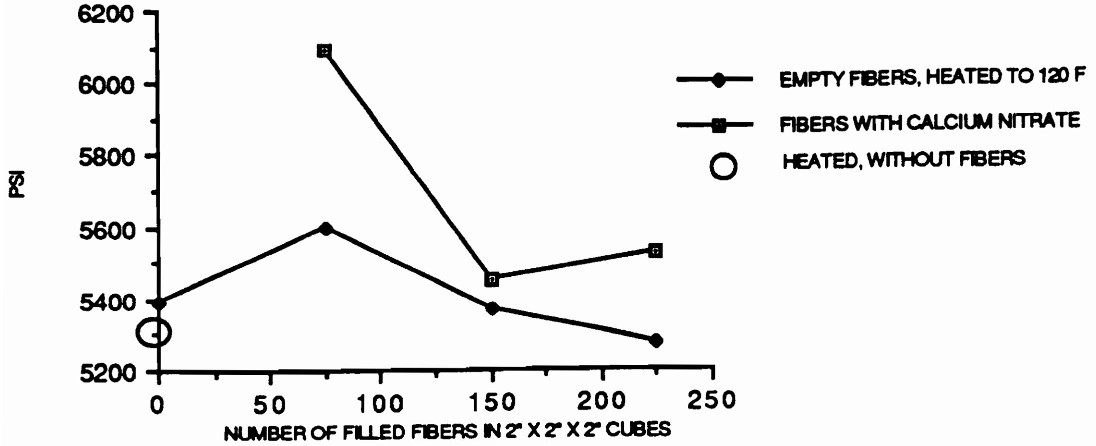


Figure 52. Effect of volume of fibers on compression strength of white cement containing calcium nitrite and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

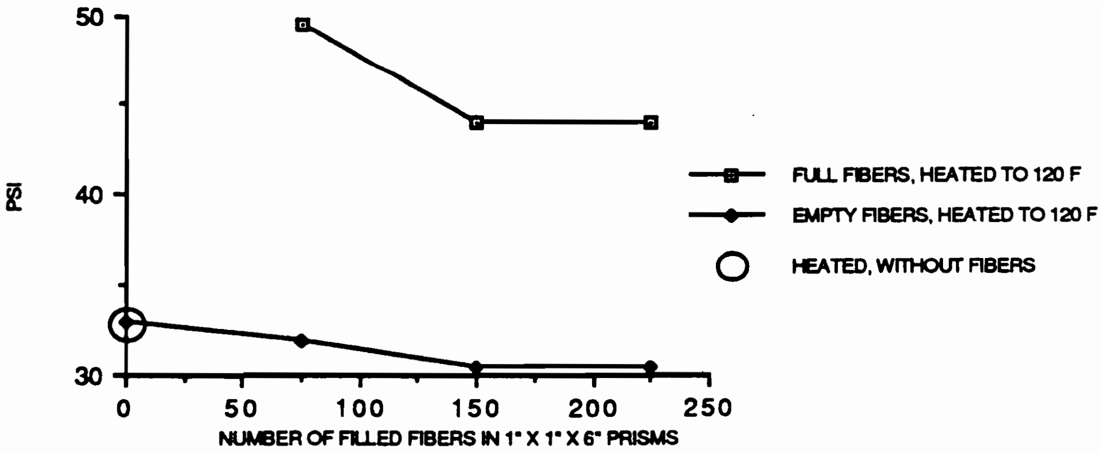


Figure 53. Effect of volume of fibers on bending strength of white cement containing calcium nitrite and wax released from porous polypropylene fibers (samples cured for 3 days--heated for 30 min).

Table 10

Tests for Affect of Fiber or Aggregate on Strength

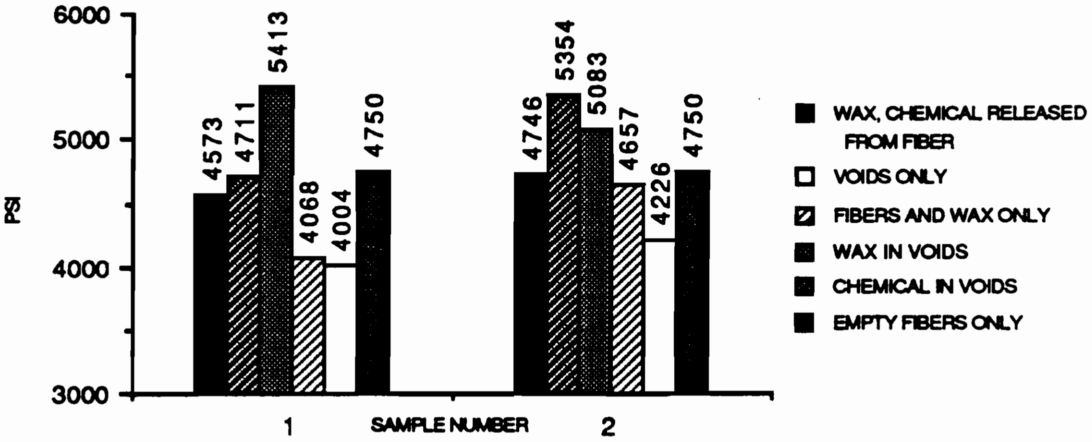
Treatment for Particular Environmental Distress	Fiber, Aggregate Chemical Coating	Fiber Type and Size	Volume of Cement Matrix	Number of Fibers Used	Affect of Fiber Volume on Strength in Bending, Compression
corrosion of reinforcing bars in concrete	hollow, porous, polypropylene fiber colored calcium nitrite chemical	hollow, porous polypropylene 1 inch long to be 400 micron inside diameter 40% porosity	samples to be fibers tested for compression 8 in^3	1x=75 fibers 2x=150 fibers 3x=225 fibers	increase in fibers causes no reduction in bending and compression strength at 2.75% volume of fibers option.
	wax coating		volume of the samples to be tested bending 6 in^3 volume of the prism	1x=75 fibers 2x=150 fibers 3x=225 fibers	
			samples to be tested for permeability 1.325 in^3 volume of cylinder	1x=25 fibers 2x=50 fibers 3x=75 fibers	

Table 10 (continued)

Treatment for Particular Environmental Distress	Fiber, Aggregate Chemical Coating	Fiber Type and Size	Volume of Cement Matrix	Number of Fibers Used	Affect of Fiber Volume on Strength in Bending, Compression
water/chemical intrusion due to permeability	hollow, porous polypropylene fibers	hollow, porous, polypropylene fiber 1" long 400 micron inside diameter 40% porosity	samples to be tested for compression 8 in^3 volume of the cylinder	1x=75 fibers 2x=150 fibers 3x=225 fibers	increase in fibers causes no reduction in compression and bending strength, but 2.75% volume is the optimum fibers before the value falls off.
	colored methyl methacrylate chemical		samples to be tested bending 6 in^3 volume of the prism	1x=75 fibers 2x=150 fibers 3x=225 fibers	
	wax coating		samples to be tested for permeability 1.325 in^3 volume of cylinder	1x=25 fibers 2x=50 fibers 3x=75 fibers	

3. <u>What is the contribution to bending strength, compression strength, or impermeability of the various factors such as coating (wax), fiber, and chemical contained</u>?

<u>Results</u>. The results separating the factors with the methyl methacrylate design were quite inconclusive (see Figures 54 through 56). The design of the experiment may have introduced other factors such as matrix solidification due to hole drilling. Tests using the Xypex prills were not much more conclusive. The wax alone is slightly stronger in bending than the wax and Xypex combinations (Figures 57 and 58). As in the methyl methacrylate samples, the wax by itself had appeared to give slightly higher strength both in bending and compression. In the permeability tests for Xypex, the Xypex prill gave better impermeability than wax alone (see Figure 59).



<u>Figure 54</u>. Contribution to compressive strength of white cement by various factors: wax, fibers, fiber voids, methyl methacrylate, wax-coated fibers, wax-coated fibers releasing methyl methacrylate (samples cured for 3 days--heated for 30 min).

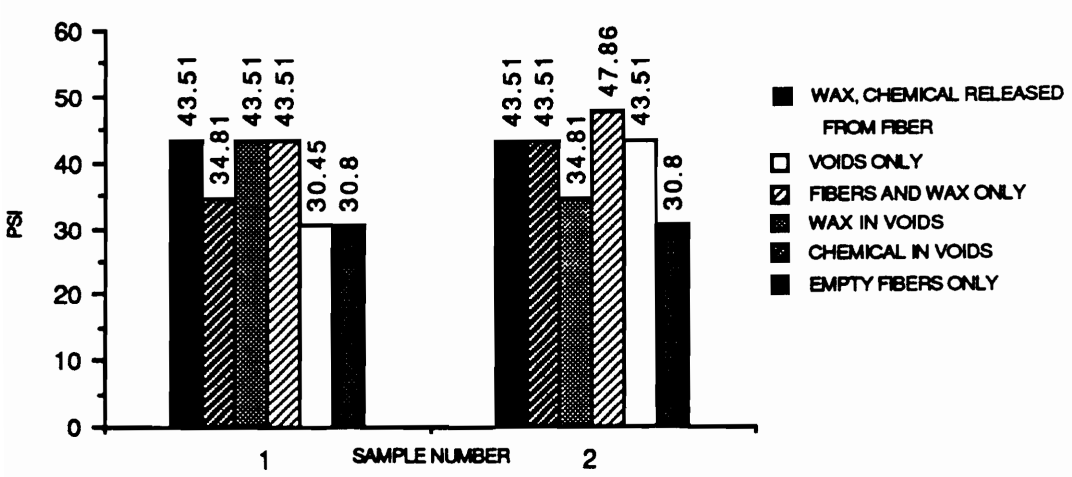


Figure 55. Contribution to bending strength of white cement by various factors: wax, fibers, fiber voids, methyl methacrylate, wax-coated fibers, wax-coated fibers releasing methyl methacrylate (samples cured for 3 days--heated for 30 min).

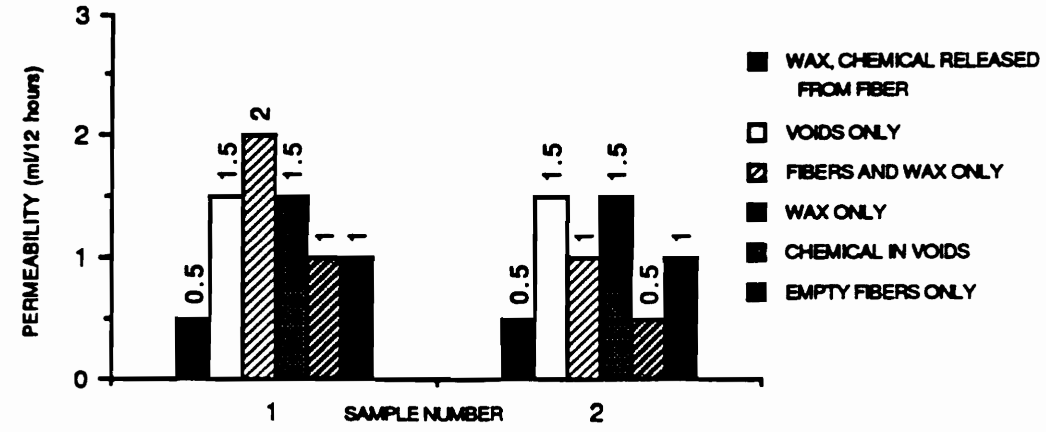


Figure 56. Contribution to permeability of white cement by various factors: wax, fibers, fiber voids, methyl methacrylate, wax-coated fibers releasing methyl methacrylate (samples cured for 3 days--heated for 30 min).

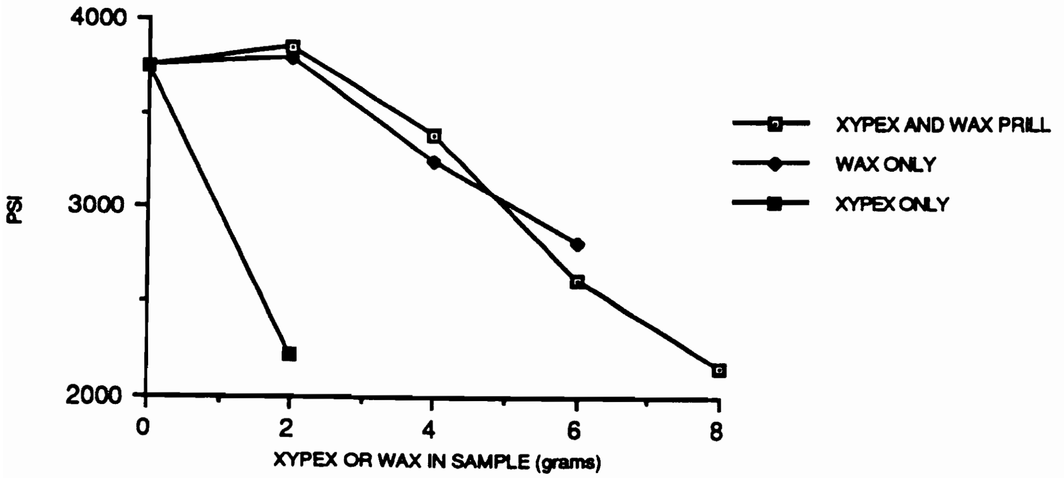


Figure 57. Contribution to compressive strength of portland cement by various factors: Xypex, wax, Xypex/wax prill (samples cured for 7 days--heated to 212° F for 30 min).

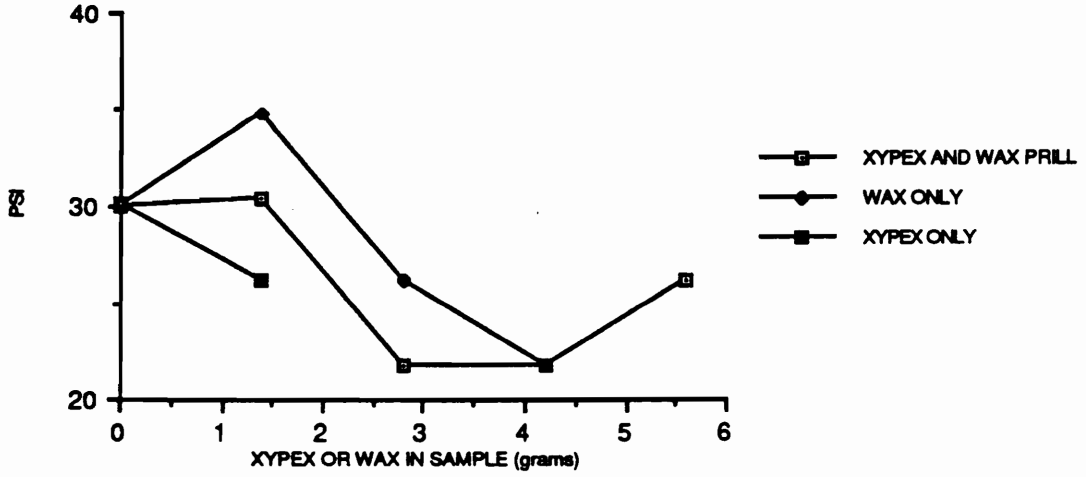


Figure 58. Contribution to bending strength of portland cement by various factors: Xypex, wax, Xypex/wax prill (samples cured for 7 days--heated to 212° F for 30 min).

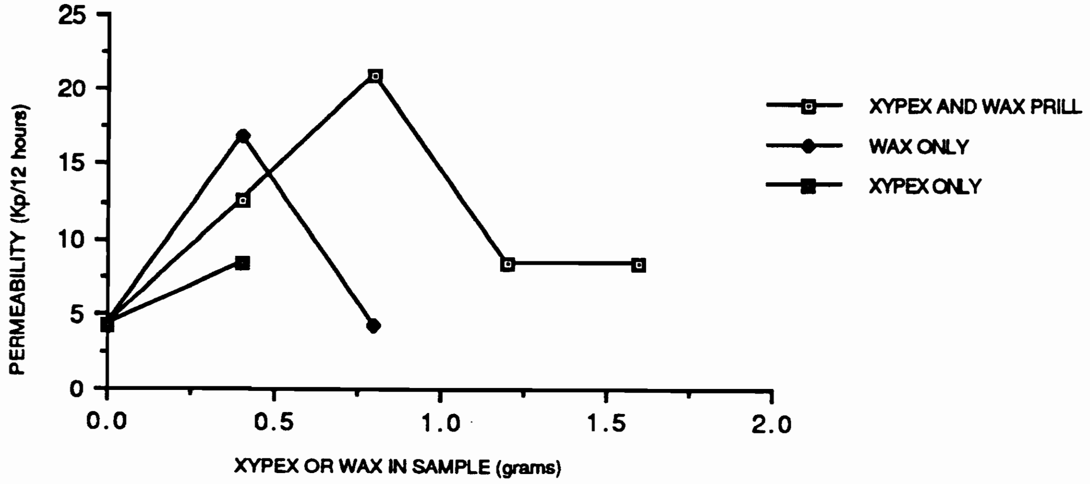


Figure 59. Contribution to permeability of portland cement by various factors: Xypex, wax, Xypex/wax prill (samples cured for 7 days--heated to 212° F for 30 min).

Research Question 4

Are these designs an improvement over conventional treatments for impermeability or crack reduction and environmental distresses?

Results. Test results are:

1. The internal release of methyl methacrylate from hollow, porous fibers was compared with the conventional polymer impregnation surface application of methyl methacrylate and inclusion of fibers (see photo 31 in Appendix C). The same amount of methyl methacrylate was added on the top of the sample as was contained in the fibers. Bending and compression strength tests and permeability were done. The

surface application was done at the same time the internal release samples were heated. As seen in Figures 60 and 61, in both bending and compression, the methyl methacrylate contained in fibers were stronger in both bending and compression than the samples in which methyl methacrylate was applied from on top as is done in the field. Permeability was also less (or better) for internal release (see Figure 62).

2. In the design to address corrosion, the internal release of calcium nitrite was compared with the inclusion of calcium nitrite in the initial mix. The comparison was made for set retardation (see Figure 63). ASTM test 191-82 was used. The results show little set retardation with calcium nitrite filled fibers but significant set retardation with calcium nitrite freely mixed in the cement.
3. In the case of linseed oil or antifreeze released internally to address freeze/thaw damage, the comparison was made with some air entrained samples. The results (as seen in Figures 29 and 32) show less weight loss damage for the internal release and less length loss damage if internal release is combined with conventional air entrainment.
4. In the case of a catalytic sealant, Xypex to reduce permeability, the comparison was made between the sealant released from wax prills contained inside the samples with the sealant applied externally with

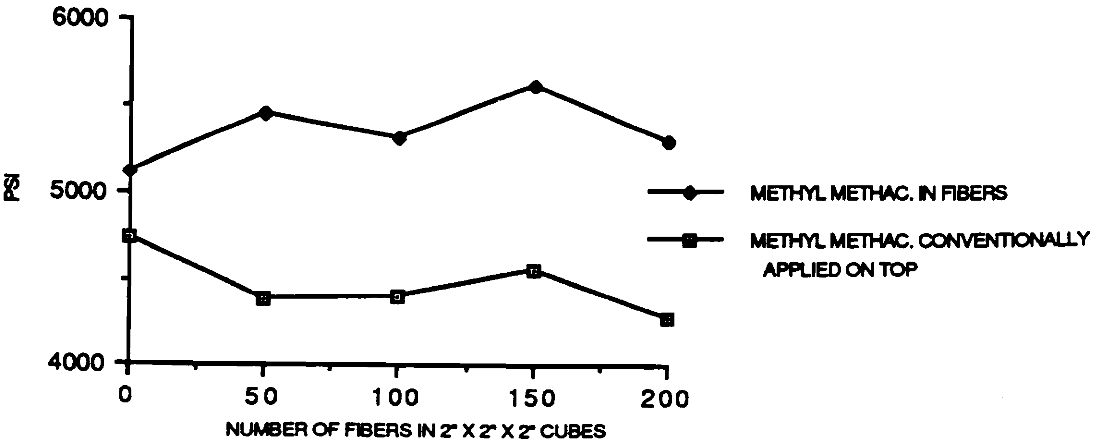


Figure 60. Effect of internal release of methyl methacrylate and wax from porous polypropylene fibers and internal polymerization vs. conventional application from the exterior top surface on compressive strength (samples heated 212° F for 30 min).

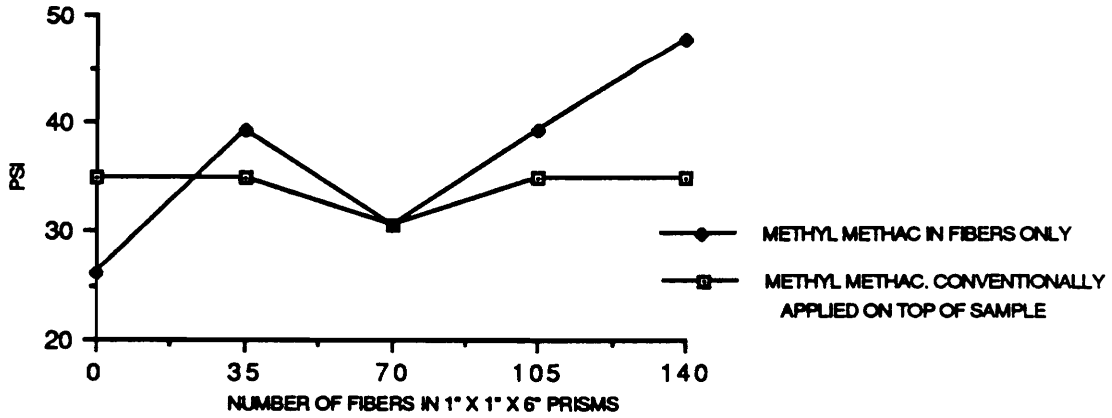


Figure 61. Effect of internal release of methyl methacrylate and wax from porous polypropylene fibers and internal polymerization vs. conventional application from the exterior top surface on bending strength (samples cured for 3 days--heated to 212° F for 30 min).

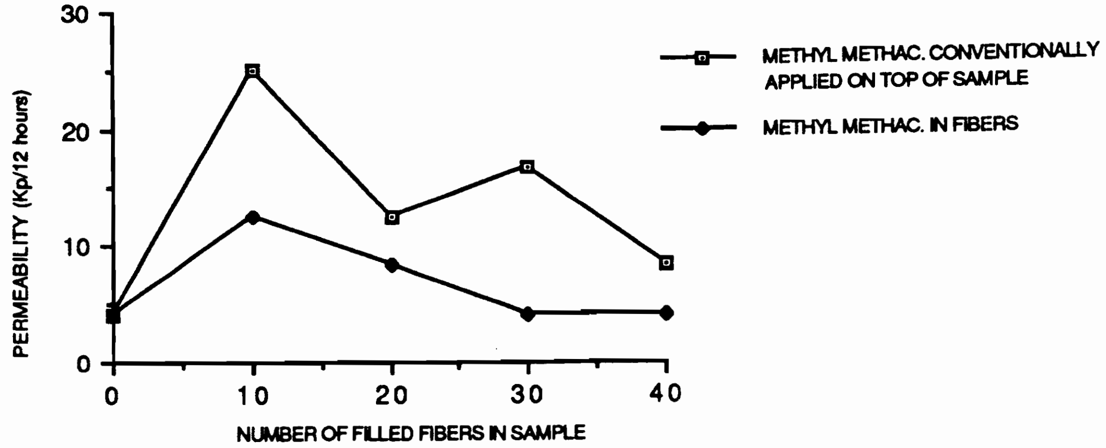


Figure 62. Effect of internal release of methyl methacrylate and wax from porous polypropylene fibers and internal polymerization vs. conventional application from the exterior top surface on permeability (samples cured 3 days--heated to 212° F for 30 min).

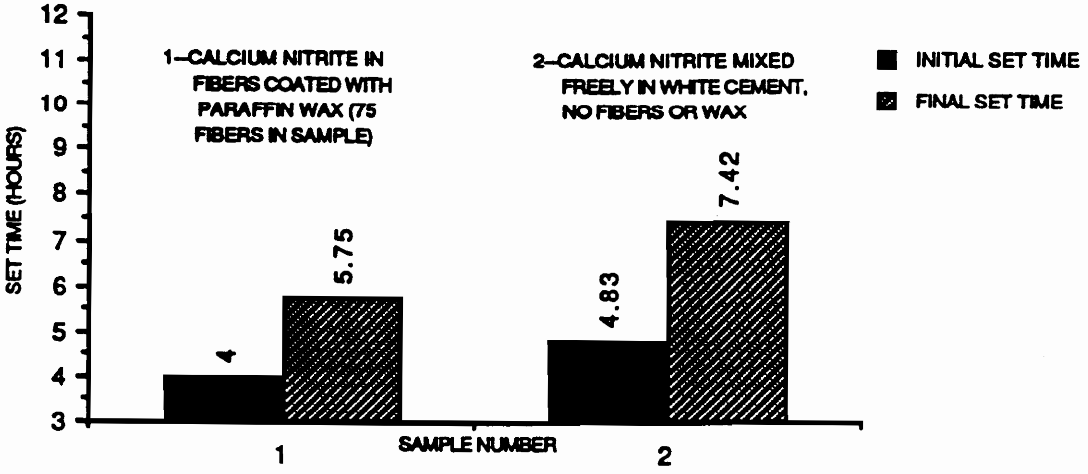


Figure 63. Time of setting of portland cement containing calcium nitrite released from wax-coated porous polypropylene fibers vs. portland cement containing free calcium nitrite.

and without wax particles in the cement. The surface application was done at the same time the internal release samples were heated. The comparisons were made for permeability and bending and compression strength. As seen in Figures 64 and 65, in the bending and compression strength were greater for Xypex wax prills in the samples than the same amount of Xypex applied on top of the sample, as is done conventionally in the field. Permeability was approximately the same for internal release (see Figure 66).

5. The timed release of water from porous aggregates in DSP compared with samples in which the all water is available at initial mix is less effective than the conventional treatment in reducing shrinkage (see Figure 67). This was the one failure and surprise.
6. There was no comparison to be made for the release into the sintered phosphate bonded bottom ash because this is a novel material.
7. The release to prevent loading cracking had no obvious comparison.

Research Question 5

What are the effects of manufacture, storage, and in-the-field problems?

Results. The results show that in open containers the chemicals evaporate, but the wax on the fibers does not melt even in outside temperatures of 85-90°. Evaluation was made for filled fibers placed in refrigeration (see photo 33).

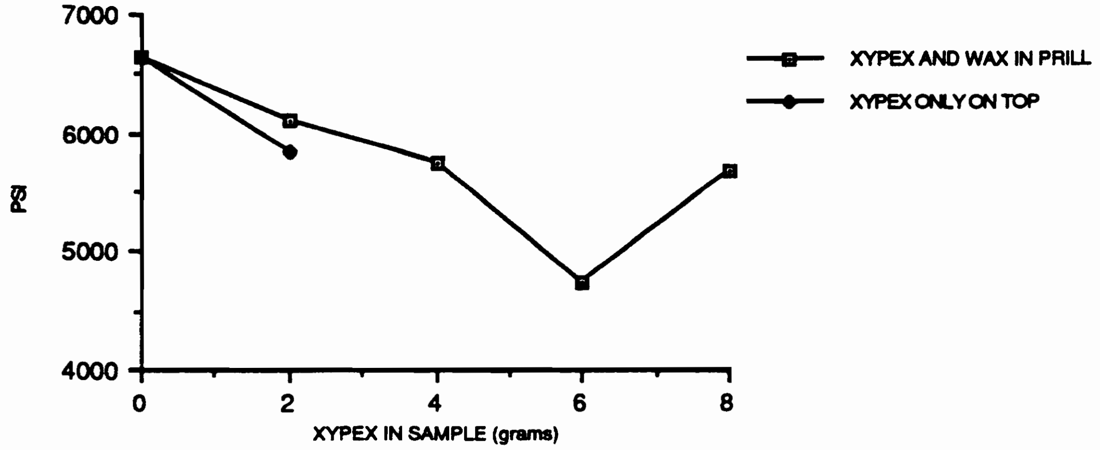


Figure 64. Effect of internal release of Xypex and wax from prills vs. conventional application of Xypex brushed on the exterior top surface on compressive strength of white cement (samples cured for 7 days--heated to 212° F for 30 min).

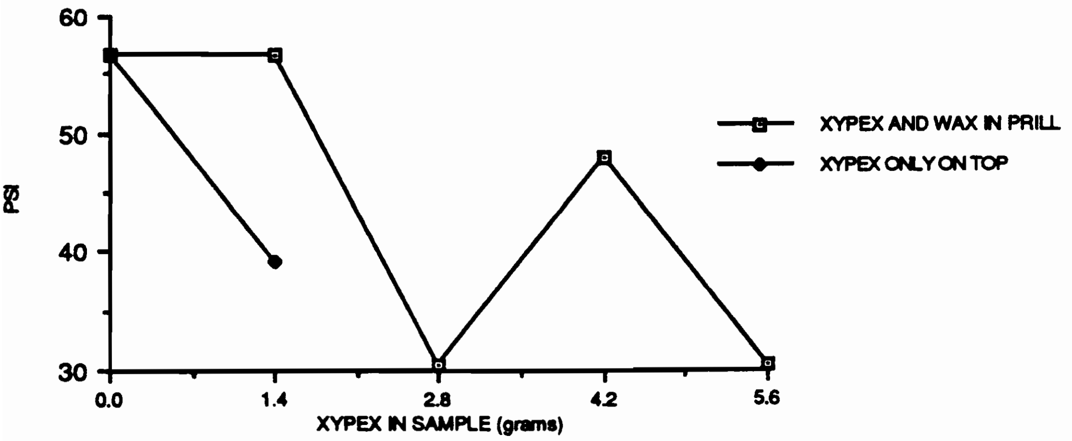


Figure 65. Effect of internal release of Xypex and wax from prills vs. conventional application of Xypex brushed on the exterior surface on bending strength of white cement (samples cured for 7 days--heated to 212° F for 30 min).

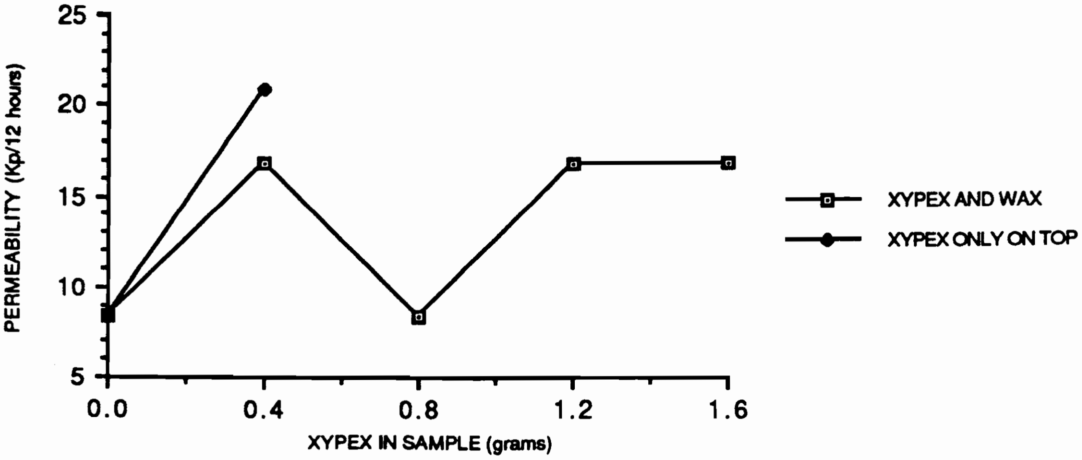


Figure 66. Effect of internal release of Xypex and wax from prills vs. conventional application of Xypex brushed on the exterior top surface on permeability of white cement (samples cured 7 days--heated to 212° F for 30 min).

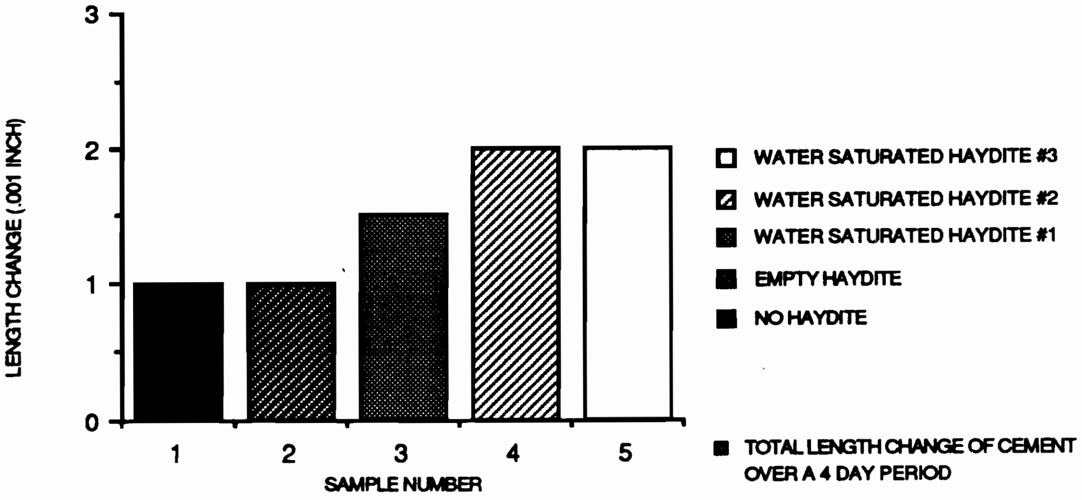
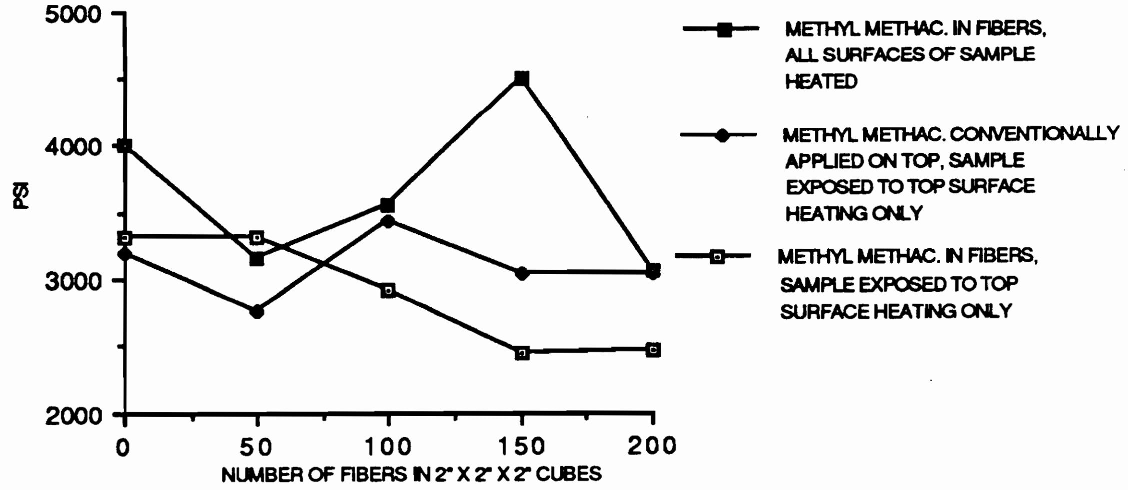


Figure 67. Shrinkage of dense silica fume cement using a water saturated, porous aggregate--haydite (expanded clay).

There was no deterioration. The simulation of infield stimuli were studied; that is, top heating for polymer impregnation was tested. The samples containing fibers and chemicals were placed in a thermal insulation material with only the top portion exposed (see photo 34) and then heated for 30 minutes. Comparisons were made (see photo 35). As seen in Figures 68, 69, and 70, the samples which were top heated had nearly as high bending and compressive strength and reduced permeability as the samples heated on all sides. The conclusion is that in the field, top heating can successfully release the chemicals.

The method of placement of fibers into the cement matrix needs to be studied. Also the effect of loading fiber volume in particular areas of a component needs to be tested.



<u>Figure 68</u>. Effect of top surface heating only of samples with methyl methacrylate on compressive strength as if done in the field (sample cured 7 days--heated to 212° F for 30 min).

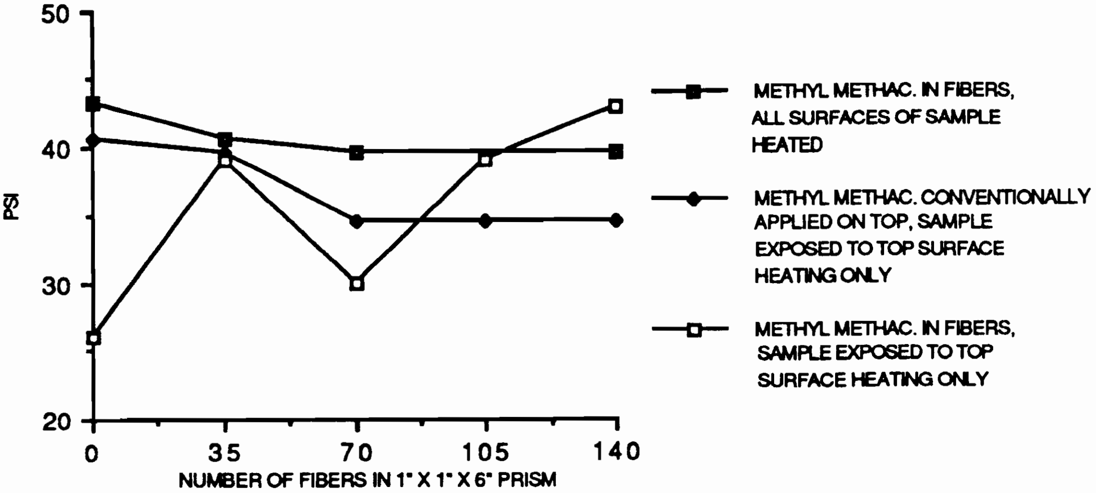


Figure 69. Effect of top surface heating only of samples with methyl methacrylate on bending strength as if done in the field (samples cured 7 days--heated to 212° F for 30 min).

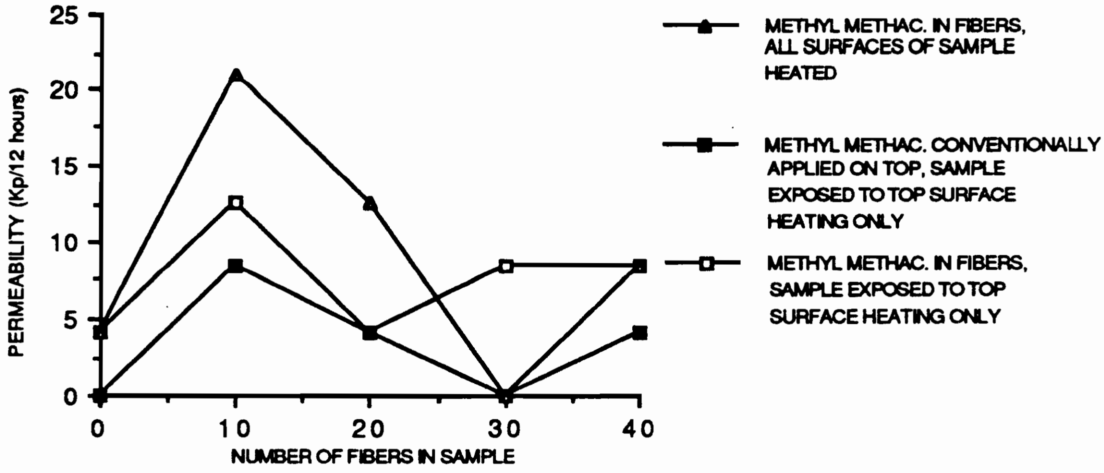


Figure 70. Effect of top surface heating only of samples on permeability strength--as if done in the field (samples cured 7 days, heated to 212° F for 30 min).

CHAPTER V

DESIGN AND COST IMPLICATIONS OF INTERNAL TIMED RELEASE FOR BUILDING COMPONENTS AND STRUCTURES

Questions to be Answered

The following questions need to be answered:

1. What would be the design implications of activated internal release in regard to the conventional designs for durability?
2. If durability is improved, how would costs for maintenance and repair be changed?
3. In a specific example, corrosion, what would be the design improvements and cost reductions by the use of internal timed release of chemicals?
    a. If a release is to be accomplished from a particular volume of fibers or aggregate located in one part of a component, what would be the cost and design implications of that?
    b. What would be the cost and design advantages in this example?
4. What would be the overall costs and design values of these design changes?
5. What new kinds of structural and/or component designs would benefit most from these internal release mechanisms?

6. What would be the specific impacts of these systems for internal release on (a) different building types, (b) for use in different environments, (c) different building details, (d) on repair regimes, and (e) on different structural systems?
7. Of what value would timed internal release be to the historic development of plastic expression in reinforced concrete?

I. Potential Impact of Activated Internal Release Materials on Conventional Treatments and Conventional Designs for Durability

Conventional designs treat durability of concrete as a property of the concrete to be embodied in the concrete from its first mix. However, new research sponsored by various institutes such as American Concrete Institute is investigating the problems introduced by some of those conventional designs.

1. The conventional design for permeability is to make the concrete more dense. The design of a system for activated internal release to reduce permeability described herein releases the crystallizing agent or the polymer impregnator after the matrix has been set up to fill in after the hydration has taken place.
2. The conventional design for loading cracking is the addition of fibers which interrupt the energy of cracking. The cement/fiber bond is weak, thus causing a reduction in compressive strength. The activated inter-

nal release of chemicals from fibers to reduce cracking described herein would increase the bond between fiber and matrix. The crack sealant would flow out of the fiber, bonding the fiber well to the matrix.

3. In high strength, silica fume concrete, the use of low water/cement ratio causes this material to self-desiccate, causing microcracking. This cracking due to self-desiccation of low water/cement ratio cements would be alleviated by the activated internal release of water from porous aggregates in the systems designed herein if they had worked as postulated.
4. Freeze/thaw damage is prevented by the use of air entraining additives in the initial mix. This can weaken the compressive strength due to the inclusion of small air bubbles. The activated internal release of anti-freeze agents or linseed oil from porous aggregates described herein eliminates the problems associated with air entraining agents.
4. Conventional designs to reduce corrosion damage involve increased concrete cover and coating steel reinforcing bars. The increased cover depth increases weight of specimens and cost. The use of coatings on steel reinforcing bars reduces the bond between matrix and bar. Internal release of calcium nitrite to protect the steel reinforcing bars against corrosion as described herein would reduce the depth of concrete cover required to prevent ion intrusion. It also would eliminate

the need for coating the reinforcing bar, thus increasing the bond between steel and concrete.

II. Potential Impact of Activated Internal Release Materials on Maintenance and Repair Issues and Costs

Bekker (1980) describes a durable asset such as a building as having a total amount of installed material used for a period of years (Q) which equals the initially installed material (C) divided by the years of life (X) taken over the life of the asset $\int$ where X_2 is extended life and X_1 is critical life. As soon as critical life is approached, one must either demolish

$$Q=\frac{C}{X}\int_{X_1}^{X_2}$$

and lose Q or upgrade to get to X_2. This takes added material investment (Bekker, 1980, pp. 56-57). The issue in conventional construction is then: will the building deteriorate to such an unacceptable level within the service life that we are left with the choice of demolition or upgrade and repair?

The major cost implication of internal timed release designs is that a large amount of life cycle costs could be reduced and any extra cost of adding internal timed release will be part of the design cost.

In summary, with these designs herein, the time until upgrade or failure and the general service life function of the asset would be extended or increased. The total life cycle costs would be reduced (see Figure 71).

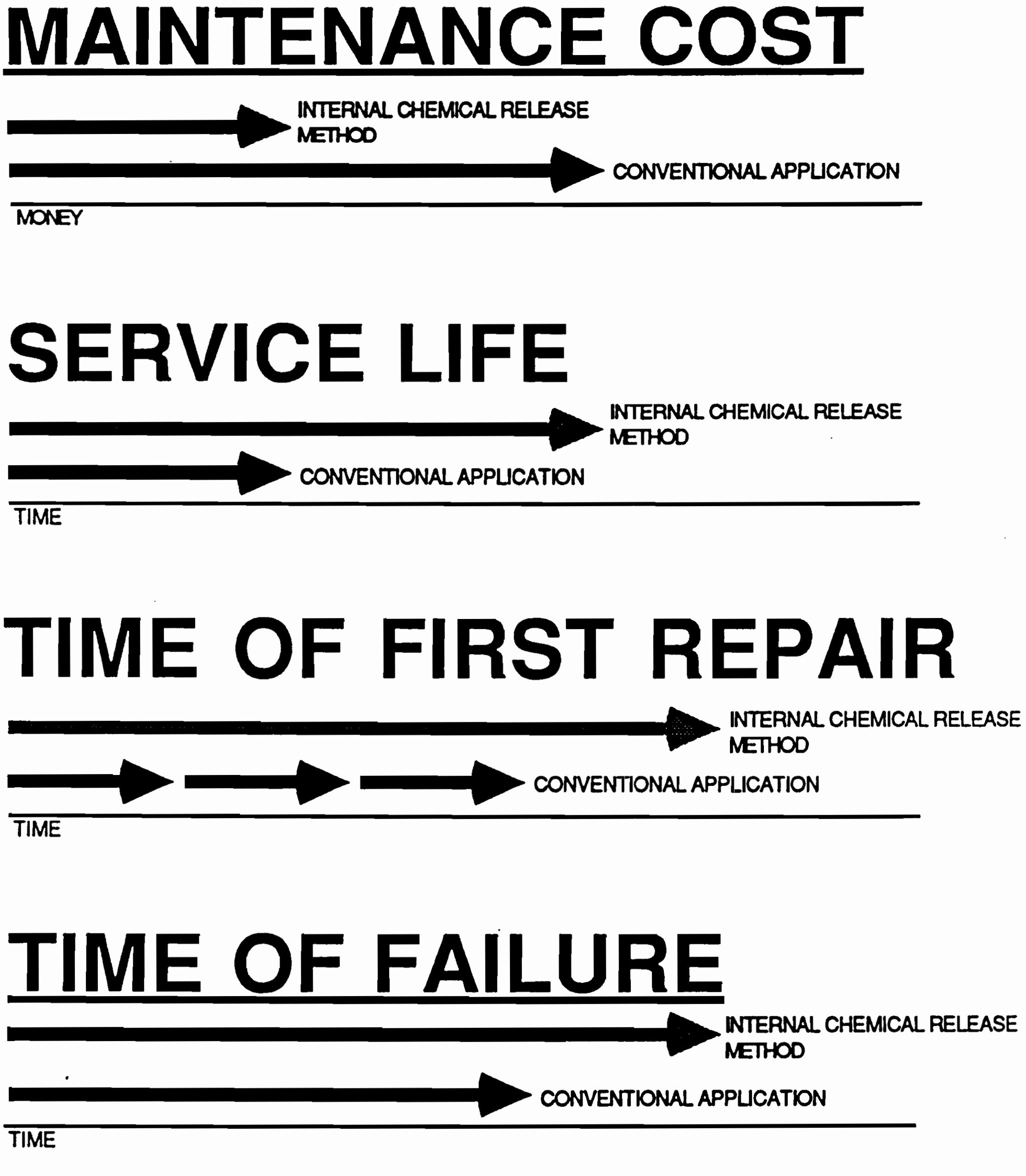


Figure 71. The advantages in reduced costs and increased life expectancy of internal time release designs.

In terms of the equation $Q=\frac{C}{X}\int_{X_1}^{X_2}$, the total amount of installed material used for a period of years will be increased in value because the period of years of life will be increased (Bekker, 1980, p. 57). This is because the years of life, X_1 will be prolonged by obtaining the extended life (X_2) without an upgrade for a longer period of time or by delaying the approach of critical life X_1 (Bekker, 1980, p. 57).

In conventional concrete, the attack by the environment has two stages: the time required to penetrate and the time for deterioration. The life of the asset function, in durability terms, is the resistance to deterioration of the particular material under a number of ingressive environmental conditions (Cabrera, 1986, p. 29).

In the designs herein, the time to first repair would be extended, and therefore the per annum costs reduced. In these designs for internal chemical release, the repair time begins with environmental penetration; that is the time when deterioration normally begins as seen in Figure 72. (In the case of stimulation by human intervention, the repairs begin when the stimulus is given, which is before environmental penetration and deterioration occurs.)

III. Corrosion as an Example of Environmentally Caused Distress in Which Design Could be Improved and Cost Reduced Through Use of Internal Timed Release Chemicals

"Corrosion is an expansive reaction that causes cracking and damages concrete. It is an electrochemical process that requires the flow of electrical

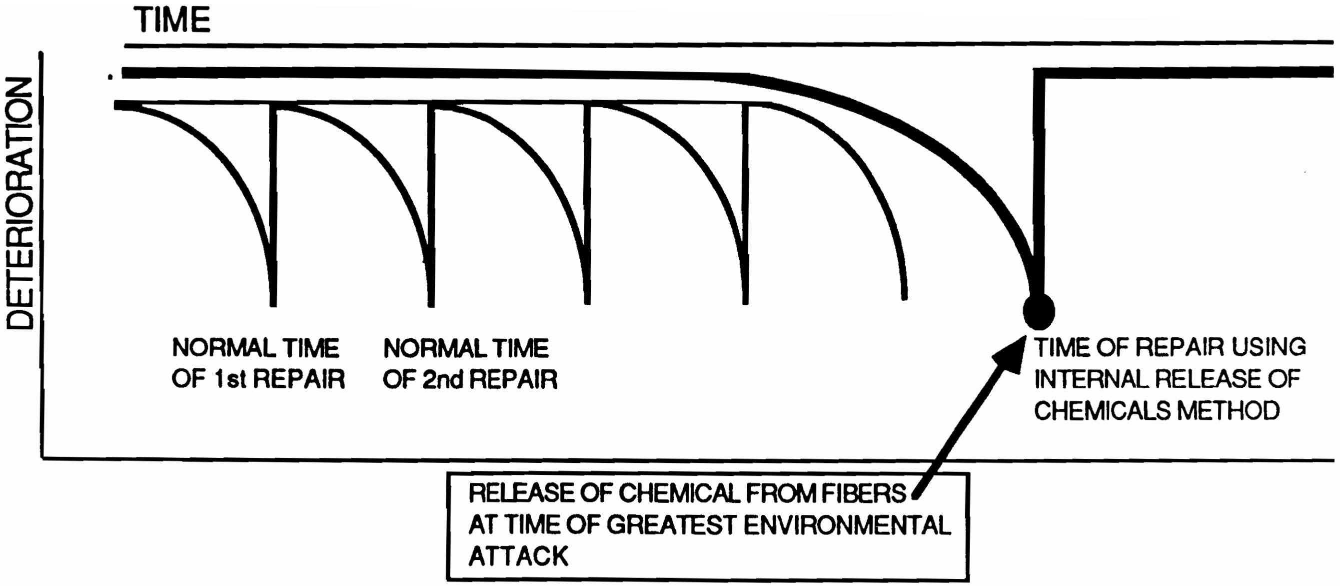


Figure 72. Repair time, in time release designs, begins with environmental stimulation; that is the same time at which deterioration occurs in conventional concrete.

current in the presence of oxygen and moisture" (Mindess and Young, 1981, p. 557). The high alkalinity conditions in concrete usually cause an outside seal to form on the surface of iron bars, preventing corrosion; however, when the Ph is reduced to 11 or below due to carbonation or the entry of chloride ions, such as from de-icing salts, this oxide layer rusts (Mindess and Young, 1981, p. 558).

Figure 73 shows that the time it takes for the environment to penetrate the steel is easier to predict than T_1, the time for the corrosion to cause damage. For design purposes:

> The time for penetration to achieve the critical chloride or carbonation level at the rebars is preferred and provides a margin of safety. . . . Carbonation and chloride penetration can be obtained by assuming a simple diffusion law: $x = k^2t$ where x - the distance penetrated after time (t). This means that doubling the cover quadruples the design life, say 15-16 years. Carbonation is unlikely to permeate more than 25mm, and therefore has a self-limiting effect but chlorides eventually penetrate the concrete completely. (Browne, 1986, p. 110).

The relative time for penetration of carbonation and chlorides is shown in Figure 74. The amount of steel at risk versus depth can be seen in Figure 75.

Normal depth of concrete cover to steel is shown in Table 11. One effect of the system proposed is that the cover depth of concrete could be reduced because the protection is at the rebars exactly where corrosion occurs.

Another aspect of the penetration process is that there is variation in the penetration front around the structure (Browne, 1986, p. 117). Vulnerable areas are drainage joints, edge beams, corners, window mullions, etc. (see Figure 76).

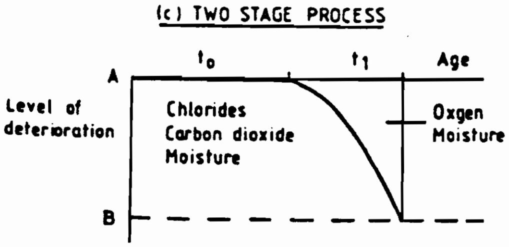


Figure 73. The corrosion mechanism (Browne, 1986, p. 105).

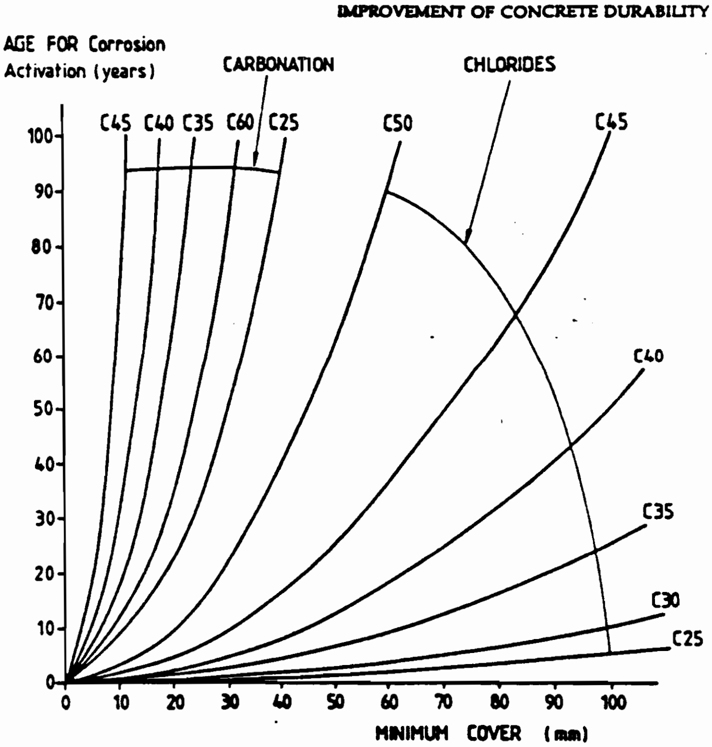


Figure 74. Suggested basis for a design chart for durability (Browne, 1986, p. 119).

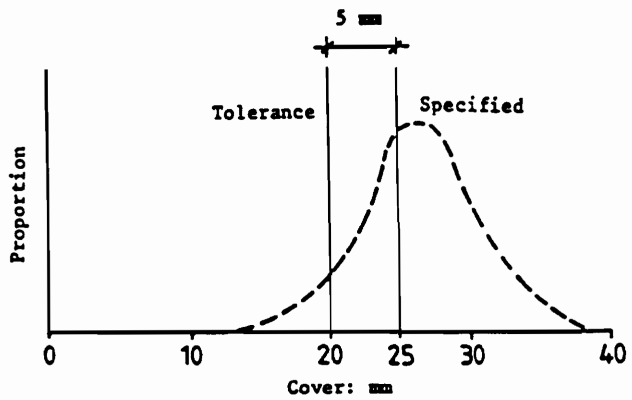


Figure 75. Amount of steel at risk versus depth (Browne, 1986, p. 120).

Estimated Cost Implications of Internal Time Release of Calcium Nitrite

The cost implications for conventional treatments for corrosion are, according to Pfeiffer, Langren and Zube (1987):

1. Service penetrating sealers and coatings which minimize chloride ion ingress are successful at a rate of 75 to 95 percent and can be applied for a 35-75 cents per square foot, including labor, materials, and preparation costs.
2. Corrosion inhibiting add mixtures such as calcium nitrite increase the cost of the base delivered concrete by 50%.
3. Low permeability concrete costs from 15-30% more than normal permeability concrete. The epoxy-coated reinforcing bars cost 30-100% more than gray bars. (p. 2)

Table 11

Specification for Durability--Reinforced Concrete

Exposure condition	Mix			Cover*: mm
	Minimum strength: N/mm^2	Minimum cement content: kg/m^3	W/C ratio (maximum)	
Mild (internal)	35	300	0.60	20
Moderate (sheltered)	35	300	0.60	35
Severe (driving rain)	40	325	0.55	40
Very severe (seawater spray or deicing salts)	40	325	0.55	50
Extreme (marine structures)	45	350	0.50	60

* Permitted tolerance = 5 mm

Note. From Browne, 1986, p. 117.

The cost of internal timed release of calcium nitrite from fibers is estimated by Neil Berke (personal communication, June 1990) in the following way: The cost of the corrosion inhibiting calcium nitrite would be reduced greatly. Rather than being 50% increase in the cost of base delivered concrete, we estimate the percent of that amount which would be an increase of 5%. However, the additional cost of the fiber encapsulation process would increase that cost. The estimated cost for fiber encapsulation, including the capital equipment for production, 1/10 based on an amortized rate. Other cost advantages are the reduced

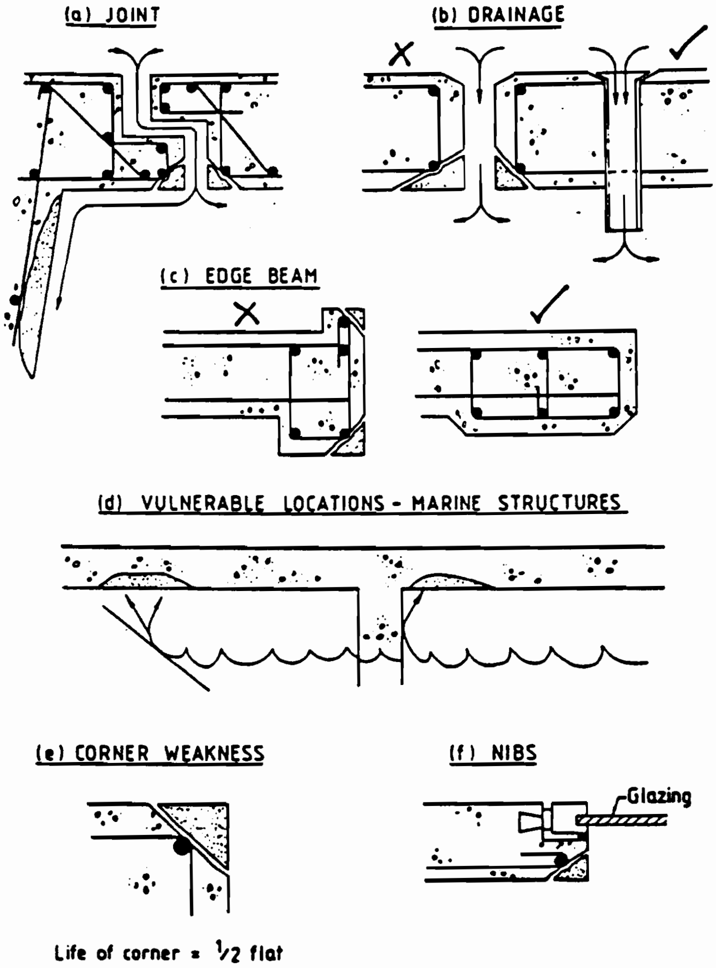


Figure 76. Common defects (Browne, 1986, p. 121).

delay in set time. The normal application time of calcium nitrite is 2 to 3 hours. Therefore, the savings would be 3 hours for 2 or 3 men, so 6 man hours per pour (Berke, personal communication, June 1990). The reduction of concrete cover could get down to as low as 1 1/2" (1 1/2" is the minimum because maximum aggregate size is 3/4" and the American Concrete Institute recommends that there be an equal amount of cover beyond the aggregate size to get mortar to bond with the aggregate). The savings and reduction in reduced concrete cover would add another savings (Berke, personal communication, June 1990).

Vulnerable areas are drainage joints, edge beams, corners, window mullions. These areas could be protected in the designs using internal timed release because the protection does not rely on the form or the cover but on the actual protection of the rebars themselves.

Estimated Cost and Design Advantages of Internal Time Release of Calcium Nitrite

Calcium nitrite, when mixed freely with the concrete, retards the set and is expensive. The advantages of the addition of calcium nitrite, released over time just at the reinforcing bars, would be: (a) reduction in the amount of calcium nitrite used, (b) no reduction in set time due to encapsulation of the calcium nitrite, (c) reduction in the concrete cover of the member because chloride penetration through a distance of concrete is not a factor, and (d) protection of joint areas.

Release of Chemical Into Only One Part of a Component

Not all areas of a component are equal in vulnerability to the environment. A hypothetical comparison of strength and w/c ratio as supplied for the construction in durability is remarkable as seen in Figure 77. One can see that the area needing strength is the area that is the weakest.

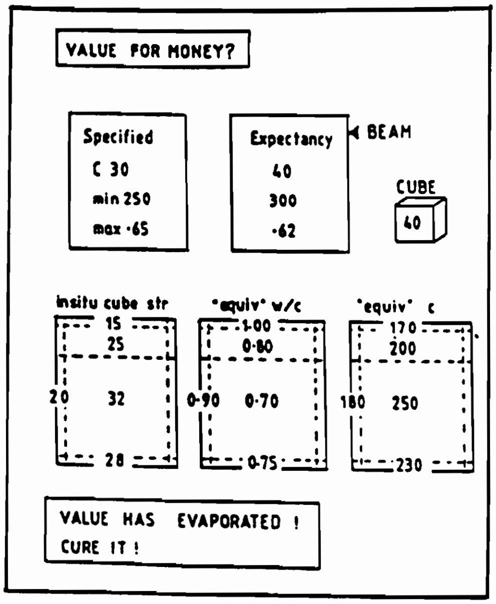


Figure 77. Expectation compared with reality in the structure--a hypothetical comparison of strengths and equivalent values for W/C and cement content in comparison with the values in the concrete supplied to the construction (Browne, 1986, p. 125).

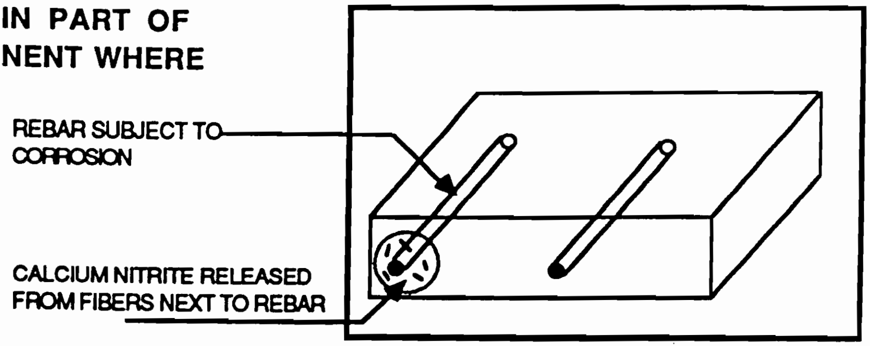
Success in treatment for a particular distress would depend upon the volume of the matrix saturated. Evaluations were made concerning the amount of chemical released into the volume of the matrix and percent of the matrix saturated: 2.75 volume fibers give a 10% to 40% wetting of the specimen surface, depending upon temperature of heating or if microwaved. The goal is not 100%

saturation of the specimen. In the case of corrosion inhibition at the reinforcing bars by the release of calcium nitrite from hollow porous polypropylene fibers coated with wax, one can postulate the fibers need only saturate the cement matrix in contact with the reinforcing bars. Experimentation has not been done for this.

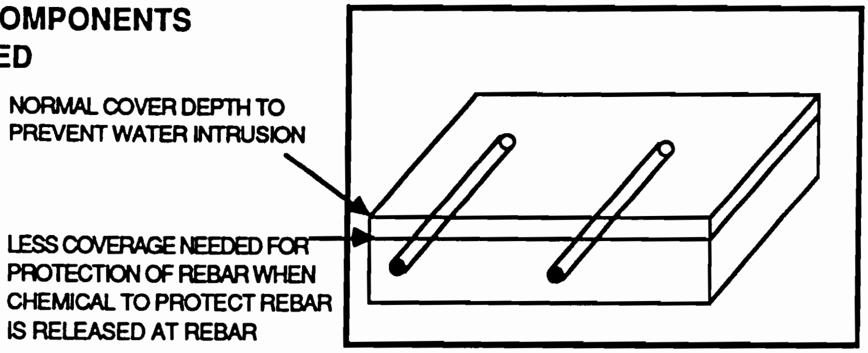
IV. What Would be the Main Cost and Design Advantages in Using Internal Timed Release of Chemicals?

1. The ability to include major maintenance repair issues in the initial design phase of the building.
2. Repair could be accomplished if chemically loaded fibers are placed near the reinforcing bars, for example; repair could thus be accomplished where needed only (see Figure 78a).
   - 2a. Reduction in the material required for durability and maintenance treatments would be likely because of the specific locatability of these chemicals.
3. The size of some components could be reduced and vulnerable areas such as joints would be better protected. The reason the size of components and joints could be designed with less cover and less concern over their durability is that the protection is of the rebar itself and does not rely on the cover depth as the protection against ingress of water (see Figure 78b).

A) REPAIR IS IN PART OF THE COMPONENT WHERE NEEDED



B) SMALLER COMPONENTS CAN BE USED



C) COMPONENTS AND STRUCTURE CAN WITHSTAND GREATER ENVIRONMENTAL ABUSE

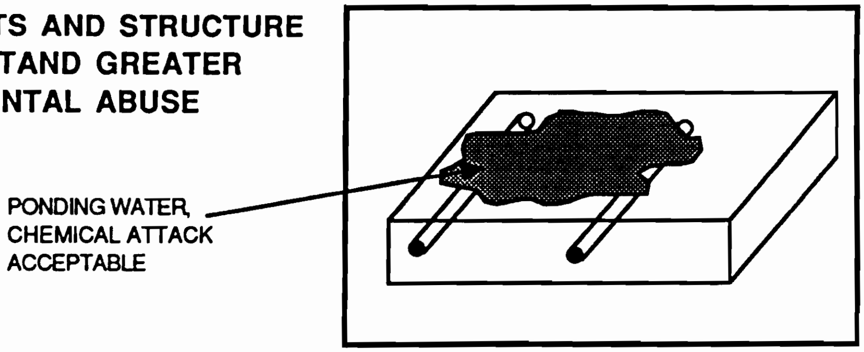


Figure 78. Some major cost and design advantages of using internal timed release of chemicals.

4. Vulnerable areas as joints would be more protected against corrosion.
5. The components and structure could take greater environmental abuse such as loading, water ponding, chemical attack, etc. (see Figure 78c)

All the stages of the deterioration process are affected (see Figures 79-82).

V. What New Kinds of Structural and/or Component Designs Would Benefit Most From These Internal Release Mechanisms?

1. Structures and components that could utilize this internal timed release mechanism the most would be those using many fibers, indeed fabrics, to reinforce (i.e., cement) matrix which is very thin and cannot have much cover. Such a system is structural sandwich panels made of non-woven fabric-reinforced cement laminates in rectangular and triangular folded core configurations. This design optimizes the sandwich panel geometric variables for minimum total material cost. They are superior in stiffness/weight ratios as compared with the widely used precast prestressed concrete floor panels (see Figure 83) (Nicholls, 1988, pp. 28).

   Brittle matrices, reinforced with ductile fabrics and polypropylene, is a commonly used economic fabric in this example (Nicholls, 1988, pp. 28-36). Potential applications for these fabric-reinforced cements are

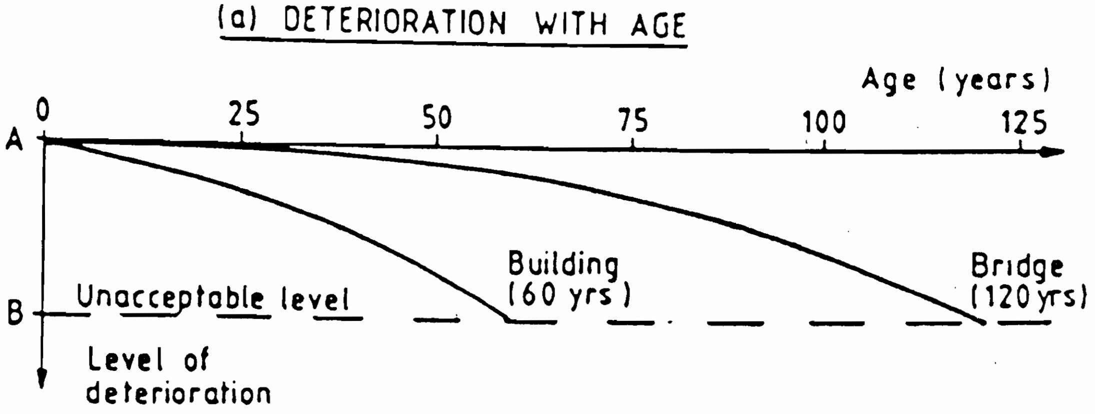


Figure 79. The deterioration with age is delayed (Brown, 1986, p. 103).

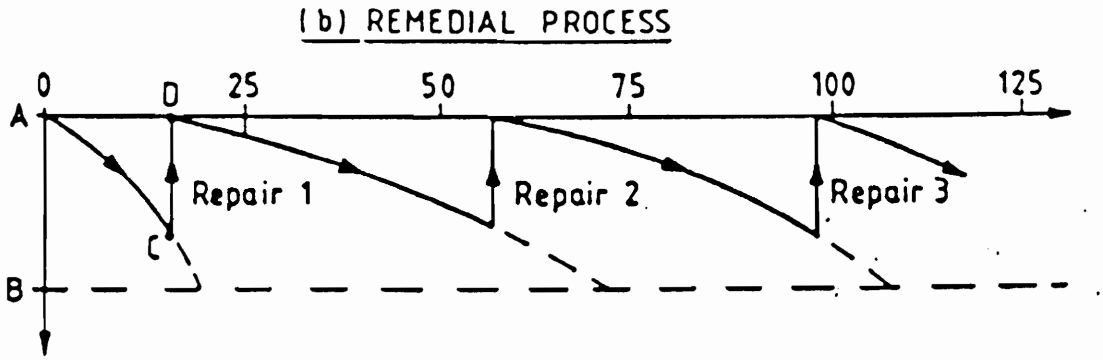


Figure 80. The remedial process occurs automatically as required (Brown, 1986, p. 103).

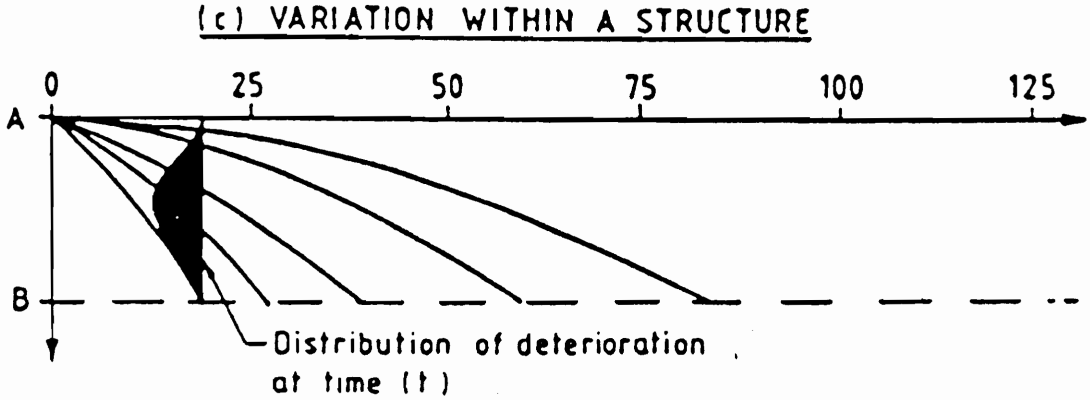


Figure 81. The variation of deterioration within a structure is reduced because the remedy is placed right where the deterioration occurs (Brown, 1986, p. 103).

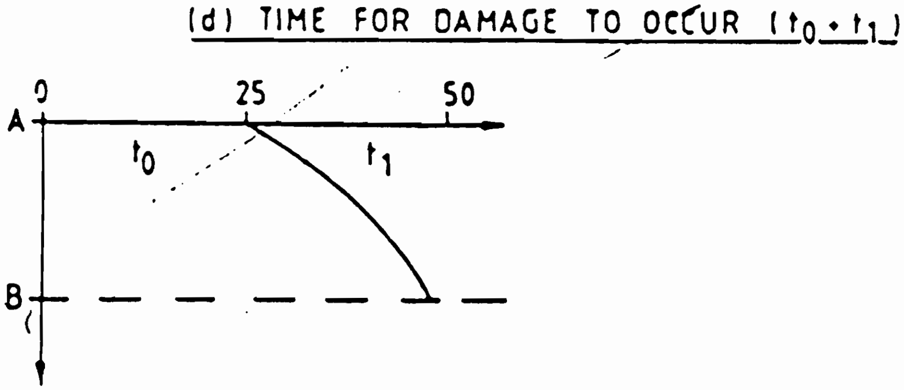
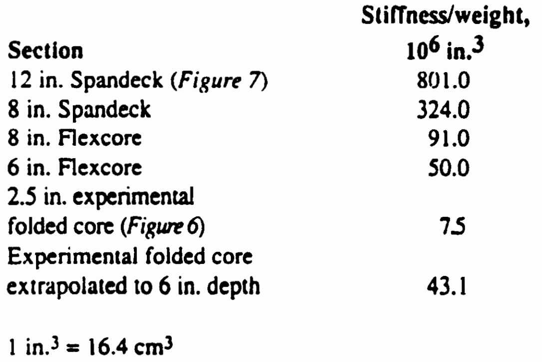


Figure 82. The time for the damage to occur is greatly prolonged because of the remedial process (Brown, 1986, p. 103).



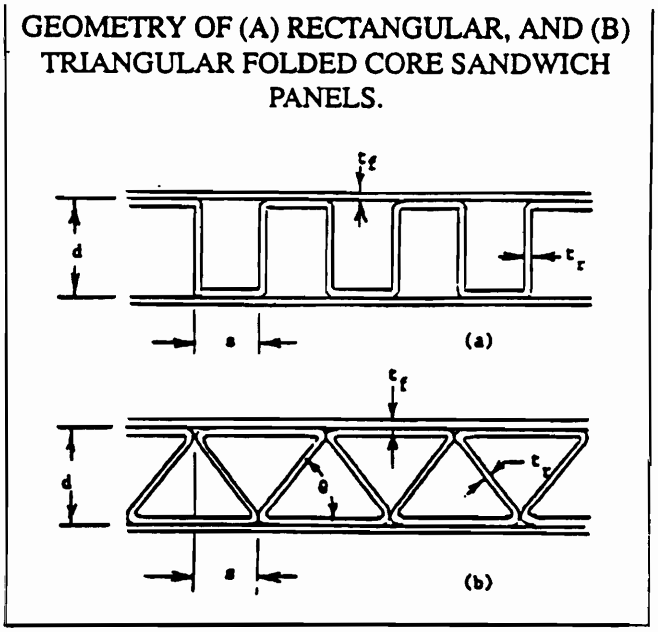
Section	**Stiffness/weight, 10^6 in.^{3}**
12 in. Spandeck (*Figure 7*)	801.0
8 in. Spandeck	324.0
8 in. Flexcore	91.0
6 in. Flexcore	50.0
2.5 in. experimental folded core (*Figure 6*)	7.5
Experimental folded core extrapolated to 6 in. depth	43.1

1 in.^{3} = 16.4 cm^3

Figure 83. Stiffness/dead weight ratios (Nicholls, 1988, p. 33).

shingles, which are lightweight, nailable, and inexpensive; folded core low bearing structural sandwich panels, made similar to corrugated board products; inflated fabric-reinforced concrete shells; foam liners for lightweight precast concrete floors, walls, and roofs; corrugated siding and roofing (Nicholls, 1988). Because of the inclusion of fabrics, these products can be nailed, cut with tin snips, and flexed by hand with little damage; for shingles, polypropylene fabrics were used because of impact resistance and nailability; for shells and precast concrete facings and folded shapes, polypropylene was used at the hinges, and mineral fabric facings were used for stiffness against buckling of the laminate (see Figure 84) (Nicholls, 1988, pp. 28, 29).

Wall and roof panels made from fabric-reinforced cement laminates made into folded core panels are lightweight and thus can reduce the cost of supporting structures. Fabric-reinforced thin sections could replace steel and eliminate the problem of corrosion. The ability to optimize the design to maximize the stiffness/material cost ratio in fabric-reinforced cement folded core sandwich panels for bending is useful and the ability to allow the designer to create folded structures to meet a variety of loading conditions makes this a useful system (Nicholls, 1988, pp. 28-29).



GEOMETRY OF (A) RECTANGULAR, AND (B) TRIANGULAR FOLDED CORE SANDWICH PANELS.

Figure 84. Geometry of rectangular and triangular folded core sandwich panels using fiber-reinforced cement laminates (Nicholls, 1988, pp. 28-29).

2. In any one component, redundant failsafe measures to improve durability and prevent corrosion and freeze/thaw damage are common place. These internal timed release of chemicals could be combined with the other measures such as sealants, coatings, coated rebars, low tensile of post tensioning to revert cracking, freely mixed calcium nitrite, etc. Structural component details for a parking garage in Minneapolis contained all the above measures (see Figure 85) (Robert Walker, personal communication, November 1990).

The impact of design of the systems for timed internal release of chemicals or combinations of them can be postulated on different building types for use in different environments, different building details, on repair regimens, on different structural systems, and on various structural or construction systems.

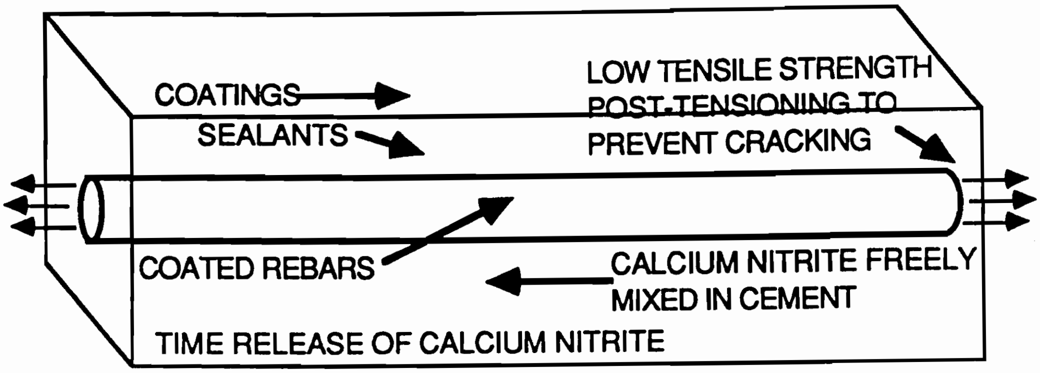


Figure 85. Redundant treatments for durability of steel reinforced concrete members.

VIa, b. Use of These Designs for:

Different Building Types and in Different Environments

1. Parking structures are the extreme case of the impact of the envrionment influencing design on a particular building type. The Pre-Cast Concrete Institute, in its publication on recommended practice on design and construction of parking structures, recommend the following measures for protection against de-icing salt and ocean atmosphere:

1. Use air entraining concrete.
2. Use adequate drainage slope; 2% is desired.
3. Use galvanized or epoxy coated exposed bearing plates and flange connections.
4. Use concrete cover of at least 1-1/2 inches in pre-cast and 2 inches in cast and placed components.
5. Use a design which will not crack in flexure at surface loadings.
6. Install sealants at construction and control joints.
7. Provide surface sealers and periodically replace them.
8. Immediately repair cracks and periodically replace sealants (Pre-Cast Concrete Institute, 1988, pp. 32-33).

The systems designed for time-delayed internal release of chemicals could reduce the importance of draining water away, not require air entraining, would reduce the depths of the cover needed for corrosion control, reduce the presence of cracks, and repair them internally when they occur, and finally, have a constant release of sealants from the interior, such that periodic surface sealing and control joint sealing would occur automatically without physical intervention or upgrade, exposed metal plates and flanges would, however, need to be epoxy coated or galvanized.

Concrete in these harsh environments will benefit most from time-delayed internal release of chemicals to protect against water and chemical intrusion because they are the most damaged by temperature fluctuations, and water intrusion. Buildings in cold, wet environments will benefit greatly because of the extreme impact of extreme temperature fluctuations which cause freeze/thaw damage and the effect of de-icing chemicals.

2. Concrete in hot, wet climates is also at risk because it expands and contracts with temperature variations. "In a hot climate, if a concrete structure which is free to change shape and volume, is not restrained, then stresses and resultant cracking due to tension will result" (Johnson, 1965, p. 64). "Common occurrences are the shrinkage of slabs on grade and shortening of foundation walls in which moisture and thermal gradients from the outside vary drastically to the inside, thus causing cracking (see Figure 86). The usual solutions are to provide expansion joints and reinforcement" (Johnson, 1965, p. 66). Inclusion of fibers which relieve cracking stresses and time-released chemicals to fill any cracks can substitute for these more conventional methods. Fibers containing anti-freeze and phase-change

materials would be a special benefit to reduce thermal shocks, both due to heating and cooling. Water absorbtion alone causes significant swelling of concrete as much as 4% along the California coast in one example (Johnson, 1965, p. 68). It is practical to prevent swelling and cracking by the internal release of sealants which will reduce the water absorbtion. This is important especially where rebars are present. An anti-corrosion agent release would also be of use.

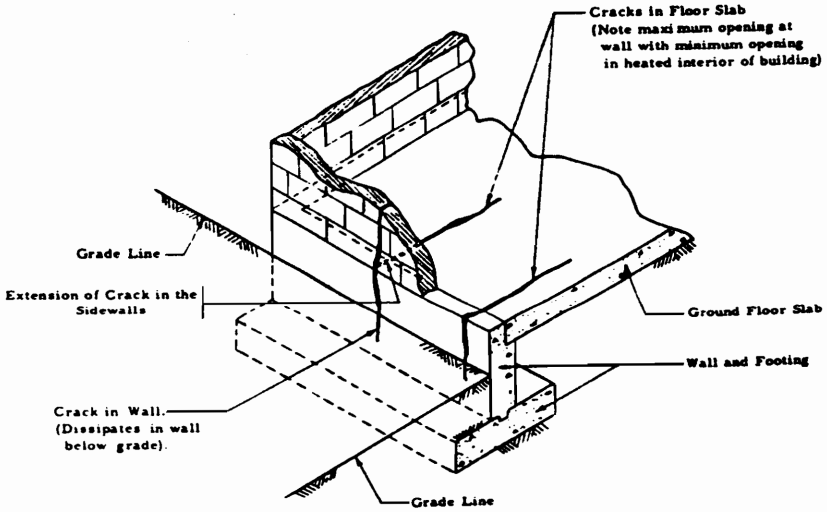


Figure 86. Temperature cracking in a building (Johnson, 1965, p. 66).

Different Building Details

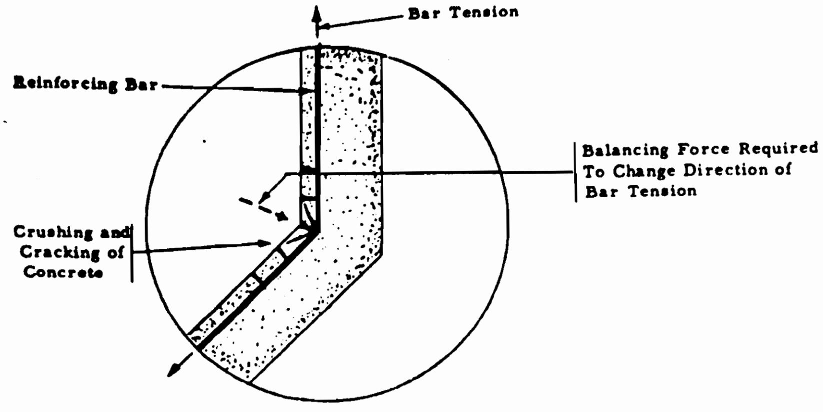
In various different environments, deterioration occurs repeatedly in certain details. Some of the damage caused by these could be prevented by internal release to seal the concrete, prevent freeze/thaw damage, and prevent corrosion. Some details causing deterioration problems, which could be addressed by time internal release, follow (see Figures 87a, b, c, through 91).

Some "unanticipated shear stresses in piers, columns or abutments and expansion bearing assemblies tend to become immobilized with time due to corrosion, dirt, grit. Longitudinal thrust, then, instead of being resisted by the fixed bearing only becomes resisted by the supports and shear is imposed. Diagonal tension cracking occurs. The normal means for preventing this is stirrups" (Johnson, 1965, pp. 91-93) (see Figure 92).

Incompatibility of Materials or Sections:

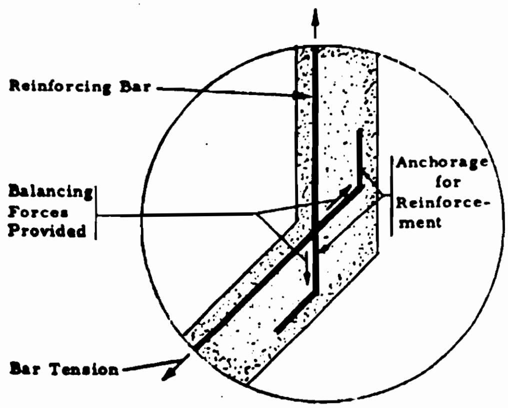
A. "Massive concrete sections abutted by and tied to thin sections do not work together, and unless adequately reinforced, cracking occurs" (Johnson, 1965, p. 93) (see Figure 93). "The condition can be actually aggravated by heavy reinforcement in the flanges so this tends to reduce shrinking to deformation" (Johnson, 1965, p. 93) as seen in Figure 94. Release of crack filler reduction of component size would help here.

(a)



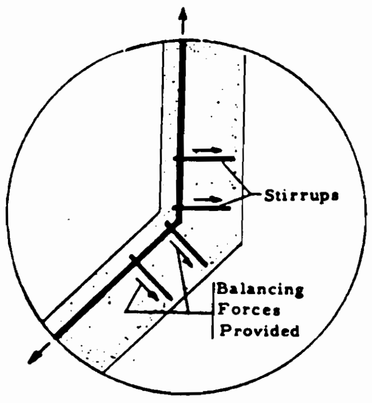
Poor Detail

(b)



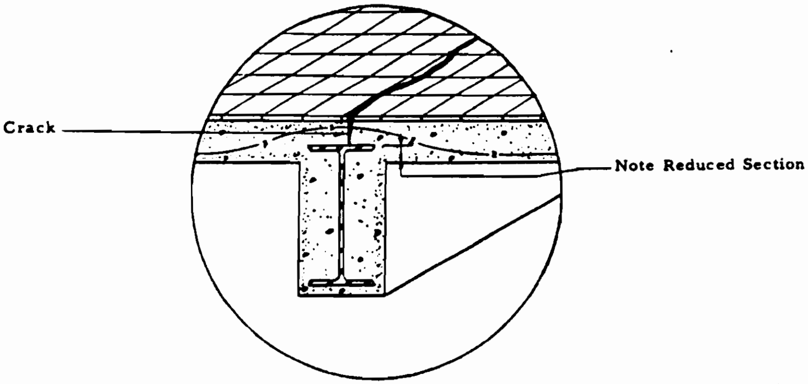
Better Detail

(c)



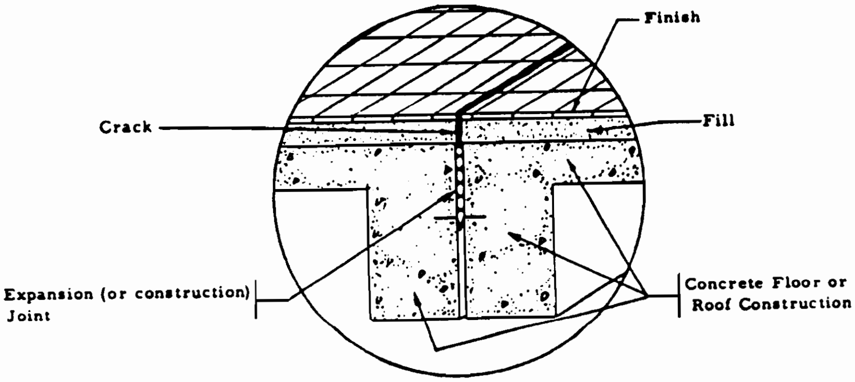
Alternate

Figure 87. These are re-entrant corners in which stresses are concentrated under reinforcing bars. (Johnson, 1965, p. 87)



Encased Steel Framing

(a)

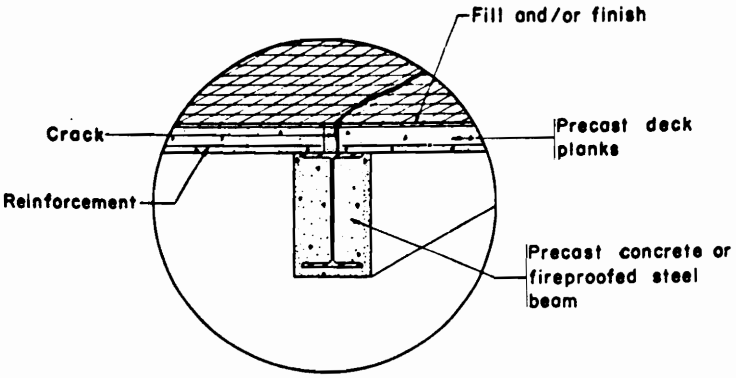


Expansion Joint Not Projected Through Floor Fill and Finish

(b)

Figure 88. Abrupt changes in section which cause stress concentrations. (Johnson, 1965, p. 88)

(a) Cracking due to deflections
of pre-cast slab unit.



(b) Cracking due to
deflection.

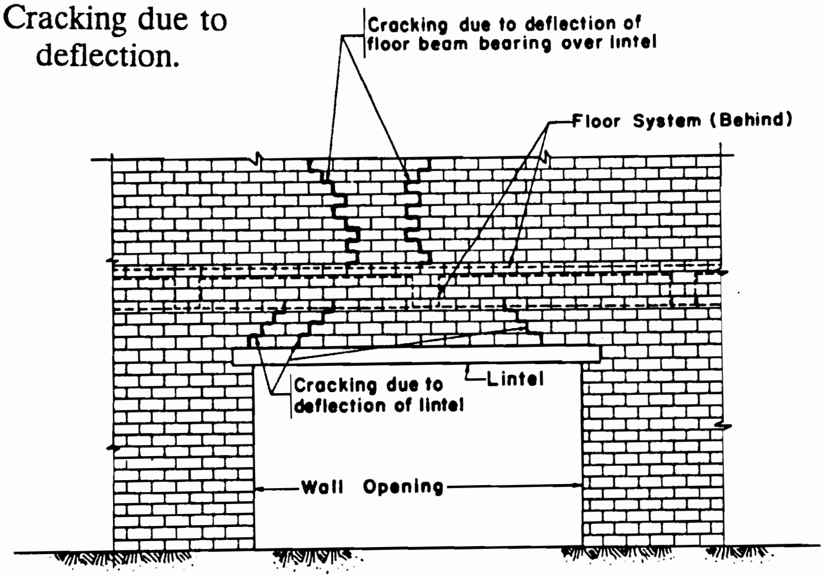
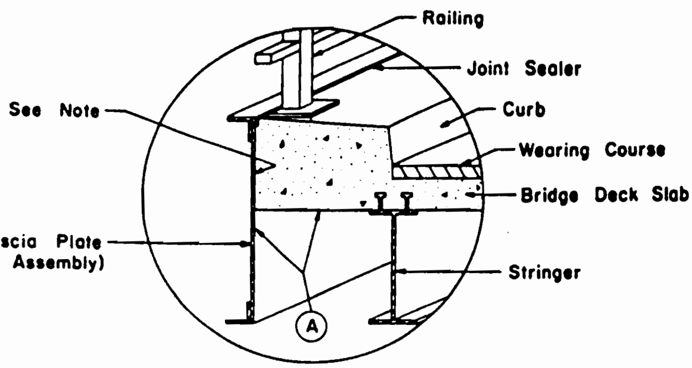
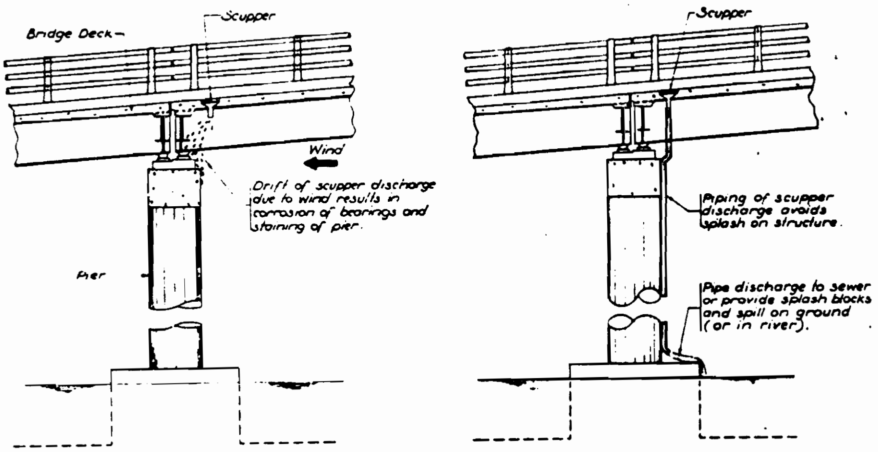


Figure 89. Deflections. "The structure can accommodate movement but a lot of deformation is absorbed by the wall or partitions. The usual solution is to make the structures stiffer and make the partitions stronger" (Johnson, 1965, p. 89).



Note: Unless the joint sealer is carefully installed, water percolation should be expected to occur along the interface between concrete and steel, causing corrosion of fascia plate at A and of any anchors securing fascia plate to concrete section.

Figure 90. Leakage through joints. "Where joints are necessary, they must be sealed and water stops provided" (Johnson, 1965, pp. 90-91).



a) Poor Practice

b) Better Practice

Figure 91. Poorly detailed drips and scuppers. "These should be provided with downspouts located so that the discharge cannot be blown against the lower construction" (Johnson, 1965, pp. 90-92).

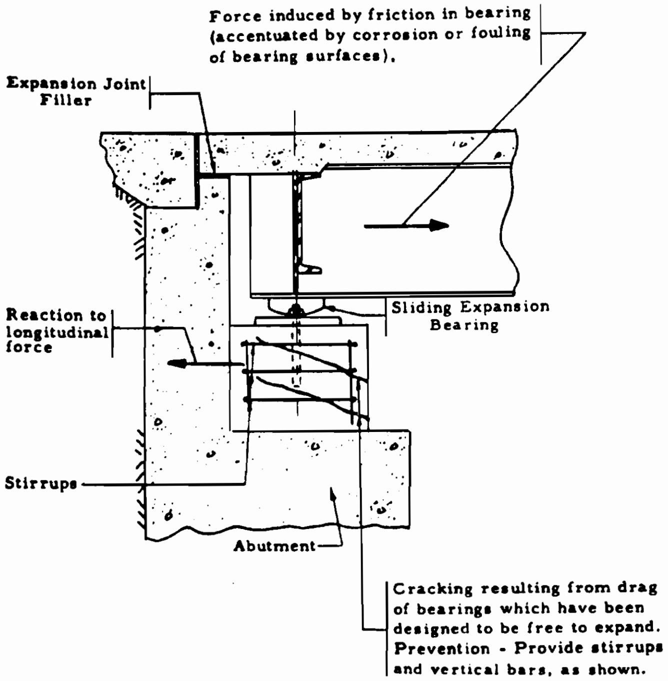
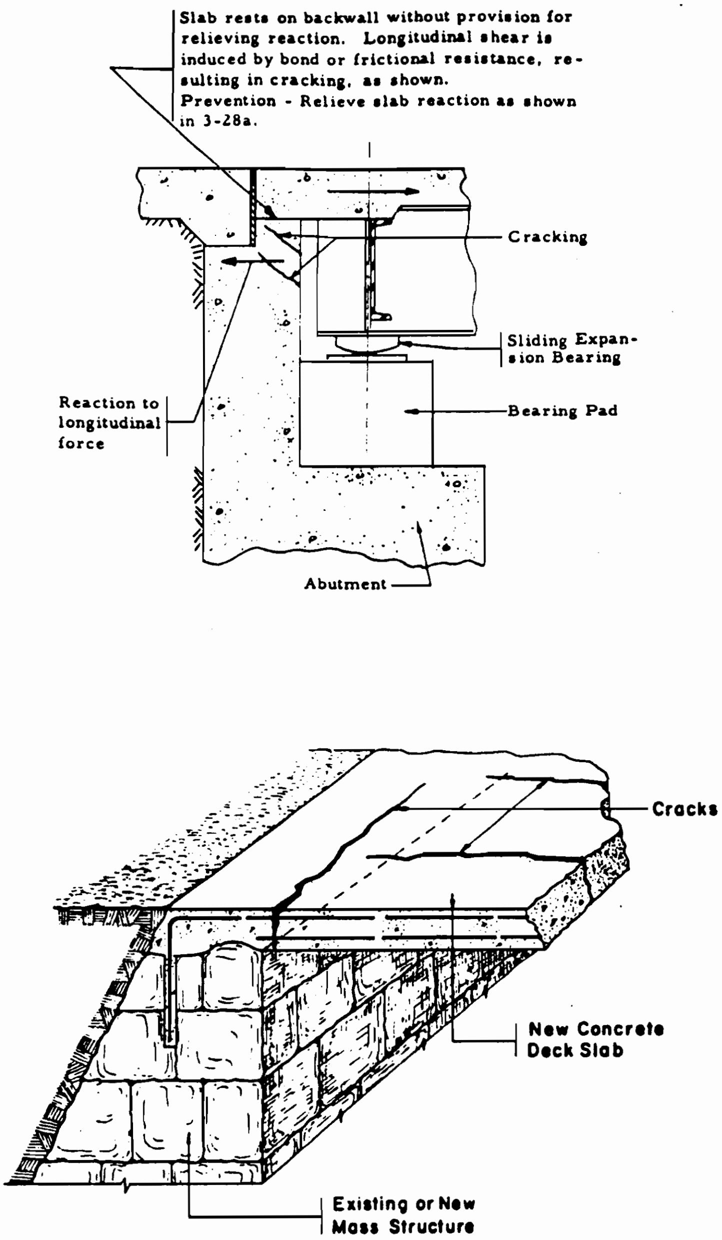


Figure 92. Cracking of beam seat (Johnson, 1965, p. 93).

B. Material incompatibility. "In concrete there is one particular incompatibility of materials that is very important and that is the lamination of the masses as a result of excessive vibration or wet mixes. Cold joints produce similar effects" (Johnson, 1965, p. 95). Release of internal adhesives at the cold joints would be helpful.



Slab rests on backwall without provision for relieving reaction. Longitudinal shear is induced by bond or frictional resistance, resulting in cracking, as shown.
Prevention - Relieve slab reaction as shown in 3-28a.

Figure 93. Cracking due to an abrupt change in section of a concrete structure. (Johnson, 1965, p. 94).

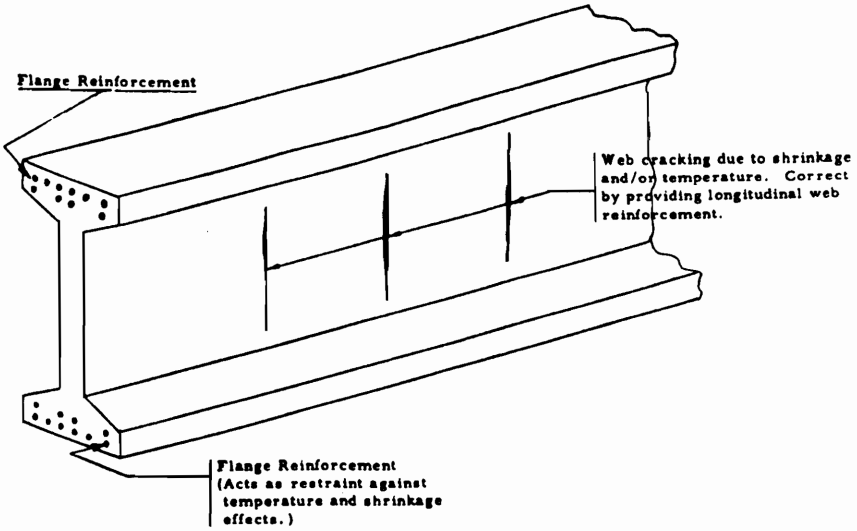


Figure 94. Web cracking in flanged concrete girder. (Johnson, 1965, p. 95).

Restructuring of Repair Regimes

Repair regimes are especially important in concrete structures because concrete is so porous and subject to environmental degradation.

A repair regimen is usually selected based on the anticipated movement, severity, and activity of cracking:

Methods of repair are:

1. Epoxy bonding is used for dormant cracks.
2. Routing and sealing involves enlarging the crack and then sealing it with a suitable material.
3. Stitching with material like sewing cloth is used to restore tensile strength [see Figure 95].
4. Overlays are used over a large number of cracks. They must be extensible. Roofing felt membrane can be used.

5. Grouting can be performed by injecting epoxy.

6. External stressing can close cracks and add tensile strength [see Figure 96].

7. Jacketing of prestressed concrete forms holds these forms together against deterioration [see Figure 97]. (Johnson, 1965, pp. 122-167)

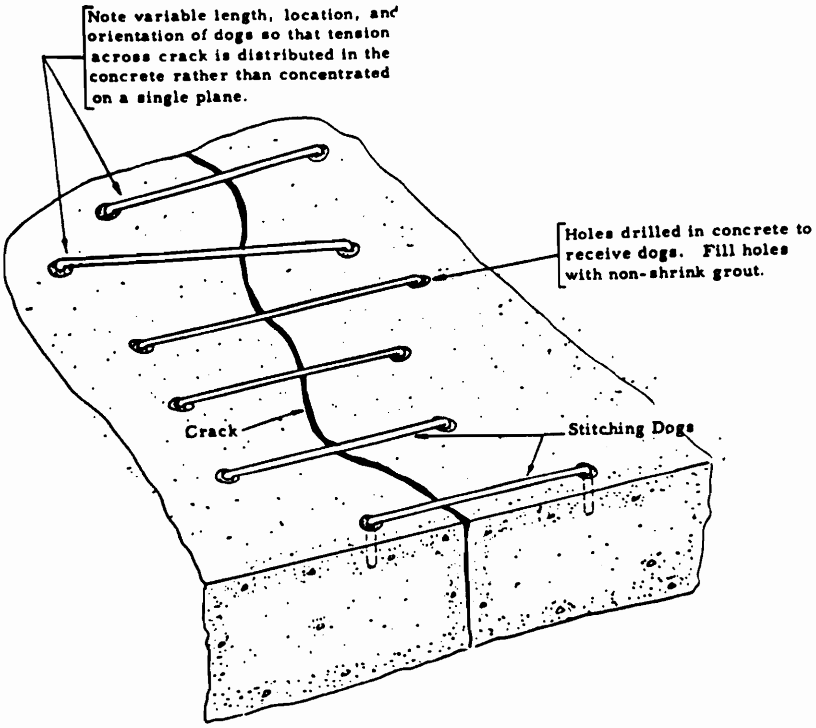
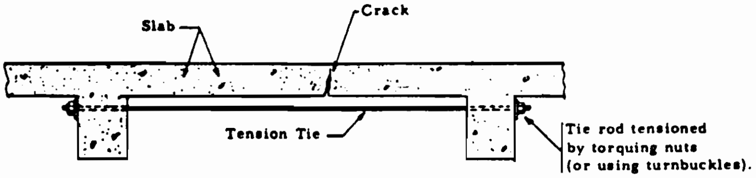
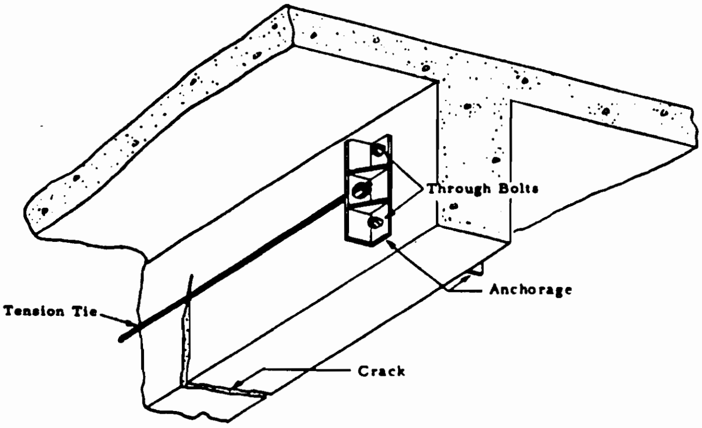


Figure 95. Repair of crack by stitching. (Johnson, 1965, p. 127)

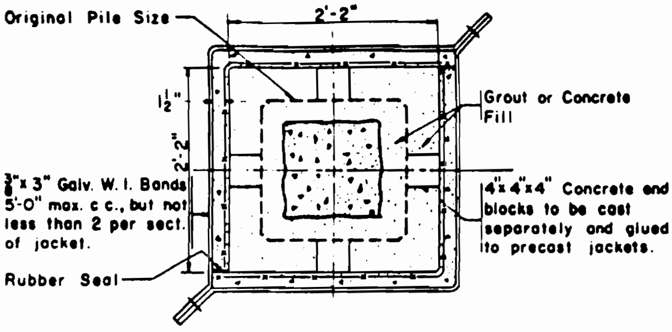


a) To Correct Cracking of Slab

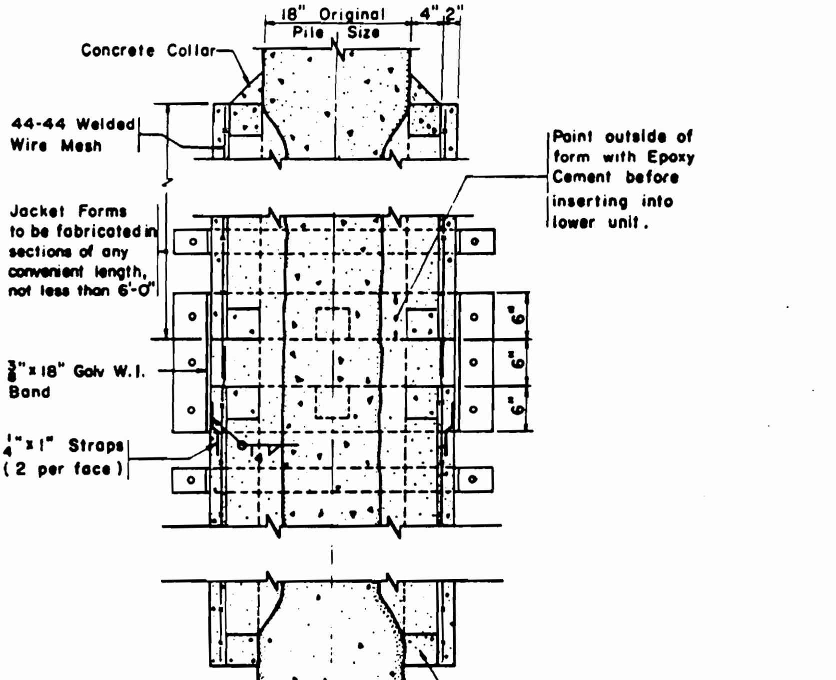


b) To Correct Cracking of Beam

Figure 96. Examples of external stressing to correct cracking of beam or slab. (Johnson, 1965, p. 129).



Horizontal Section



Vertical Section

Figure 97. Jacketing of precast concrete form. (Johnson, 1965, p. 164)

These repair regimes all involve release of a sealant or adhesive into cracks and/or addition of fibrous tensile material. Internal release of sealants adhesives in a crack as they occur and the presence of fiber increase toughness strength and could vastly reduce the need for these repair regimes (see Figure 98).

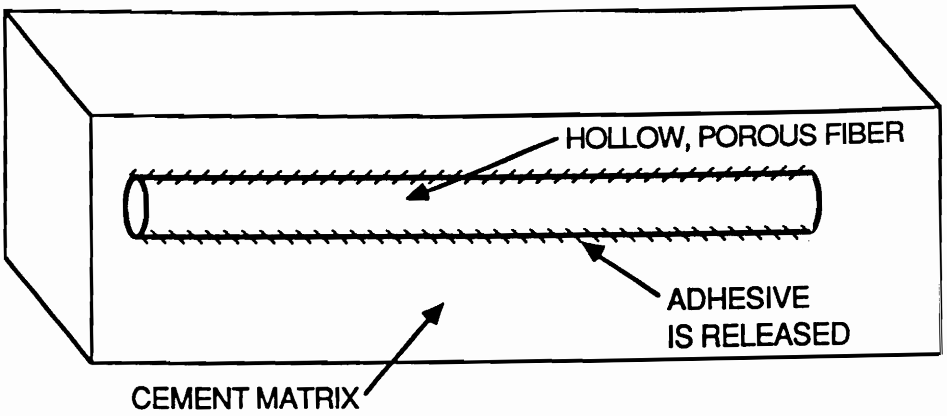


Figure 98. Internal release of adhesive gives improved adhesive bond at reinforcement bar.

Impact on Structure and Construction Systems

The following descriptions of structural or construction systems are from those concrete systems discussions from the Building Systems Integration Handbook by Rush (1986). These systems are post tensioned concrete, pre-cast frames, and tilt-up wall construction.

Post tensioned concrete:

Post tensioning is used to reduce the depth and thus the weight of a concrete slab in the structure (as seen in Figure 99) where slab depth and overall building height must be minimized or where heavy loads would produce unacceptably thick slabs (Rush, 1986, p. 126).

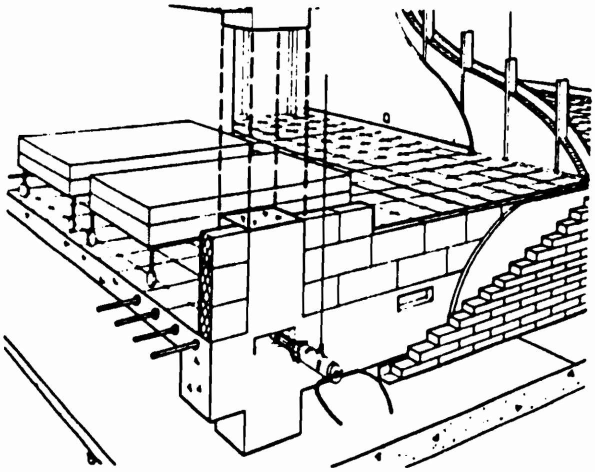


Figure 99. Post tensioned concrete. (Rush, 1986, p. 126)

Post tensioning reduces tensile stresses by the tensioning of steel tendons (cast-in-place tubes) after the concrete has set up (Rush, 1986, p. 126). Performance depends upon integrity of the tendons. They are frequently subject to the damaging effects of corrosion, even though enclosed in pipes and in dense concrete.

The timed delay release of anticorrosion calcium nitrite could prevent damage from the ongoing corrosion. In this case, the advantages of having release near or at the tendons is considerable. The fibers containing the chemicals would also increase the tensile strength. The timed delay release of internal sealing material to prevent water intrusion would also be useful.

Precast frames:

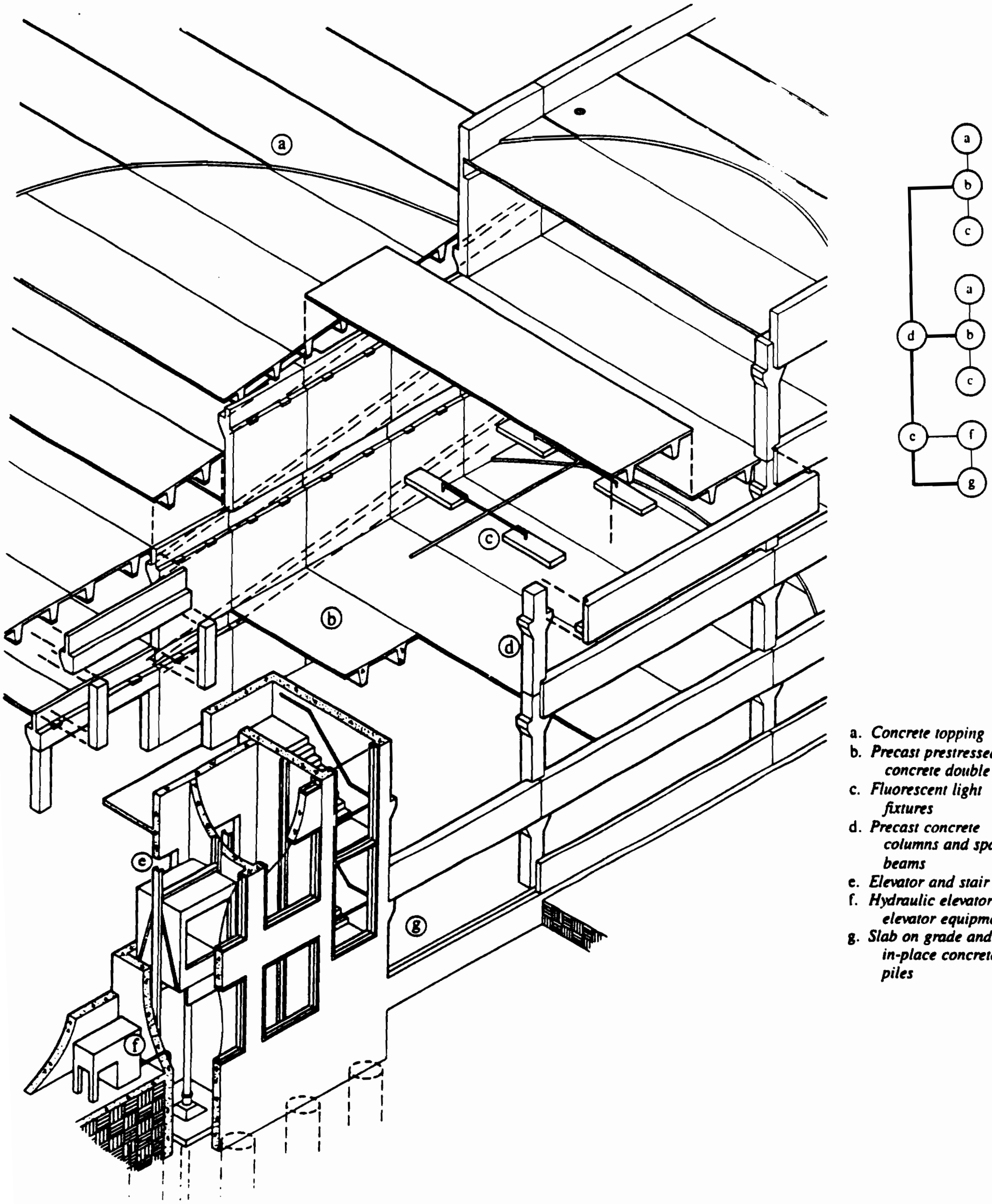
The precast frame uses pretensioning and the components are usually precast so that these precast concrete components can allow regular column free spans for economical purposes (see Figure 100) (Rush, 1986, p. 132). Internal timed delayed release of fibers containing chemicals would be relatively easy to include in precast elements. Release near joints would be important in a system which relys so heavily on joining into a frame.

Tilt-up wall construction:

Tilt-up walls which are on-site precast use the grade as casting surface and are tilted or lifted into position (see Figure 101) so that time is conserved but extra forming material or strong back frames may be needed for lifting and internal reinforcing may be required to resist the bending loads (Rush, 1986, p. 136). The fibers containing chemicals or preferably fabric would be a useful replacement for strong backs to provide internal resistance for bending stresses.

VII. The Development of Plastic Expression in Reinforced Concrete Architecture

Concrete is a miracle material. Due to its plastic nature, it has allowed architects to express their forms directly from their imaginations into reality. According to Reyner Banham (1986), in his book A Concrete Atlantis, the impact of functional ability and industrial aesthetics of concrete upon design and architecture from 1900-1925 was profound and reveals that concrete is a uniquely



- a. *Concrete topping*
- b. *Precast prestressed concrete double T's*
- c. *Fluorescent light fixtures*
- d. *Precast concrete columns and spandrel beams*
- e. *Elevator and stair core*
- f. *Hydraulic elevator and elevator equipment*
- g. *Slab on grade and cast-in-place concrete piles*

Figure 100. Precast concrete frame. (Rush, 1986, p. 133)

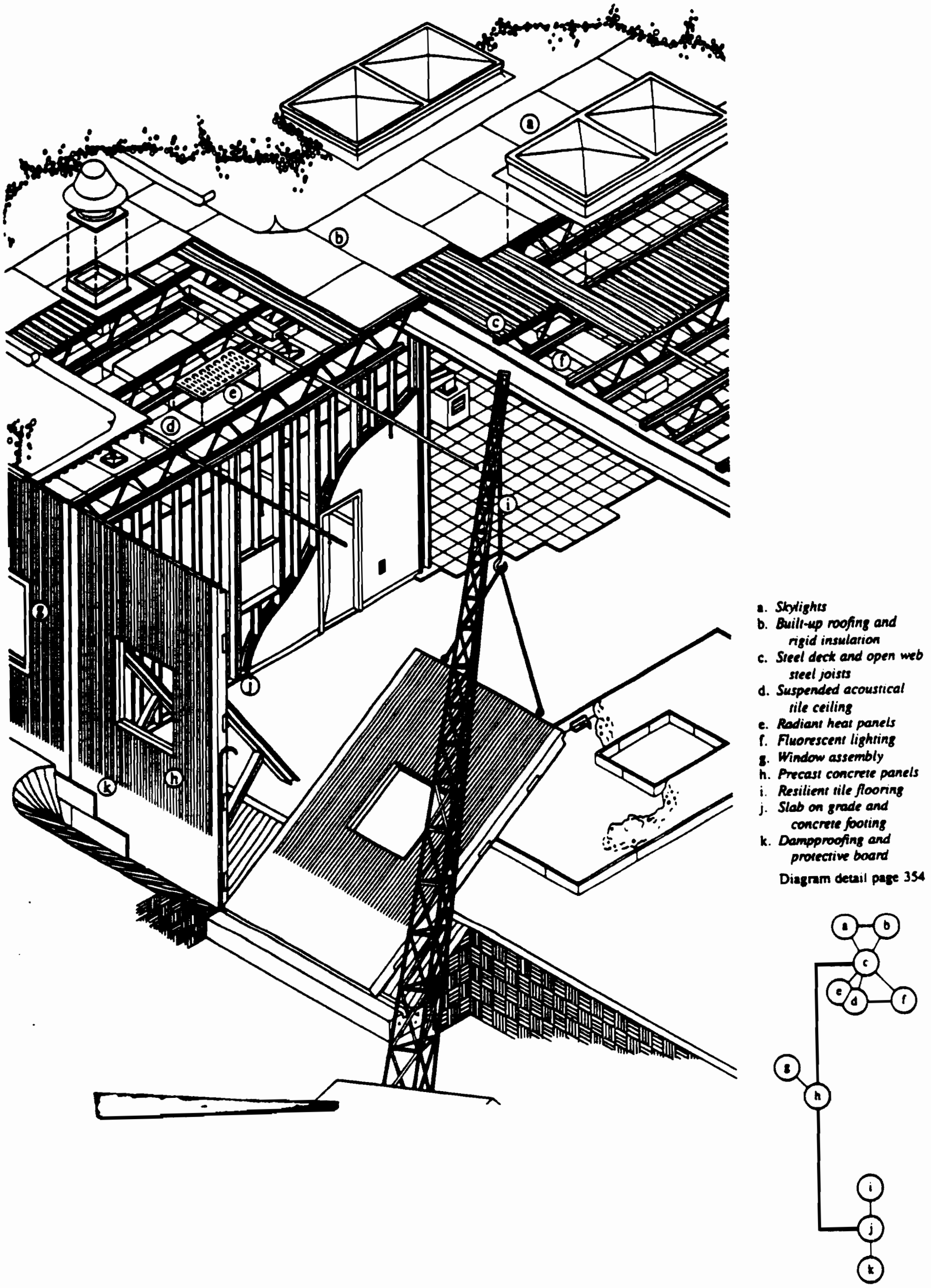


Figure 101. Wall panels in tilt-up construction unify the envelope, structural, and interior systems. (Rush, 1986, p. 137).

adaptive material and a maleable medium for expressing the style and aesthetics of the times. Banham makes a direct connection between the master works of explicit architectural modernism from 1920 to 1925 "and the utilitarian structures of a certain period and type of North American industry" (p. 3). Following this period in which North American building and classic modernist architecture of the international style in Europe merged, engineers further exploited the beautiful possibilities of concrete (Banham, 1986, p. 3). Luigi Nervi designed exceptionally beautiful cement facilities, and those at Turin being among the most famous (see Figure 102). Nervi expressed structural geometries which alluded to natural forms.

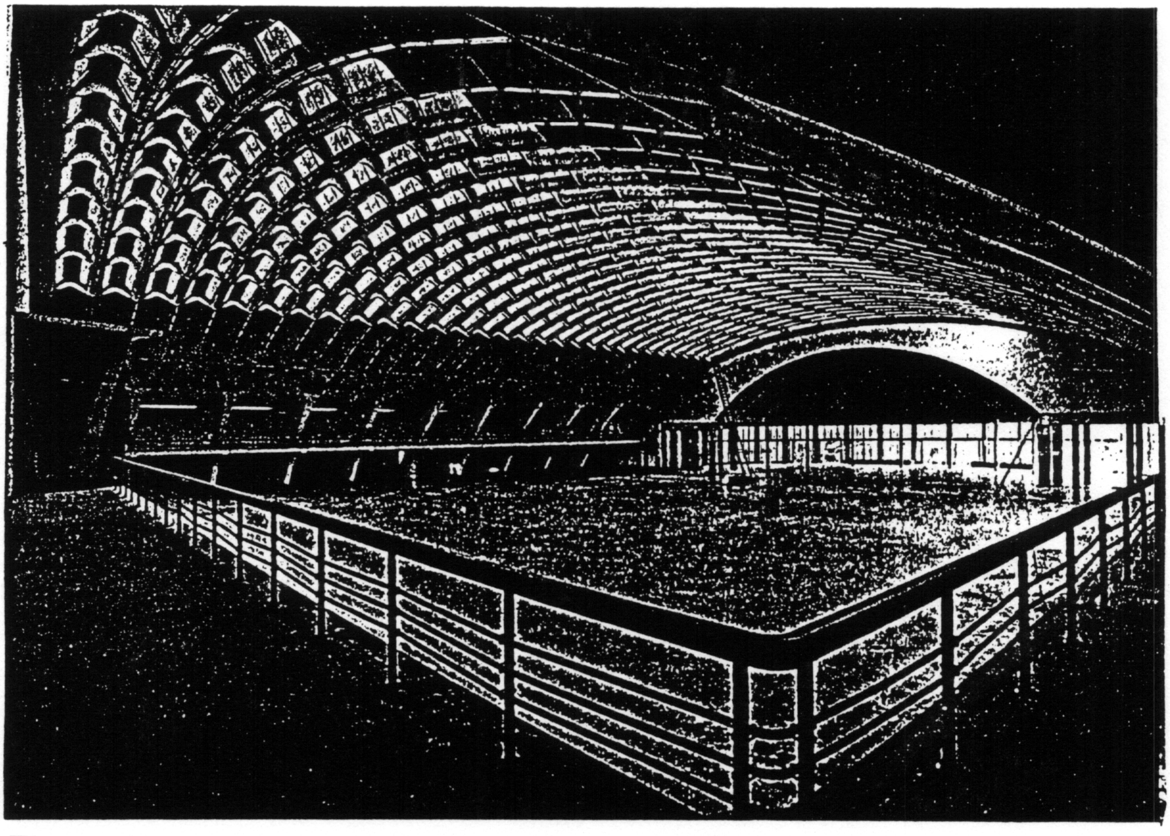


Figure 102. Exhibition Hall at Turin, Italy. (Architect: R. Biscaretti di Ruffia; Engineer: Pier Luigi Nervi, 1969, p. 115)

"Here, the purpose of structure and space enclosure was largely governed by a linear conception, and this can be seen in the lattice work of Nervi in his space enclosures. Robert Maillart, a Swiss engineer, then began to develop the two-dimensional structural element, followed later by the three-dimensional conception of shell construction, deriving the maximum strength from the material employed by means of appropriate structural shape" (Michaels, 1950, p. 3). Maillart was the first engineer to realize, in practice, "contemporary structural materials lend themselves to forms beyond the linear conception of skeletal framing members" (Michaels, 1950, p. 81) (see Figure 103).

"In Maillart's experiments with beamless flooring, the slab, was used as an elastic diaphragm reinforced according to stress distribution and pre-stressing permitted a reduction in the dead weight of the slab as well as increasing the economical use of steel" (Michaels, 1950, p. 82). The folded slab enables considerable spans with a comparatively thin slab (Michaels, 1950, p. 94). In the barrel shells, direct forces are transmitted in the surface of the vault with internal bending moments virtually nonexistent" (Michaels, 1950, p. 103) (see Figure 104). This replacement of bending moments by direct forces results in considerable economy of material, moving them from the curved slab into an extreme of the curved slab, the shell (Michaels, 1950, p. 102). Reinforced concrete is the material mainly used for this shell form of construction.

Figure 103. Bridge over the Toess near Wulflingdon, Switzerland. (Michaels, 1950, p. 80)

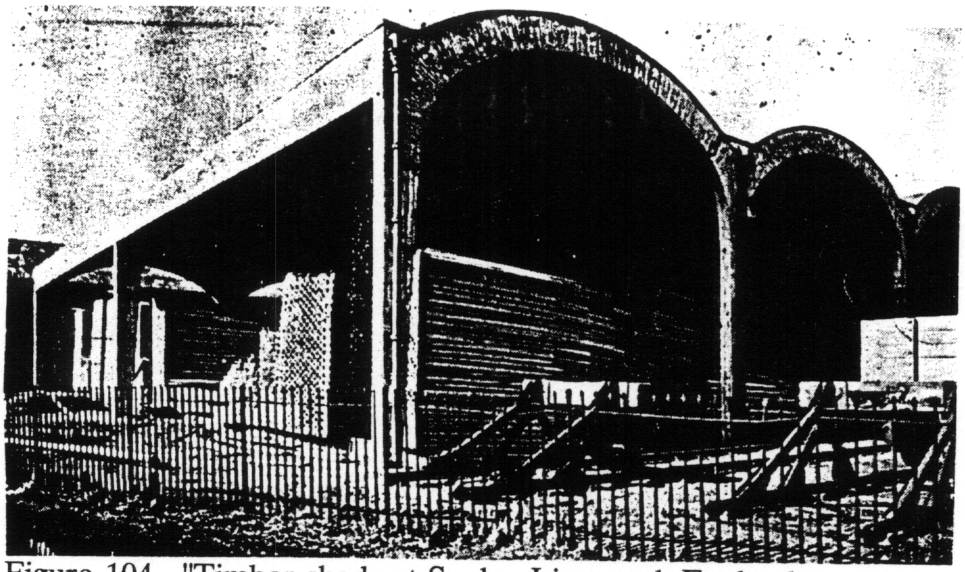


Figure 104. "Timber sheds at Speke, Liverpool, England, constructed of 55 ft. span barrel shells supported on and stiffened by rigid frames" (Michaels, 1950, p. 105).

The French engineer Freyssinet designed a corrugated shell in which the arches curve in two directions (see Figure 105). (His earliest application of this was in the airship hangers at Orly, France.) (Pier Luigi Nervi, also used it at times (Michaels, 1950, p. 115.) Later, a flexible fabric draped over the steel arch formwork on which a thin layer of concrete is poured was used in the storage

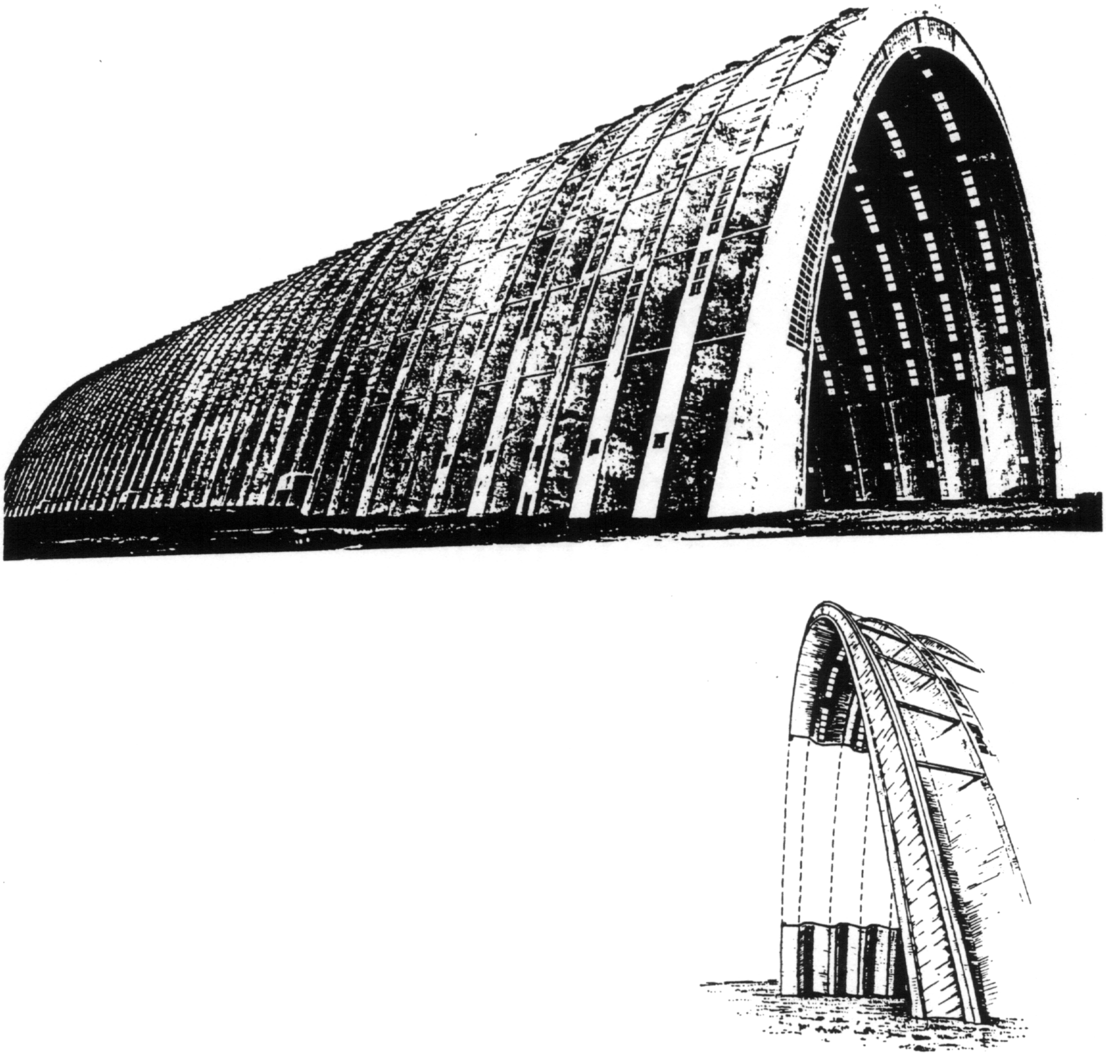


Figure 105. "A special case of the shell curved in two directions used in the airship hangars at Orly, France, which have a span of 320 ft. and a rise of 195 ft." (Michaels, 1950, p. 114).

building at Umtali, Southern Rhodesia by Barchild Construction (see Figure 106; Michaels, 1950, p. 117).

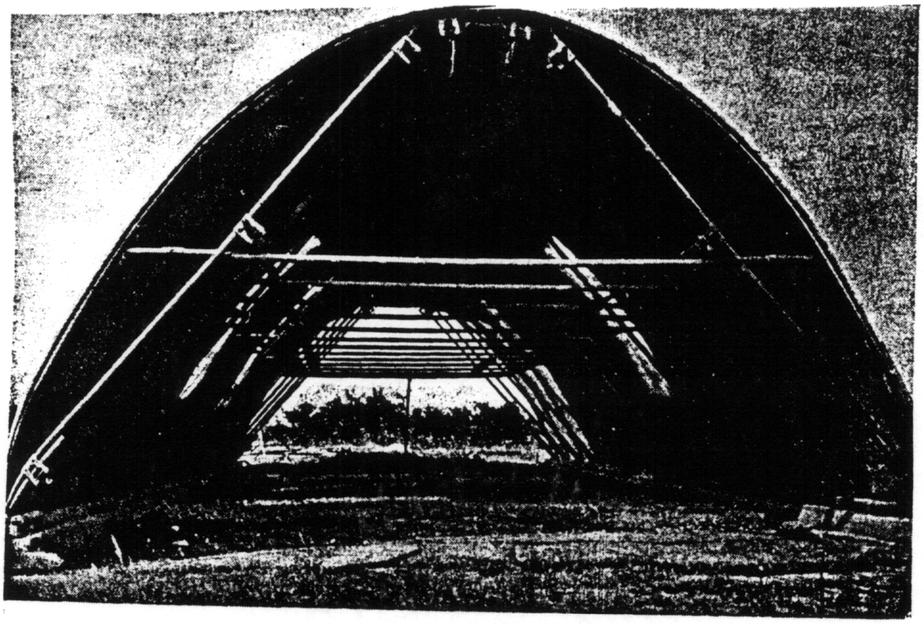


Figure 106. "Flexible jute fabric draped over steel arch ribs provides a simple formwork for pouring a thick arched concrete shell of corrugated section." A building at Umtali, South Rhodesia. (Engineers: Barchild Constructions, Ltd.) (Michaels, 1950, p. 117)

In summary, the curved shell was possible entirely because of modern reinforced concrete; the dome no longer needed massive embuttments in continuous support but could become thinner, curved in two directions, having multiple shapes (Michaels, 1950, pp. 120-121). The shell dome carried on columns was developed into elliptical shells where the load was not on columns but was transferred by means of the shells itself (Michaels, 1950, p. 124). "Domes made in this way could span 150 ft. with a minimum thickness of 3-1/2 inches" (Michaels, 1950, p. 124) (see Figure 107).

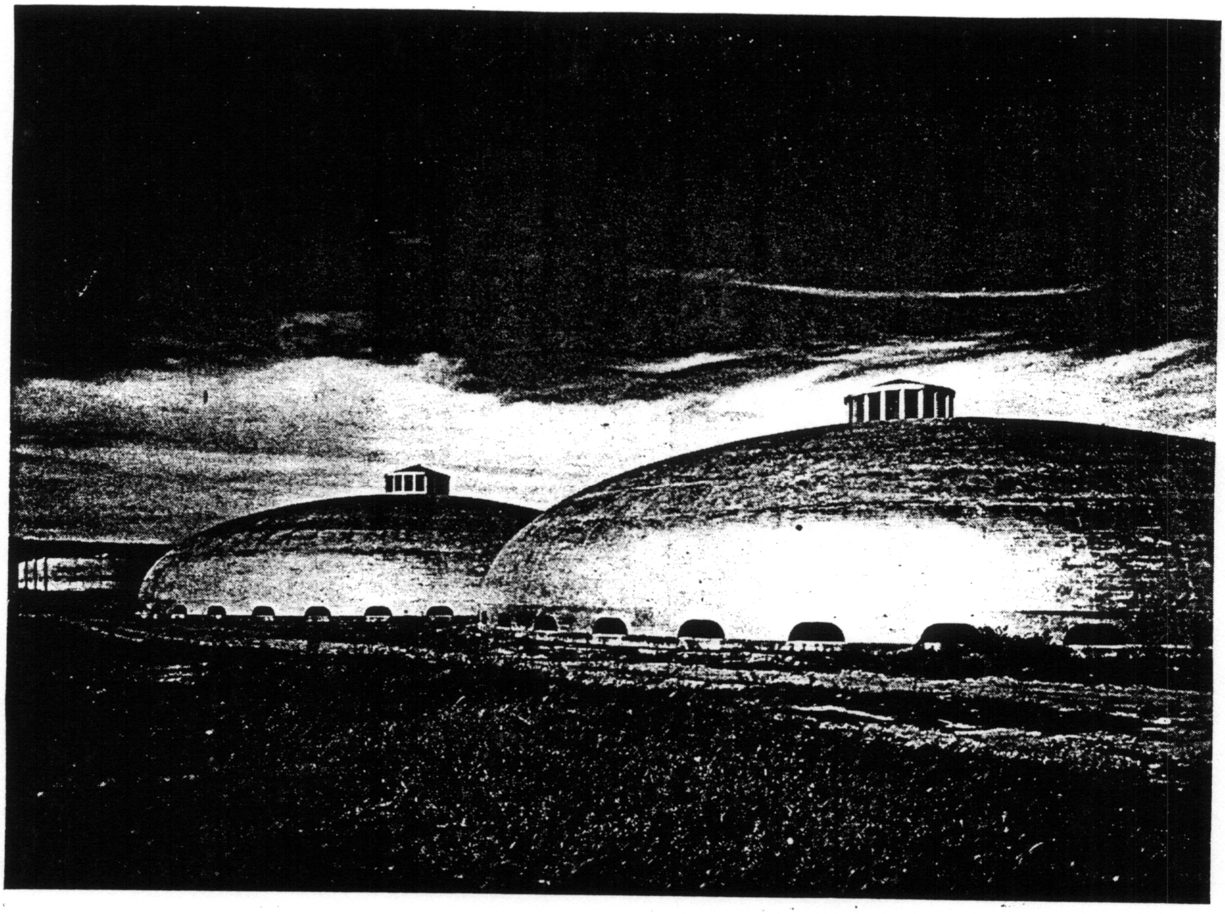


Figure 107. Eliptical concrete shell domes at the Sewage Treatment Plant, Hibbing, Minnesota. (Michaels, 1950, p. 124)

At first, reinforced concrete took on the forms of iron construction; however, with the development of the slab and the shell, the nature of this material was exploited to develop the structure as a whole. When used with steel to resist bending, much of the concrete falls below the neutral axis that is required for shear but is not used structurally as a compression material; forms were used to remove some of the excess material below the neutral axis of the structure and also pre-stressing was used (see Figure 108) (Michaels, 1950, p. 205). The elimination of excess concrete material is especially important because of the cost of the reinforcing steel and the requirement of reducing the dead weight of the structure to a minimum (Michaels, 1950, p. 206).

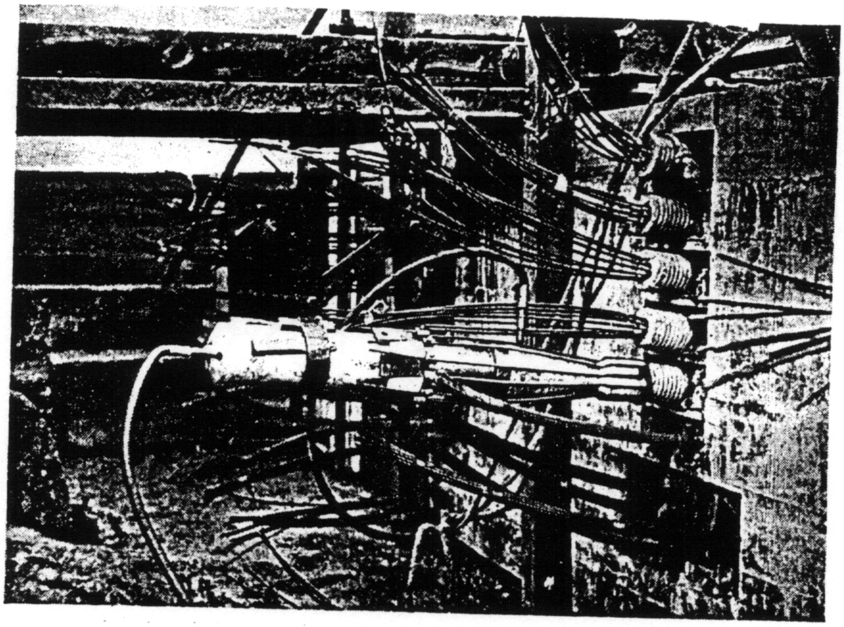


Figure 108. Type of pre-stressing jack developed by E. Freyssinet and operated by compressed air. (Michaels, 1950, p. 210)

Further Development of Plastic Expression Using Time Internal Release of Chemicals Into Concrete From Fibers or Fabric

Internal release of chemicals in concrete would have the advantage of both allowing the reduction of the dead weight of the structure and the actual reduction of tensile members, and the even distribution of tensile stresses by the use of fabrics or fibers (see Figure 109). The advantage of using internal release of chemicals would be that the cracks in the tension zone are sealed, thus protecting the steel. The bond between the steel and the concrete would be enhanced by release of adhesives also (see Figure 110).

The principal disadvantage in reinforced concrete is the costly formwork required for three-dimensional expression. Flexible fabrics utilizing timed delay release of chemicals would provide temporary support replacing formworks (see Figure 111). The internal release of a chemical that sets up quickly before cement hydration would provide temporary support. Such a type of chemical to be released from the fabric is called a condensation reaction in cement chemistry. In it, water is released from the polymeric reaction which then serves to hydrate the cement (see Figure 112). These systems to replace formwork would also enhance flexural strength.

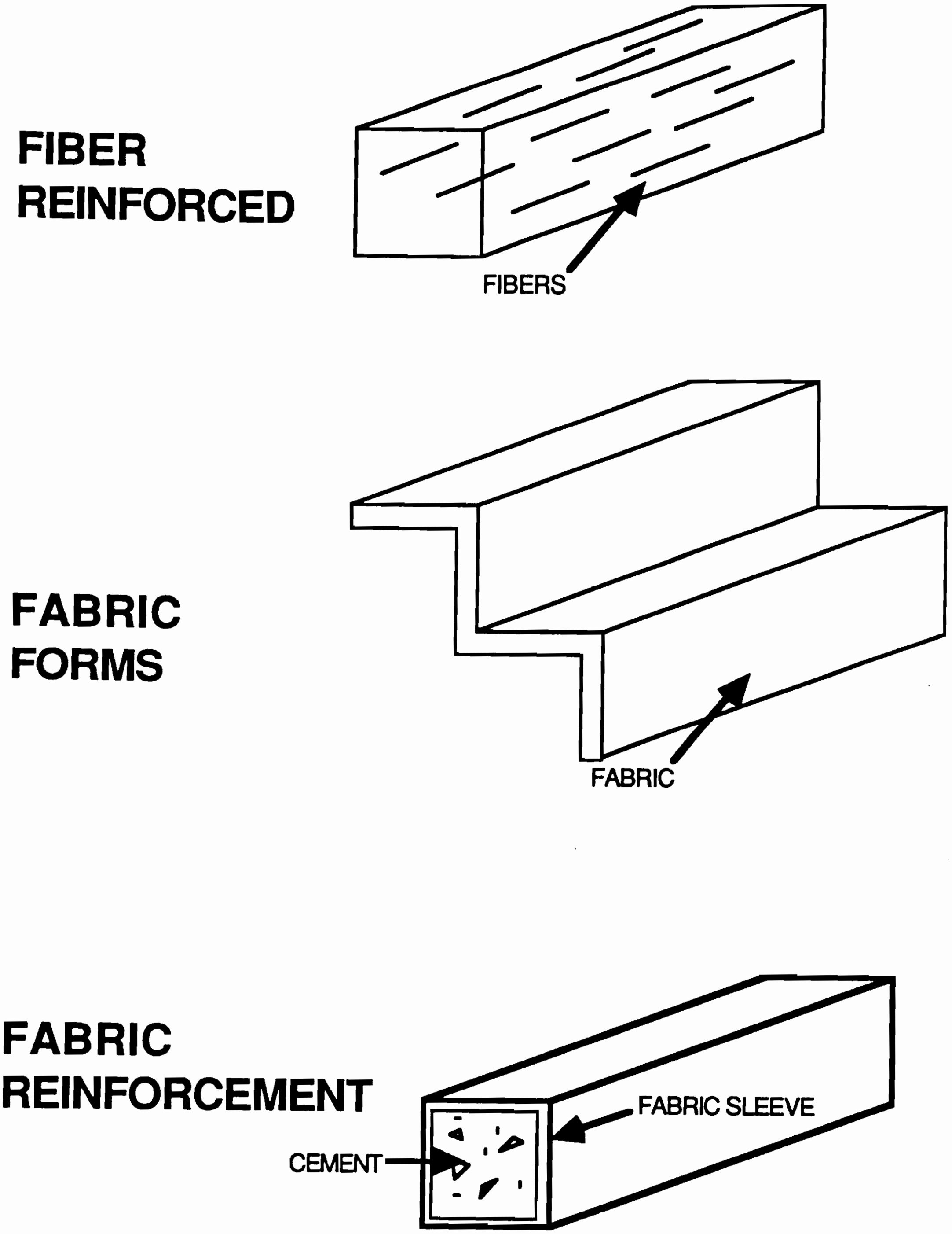


Figure 109. Use of internal timed release of chemicals allows even distribution of tensile strength by use of fibers or fabrics.

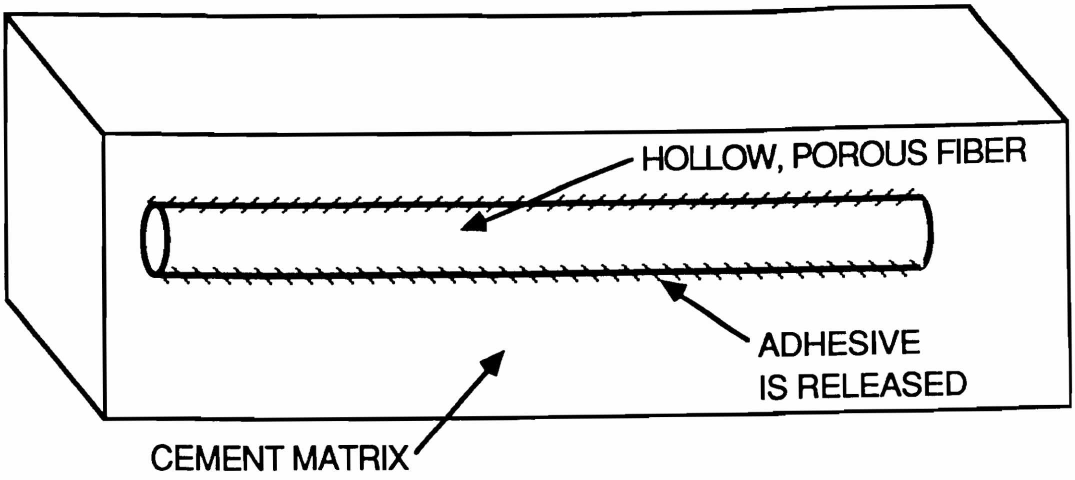


Figure 110. Internal release of adhesive gives improved adhesive bond at reinforcement bar.

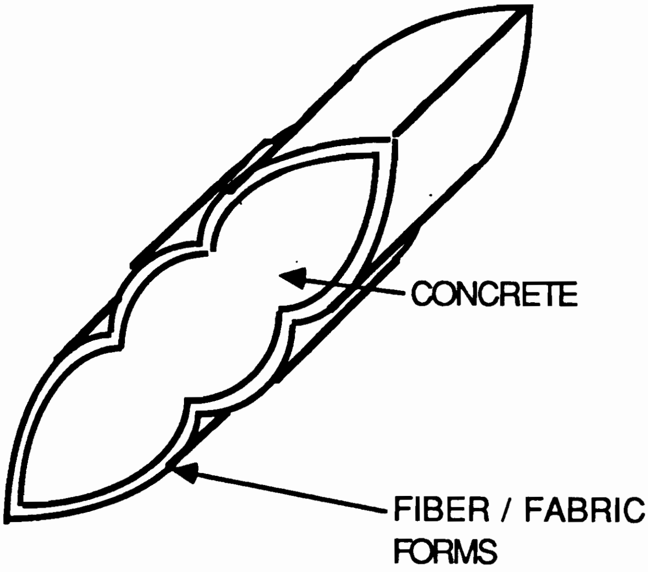


Figure 111. Using fiber forms requires less support of formwork and allows freedom of expression.

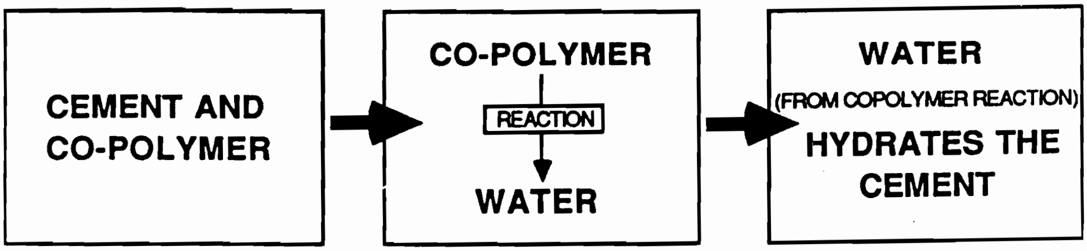


Figure 112. Polymeric condensation reaction provides water for cement hydration.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The feasibility of using the various fiber/chemical/coating combinations was determined by the ability of the chemical to be taken up into the fiber (some chemicals are too viscous) and the ability to isolate the chemical in the fiber until the desired release (coating the fiber). The combinations that were successful to this point were then tested for release into the matrix by an external or internal stimuli and further, movement of the chemical into the matrix. Success of chemical release into the matrix, and movement of the chemical into the matrix, is dependent upon the stimuli for release accomplishing both the release of the chemical and the preparation of the matrix to receive the chemical. The most successful examples were heat melting the wax coating to allow methyl methacrylate (or calcium nitrite) to release from the fibers and also the heat drying the matrix in preparation to receive the methyl methacrylate (or calcium nitrite). In the case of methyl methacrylate the heat polymerizes the methyl methacrylate. Another successful design example is freeze/thaw action driving the propylene glycol or linseed oil from the porous aggregate into the matrix. Xypex was also successfully released from wax prills. The design to release from fiber upon structural loading to fill cracks failed because the fibers either stretched or broke and did not release upon structural loading. The methyl polyimide to be released in the bottom ash/phosphate bonded/sintered matrix upon heating is compatible with the acid present in the matrix and the high temperature, but it was viscous and was put in the outside pores of porous fibers from which it seemed to release.

Next, tests were made to evaluate the effectiveness of the successful combinations for the treatment of particular distresses. It was concluded that the methyl methacrylate released from fibers and then polymerized in the matrix increases impermeability, and that the Xypex chemical did not increase permeability. Also, freezing damage was reduced somewhat by the release of chemicals during freezing. Calcium nitrite in fibers did not retard the set which is the desired result. The actual corrosion tests were too lengthy for this research study. The timed release of water into dense silica fume cement was an unexplained failure. The presence of methyl polyimide in the matrix reduced the permeability of the bottom ash.

Because success in treatment for a particular distress may in some cases depend upon the volume of the matrix saturated, evaluations were made concerning the amount of chemical released into the volume of the matrix and percent of the matrix saturated. In the calcium nitrite and the methyl methacrylate samples containing 2.75% volume fibers, there was usually about 30% wetting of the specimen surface, depending upon temperature of heating or if microwaved. The goal is not 100% saturation of the specimen in most cases.

One can postulate that the fibers need only saturate the cement matrix in contact with the reinforcing bars, for example, in the case of release of calcium nitrite to cause corrosion inhibition at the reinforcing bars. In the case of methyl methacrylate released from hollow porous polypropylene fibers coated with wax to accomplish polymer impregnation, the release could occur in the total volume of the matrix or it may be useful if the chemical is only released at a certain depth and migrates to the surface for protection. These postulations have not been tested.

Before testing it was postulated that damage may occur to the strength properties of the cement by the use of fiber volumes and stimuli such as heat. These factors were researched. In the cases of release of either calcium nitrite or methyl methacrylate from hollow porous polypropylene fibers coated with wax, the conclusions are similar. These are: as the number of filled fibers is increased, and as the volume saturated increases, the compression and bending strength increase. In preliminary tests with the limit of 2.75% volume of fibers, that is where the compression and bending strength began to decrease. These samples were heated but not to temperatures high enough for polymerization to occur (120° F). Other samples were heated to 212° F or microwaved. It was found that heating increases strength. Separating the strength contribution of various factors in the methyl methacrylate and Xypex examples was equivocal, but it was seen that wax adds bending strength.

Conclusions drawn from tests, in comparison with conventional treatments, are that the internal fiber release of methyl methacrylate is an improvement over the conventional external polymer impregnation. Xypex results were better for the timed release than conventional applications. Freeze/thaw damage, as measured by weight loss, was less with the system for internal timed release of chemicals than with air entrained concrete, but not as good if measured by length change as those combining the internal release and conventional treatment. Calcium nitrite in fibers retards the set not at all, while the conventional fully mixed chemical does retard the set.

Storage of filled fibers seems to present no problem if closed containers are used to prevent chemical evaporation. Longer time in field testing of all factors is needed, as well as a study of manufacturing issues.

The anticipated major cost and design implications of internal timed release is that a large part of life-cycle costs can be predicted as part of the design cost. The time to first repair would be extended, and therefore the per annum costs reduced. In these designs the repair time begins with environmental penetration; that is the time when normal deterioration begins. In the cases of human stimulation, the repairs begin when the stimulus is given, which is before any environmental penetration and deterioration occurs.

These designs may be most effectively used in new structural systems which require the use of many fibers or fabric and little cement to wet fabric reinforced cement laminates.

In the order of importance, the conclusions that can be drawn are:

1. The sequence of release of chemicals into the matrix was accomplished and shown to be feasible. It has been shown that by incorporating chemical means into the matrix material, later release can occur upon stimulation, allowing the matrix to be physically different from that at the initial set.
2. Benefits in terms of cost and design implications are that major maintenance and repair issues could be included in the initial design of the building, and components and structures could take greater environmental abuse such as loading, chemical attack, etc.
3. The impermeability was significantly increased with the design using methyl methacrylate.
4. In every case tried, except the dense silica fume example, the treatment using time release of chemicals was more successful than the treatments in common usage.
5. The inclusion of filled hollow porous fibers or prills did not degrade the strength properties as predicted by the American Concrete Institute reviewers of the work. However, above a certain volume of

fibers, namely, 2.75% volume, the strength properties do degrade as they would in conventional fiber reinforced concrete.

6. When the chemical is released from the fibers or prills, the relationship between the number of fibers, the volume of chemical included in the fibers, and the amount of chemical wetting the samples surfaces is predictable.
7. The wax by itself contributes to bending strength properties.
8. Practical considerations such as storage of the fibers do not seem to be a major problem, nor is the top-heating only as occurs in the field.

Unique Attributes of Each Design

Each of the systems designed would use the internal timed release in its own unique way. For instance, the design of time-release of calcium nitrite relies on the delay of the release, until after the concrete is set so that the set time will not be extended as occurs in the conventional free mixing of calcium nitrate into the concrete. The fact that release is internal would be especially valuable in the example of corrosion-resistant design because the release could occur right at the rebar where it is needed, and also reduce the amount of chemicals needed (these long-term tests are ongoing). The factor of slow release would be an important factor in the design of the release of water into DSP cement to reduce self-dessication and, therefore, cracking (if it had worked). The ability to release the

Xypex after the cement matrix is set is the valuable attribute in that design because the Xypex cannot be in contact with the cement while it is hydrating or it degrades the strength. The internal inclusion of the Xypex was also advantageous because it has less distance to migrate; therefore the crystallizing, blocking action can occur faster than if put on from the top external surface. (The top surface application can take three weeks to penetrate through a layer of concrete several feet thick.) In the methyl metacrylate example, the stimulus of heat is the factor that opens the fiber to release the methyl methacrylate, prepares the matrix to accept the methyl methacrylate, and finally polymerizes the methyl methacrylate. In the design to resist corrosion in which the fibers are coated with polyol, the polyol would degrade in reduced alkalinity which is the very factor that is responsible for corrosion itself.

Summary of Answers to the Research Questions

1. Does the design for time release of internal chemicals work? The answer is definitely, yes.
2. Does the successful release alleviate the particular environmental distress or reduce cracking or permeability? The answer is that in most cases the environmental distress was alleviated or permeability was reduced. One of these tests, the long-term test for corrosion-resistance was outside the framework of this endeavor.

    2a. Is the volume of chemical wetting significant? Yes, and it is proportional to the number of fibers and amount of chemical included.

3. Do fibers and stimulus reduce or increase strength? The heat stimulant increases the strength properties, whereas the number of fibers up to 2.75% volume do not degrade the strength properties but increase them.

    3a. The question of the strength contributions of the various factors was difficult to answer. It appeared that the wax contributed to bending strength. This was a surprise.

4. Do these designs represent improvements of a conventional treatment for impermeability or crack reduction and particular environmental distresses? The answer is yes in all cases tried, except for the treatment to reduce drying shrinkage in DSP cement or in the case of methyl polyimide in bottom ash where no comparison could be made.

5. What are the effects of manufacture storage and infield problems? The issues that we could assess reveal no serious problems. Storage is manageable and top heating will release chemicals successfully. The larger issues of infield testing and method of placement of the fibers into the cement matrix is needed to be addressed in full-scale field tests.

6. What would be the estimated design and cost implications of internal timed-release for building components and structures? The most important implication is that a large part of the life cycle cost can be predicted and included as part of the design cost. The time of the first repair would be extended. The size of some components could be reduced. The components or structure could take greater environmental abuse such as loading, water ponding, chemical attack, etc. New designs such as folded fiber concrete structures may benefit more from these systems than conventional designs.

The questions were framed so that the data necessary to answer them are comparative among controls and experimental results. The fact that numerous processing factors affect performance attributes of cement/concrete make it very difficult for researchers in the field to get results upon which meaningful comparisons can be made. Few comparisons to data in the literature are made because of this.

Recommendations for Future Research

Recommendations for future research include the following suggestions:

1. Designs should be tested in which only partial saturation of a component is desired. For example, in the case of corrosion inhibition at reinforcing bars by the release of calcium nitrite from hollow wax-

coated fibers, the fibers may need to only saturate the cement in contact with the reinforcing bars. The questions to answer would be: How far does the chemical migrate away from the area where it is released? How does this concentration of fibers and chemical at the interface affect strength properties? In the case of methyl methacrylate released from porous wax-coated fibers, if the chemical is to be released at a certain depth for migration to the surface for protection, can the chemical be moved in that way? Will it stay there? What is the effect on strength and permeability properties? The inclusion of timed release chemicals into fabric reinforced cement laminates should be tested and evaluated also. Also less viscous methyl polyimides should be tested with fiberglass fibers and bottom ash matrix. Long-term corrosion tests need to be completed.

2. Longer term tests and field tests are needed. The filled fibers should be stored for longer periods in various settings. In-field testing of all factors is needed. The successful release in top heating could be a topic of a longer investigation.
3. The method of placement of fibers in the cement matrix needs to be studied and tested as well as the cost of fiber filling, storage and use.
4. Other designs using internal delayed release chemicals into materials should be investigated. For instance:

a. The release of adhesive or other binding chemicals from the fibers to the matrix could act to bond the fibers to the matrix more firmly. Conventional fiber reinforced materials have the problem of fiber pull-out or debonding from the matrix, this design would address that issue.

b. Either the release of the chemical from inside the fiber or the release of the chemical on the outside of the fiber into the area between the fiber and the matrix has the advantage of acting as a third material or third phase between the fiber and the matrix. This is especially useful in the case of high temperature ceramics where the differential thermal extension of fiberous material and the matrix cause fracture and other problems. The use of an intermediate material between these with an appropriate rate of thermal expansion such as viscoelastic materials may be advantageous.

c. The infiltration of a ceramic or other materials into bundles of fibers is a common problem in ceramic engineering. It may be made more efficient if the fibers are either a bundle with spaces in between which effectively acts as one large fiber or if the fibers or bundles of fibers have pores and are hollow. These pores or hollow spaces would be filled with the ceramic slurry.

d. The timed release of a chemical from a rather large or hollow and/or porous fiber such as ceramic biomedical implants could greatly enhance the strength as well as the amount of chemical released. These implants are shaped like short fibers (they are one inch long by one-quarter inch in diameter). Longer or shorter versions can act as small reinforcing bars.

e. Fibers or capsules, which can themselves dissolve or are conductive, could be researched.

f. Chemicals that have unusual properties may be utilized, such as hydrophilic chemicals, which eliminate the need for fiber coatings or cross-linking polymer chemicals could be used.

g. A match may be made between chemical and pore structure of the fiber so that the chemical moves in one direction through the membrane of the fiber and yet other chemicals cannot move back in. Also other chemicals could move into the fiber but other chemicals inside the fiber could not move out.

h. Matrix materials could be used which have different properties from cementitious, porous materials or ceramics such as asphaltic or polymeric matrices.

CHAPTER VII

SUMMARY

This research has shown that by incorporating chemical means into the matrix of the material, later release can occur upon stimulation, allowing the matrix to be physically different from that at initial set. The matrix parameter of permeability can be altered, and therefore probably durability. The impermeability was significantly increased by internal release of methyl methacrylate from a fiber which was then polymerized. Tests on other designs determined how much these time-released materials were able to aid the resistance to environmental intrusion such as freeze/thaw damage and chemical/water intrusion damage. Freeze/thaw damage was reduced somewhat by delayed release of linseed oil and antifreeze. Longer term corrosion tests are ongoing. Of the designs tested fully, all were more successful than conventional treatments, except for the one adding water released from porous aggregates into dense silica fume cement.

Significant reduction in compression and bending strength caused by increased fiber loading or porosity of fibers or aggregate did not occur, nor did strength reduction due to heating, instead both increased the strength properties.

The percentage of wetting is proportional to heating temperature and volume of fibers or aggregate. The volume of chemical wetting required and the related placement of fibers for maximum benefit has to be researched in the future.

Long-term testing needs to be done to assess the amount of the improvement over conventional means of alleviating environmental distress or repairing cracking and reducing permeability. Brief storage testing was done. Field testing is needed in the future. The value and design implications of these improvements needs to be assessed as a result of field testing; nevertheless, one can estimate the effect now.

The main advantage of the designs would be the ability to include major maintenance and repair issues and cost in the initial design phase of the building, and delay the time when repairs are needed. The size of some components could be reduced. The components and structure could take greater environmental abuse, such as loading, water ponding, chemical attack, and so forth. These designs may be the most useful in new structural systems requiring fabric such as fabric reinforced cement laminates. Many other designs should be investigated also.

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APPENDIX A

GLOSSARY

Note. The definitions are from ACI publication SP-19C85 Cement and Concrete Terminology (see References).

ACI--American Concrete Institute.

ASTM--American Society for Testing and Measurement.

Bond--Adhesion and grip of concrete or mortar to reinforcement or to other surfaces against which it is placed, including friction due to shrinkage and longitudinal shear in the concrete engaged by the bar deformations; the adhesion of cement paste to aggregate; adherence between plaster coats or between plaster and a substrata produced by adhesive or cohesive properties of plaster or supplemental materials; also in United Kingdom the arrangement of units in masonry and brickwork so that vertical joints are discontinuous.

Bottom ash--The finely divided residue resulting from the combustion of ground coal which is deposited in the fire box.

Carbonation--Reaction between carbon dioxide and a hydroxide or oxide to form a carbonate, especially in cement paste, mortar, or concrete; the reaction with calcium compounds to produce calcium carbonate.

Cement, white--Portland cement which hydrates to a white paste; made from raw materials of low iron content the clinker for which is fired by a reducing flame.

Corrosion--Destruction of metal by chemical, electrochemical, or elctrolytic reaction with its environment.

Corrosion inhibitor--A chemical compound, either liquid or powder, that effectively decreases corrosion of steel reinforcement before being embedded in concrete, or in hardened concrete if introduced, usually in very small concentrations, as an admixture.

Cover--In reinforced concrete, the least distance between the surface of the reinforcement and the outer surface of the concrete.

Cracking load--The load which causes tensile stress in a member to exceed the tensile strength of the concrete.

Deterioration--(a) Physical manifestation of failure (e.g., cracking, delamination, flaking, pitting, scaling, spalling, staining) caused by environmental or internal autogenous influences on rock and hardened concrete as well as other materials; (b) Decomposition of material during either testing or exposure to service.

Distress--Physical manifestation of cracking and distortion in a concrete structure as the result of stress, chemical action, or both.

DSP--Dense silica fume cement.

Durability--The ability of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service.

Durability factor--(a) A measure of the change in a material property over a period of time as a response to exposure to an influence that can cause deterioration, usually expressed as percentage of the value of the property before exposure; (b) in ASTM C 666, a measure of the effects of freezing and thawing action on concrete specimens in which resonant frequency of vibration is used as the property measured.

Dynamic modules of elasticity--The modulus of elasticity computed from the size, weight, shape, and fundamental frequency of vibration of a concrete test specimen, or from pulse velocity.

Environmental distress--Physical manifestation of cracking and distortion in a concrete structure as the result of stress, chemical action, or both.

Formwork--Total system of support for freshly placed concrete including the mold or sheathing which contacts the concrete as well as all supporting members, hardware, and necessary bracing; sometimes called Shuttering in the United Kingdom.

Freeze/Thaw--The rapid freezing and thawing of cement samples in which the procedure similates the thermal cycling which can cause internal cracking.

Initial setting time--The time required for a freshly mixed cement paste, mortar or concrete to achieve initial set.

Matrix--In the case of mortar, the cement paste in which the fine aggregate particles are embedded; in the case of concrete, the mortar in which the coarse aggregate particles are embedded.

PIC--Polymer impregnated concrete.

Permeability to water, coefficient of--The rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions, usually 20° C.

Polymer--The product of polymerization; more commonly a rubber or resin consisting of large molecules formed by polymerization.

Porosity--The ratio, usually expressed as a percentage, of the volume of voids in a material to the total volume of the material, including the voids.

Precast concrete--Concrete cast elsewhere than its final position.

Prill--A form of containment in which the container and material to be contained are completely mixed.

SEM--Scanning electron microscope.

Silica fume--Very fine noncrystalline silica produced by electric arc furnaces as a byproduct of the production of metallic silicon or ferrosilicon alloys; also known as condensed silica fume.

Sintering--The formation of a porous mass of material by the agglomeration of fine particles by partial fusion.

Water/cement ratio--The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of cement in a concrete or mortar mixture; preferably stated as a decimal by weight.

APPENDIX B

DATA ON MATERIALS USED

Table B-1

Fiber and Aggregate Data

Fiber/Aggregate /Prill	Material	Supplier	Comments
Polypropylene fibers X-20	Polypropylene	Hoechst Celanese Separations Product Division 13800 S. Lakes Dr. Charlotte, NC 28217	Low strength fiber, highly elastic, easy to place; 40% porosity, hollow-400 micron inside diameter
Fiberglass fibers	Fiberglass	Pittsburgh Plate Glass	Hollow, porous, withstands high temperatures & acid, hard to place
Limestone aggregate	Limestone	Cement Supply Co. Champaign, IL	Porous aggregate
Haydite Porous expanded clay aggregate	Expanded clay	Cement Supply Co. Champaign, IL	Porous aggregate
Wax prill	Parafin wax	Any hardware store	Melts, solidifies

Table B-2

Chemical Data

Material Contained in Fibers, Aggregates or Prills	Function	Supplier	Comments
Calcium nitrite	Corrosion inhibition at rebars	W. R. Grace Cambridge, MA 02138	Low viscosity
Conslidec, SX and salt guard, a siloxane	Prevents water intrusion	Pro So Co., Inc. P.O. Box 171677 Kansas City, KS 66117	Low viscosity, insoluble in water
Polypropylene Glycol	Anti-freeze to reduce freeze/thaw effects	Any gasoline station	Viscous
Linseed oil	Seals, repels water	Any hardware store	Viscous
Methyl methacrylate	Polymer impregnator	Alrich Chemical Co. Wisconsin	Low viscosity, polymerizable fluid at room temperature
Water	Prevents self-desiccation, promotes cement hydration	Municipal water supply	Low viscosity
Polysilazane	Prevents water intrusion, sealant	Southwest Research Institute San Antonio, TX	Withstands high temperatures
Xypex	Fills pores to prevent water intrusion	Xypex Corporation 13731 Mayfield Place Richmond, B.C., Canada	Crystallizes upon contact with water
Methyl polyimide PI-2611	Prevents water intrusion, sealant	Dupont Wilmington, DE	Withstands temperature of 500° C; compatible with acids, viscous. Viscosity of 110 pois.

Table B-3

Chemical Coating Data

Coating Material	Function	Supplier	Comments
Paraffin wax	Melts with heat; solidifies at room temperature	Hardware store	Is waterproofer
Polyol	Gradually dissolves in alkaline solution; liquifies with heat	Union Carbide 39 Old Ridgebury Rd. Danbury, CT 06817-0001	Time unknown for dissolution
Shellac	Brittle and cracks under loading	Hardware store	Encapsulated methyl methacrylate evaporates through coating
Sartomer	Makes prills	Sartomer Company Marshall Building West Chester Pike, PA 19382	Chemicals difficult to handle

Table B-4

Matrix Chemical Data

Matrix Material	Function	Supplier	Comments
White cement	White cement matrix can reveal colored chemicals	Cement Supplier Champaign, IL	Alkaline chemistry changes over time
Portland cement	Cementitious matrix	Cement Supplier Champaign, IL	Alkaline chemistry changes over time; promotes corrosion of reinforcing bars
Dense silica fume cement	Particles pack closely for a dense waterproof cement	W. R. Grace, Inc. Cambridge, MA 02138	Low water/cement ratio of DSP cements causes self-desiccation and drying cracking
Phosphate-bonded/sintered bottom ash and phosphoric acid	Low-cost lightweight cementitious material	Bottom ash from American Electric Power, Inc. Columbus, OH	Sinters at 600° C; highly permeable

APPENDIX C

PHOTOGRAPHS OF CONCRETE TESTING

Photo 1. The chemical is drawn into fibers by use of a vacuum flask.

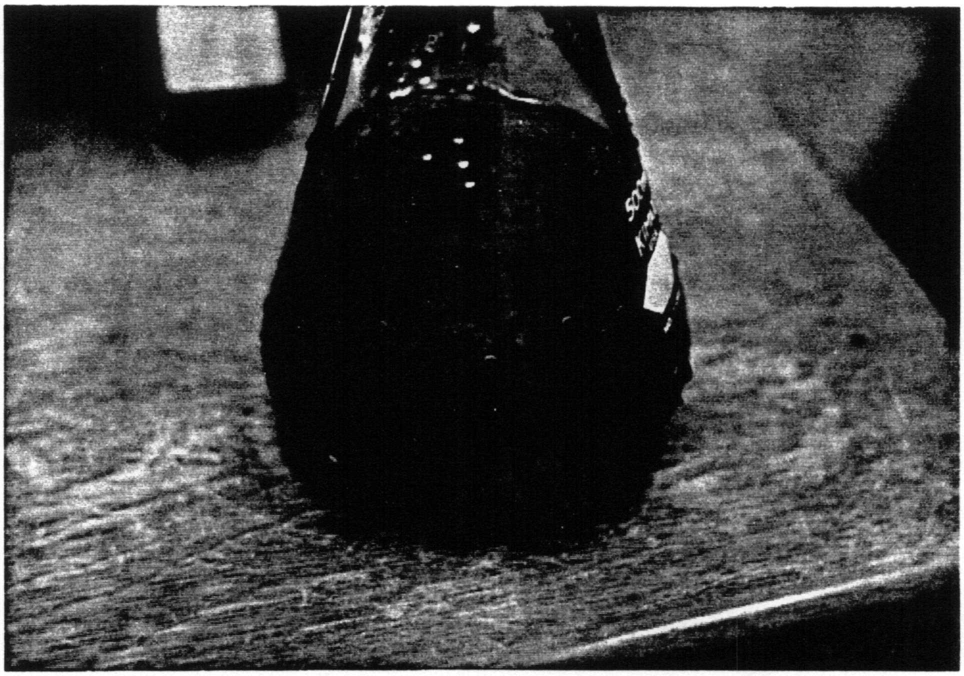

Photo 2. Porous aggregate in a flask is saturated with chemical by vacuum action.

Photo 3. The porous fibers are coated with wax before cutting into 1" lengths.

Photo 4. Filled fibers are cut in 1-inch lengths.

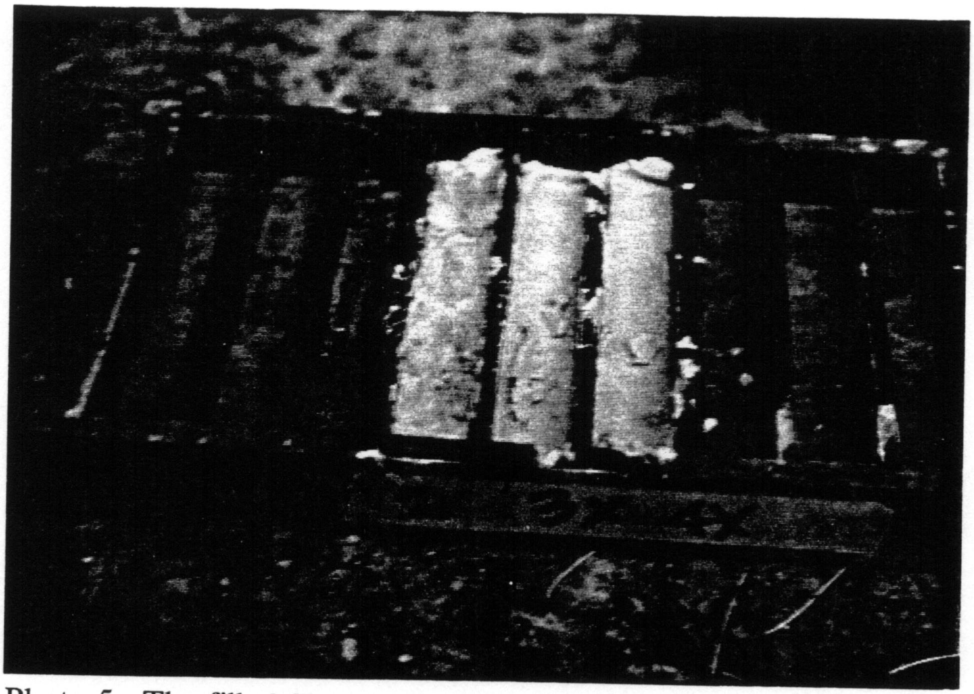

Photo 5. The filled fibers are added to the sample.

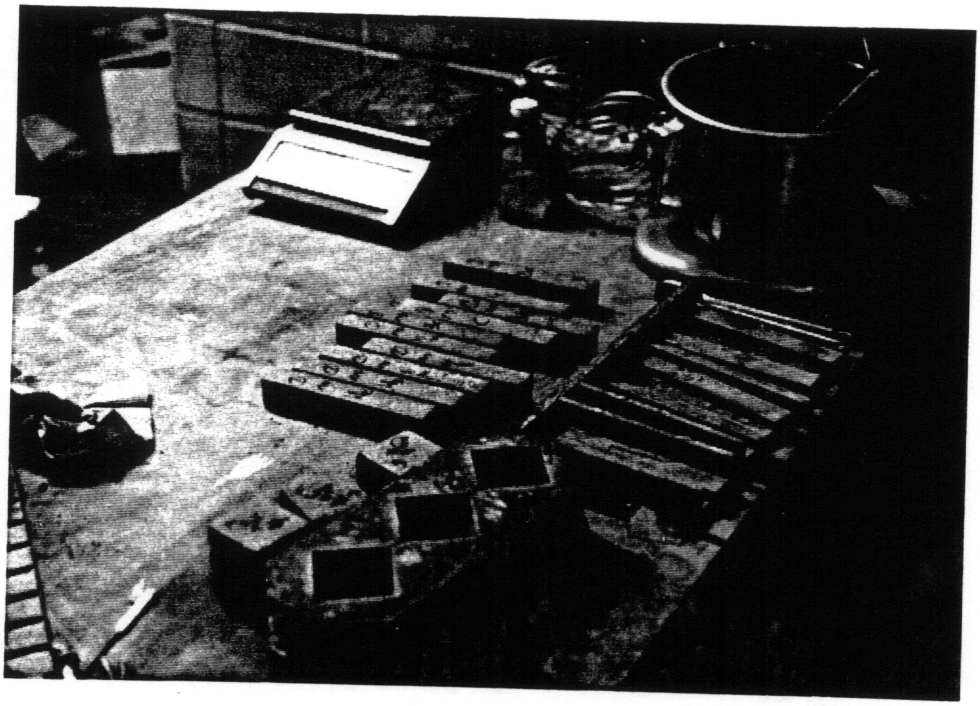

Photo 6. Molds are used for flexure and compression tests.

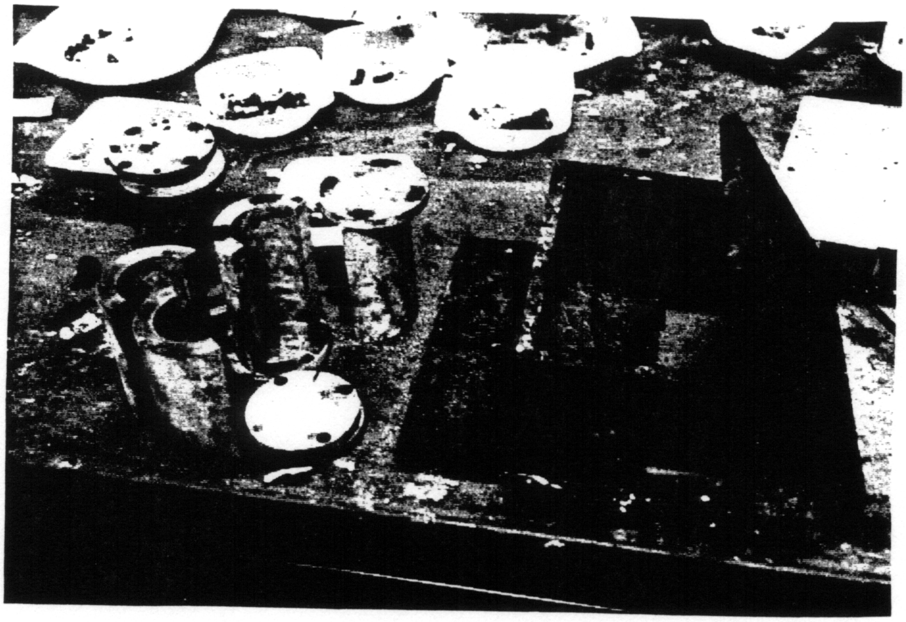

Photo 7. The molds for testing of bottom ash matrix are closed on all surfaces.

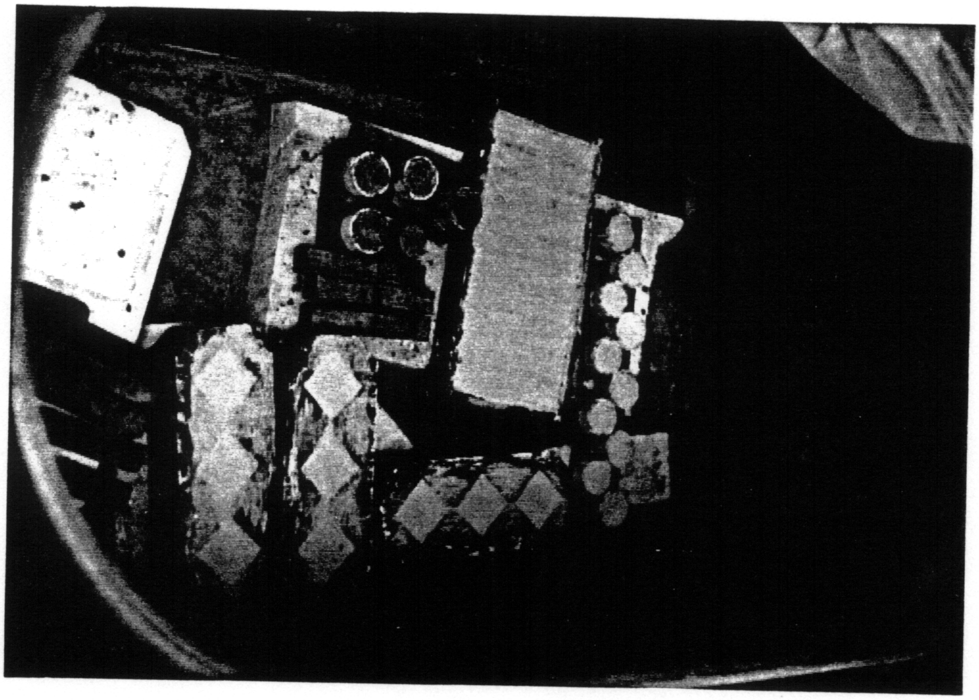

Photo 8. Samples are kept in a wet environment prior to placement in curing room.

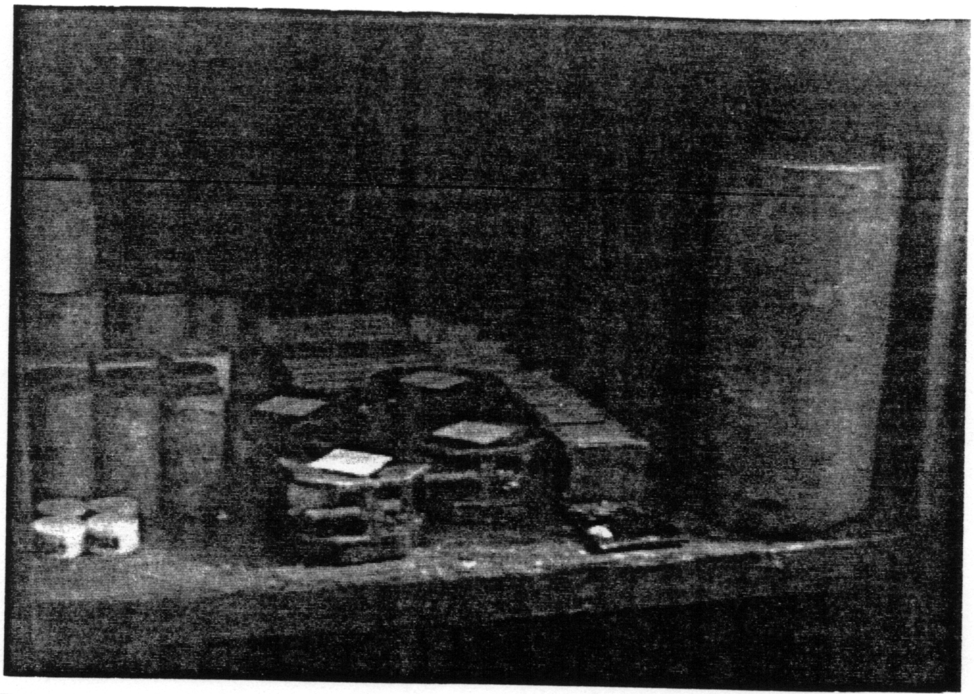

Photo 9. The internal release samples are put in the curing room.

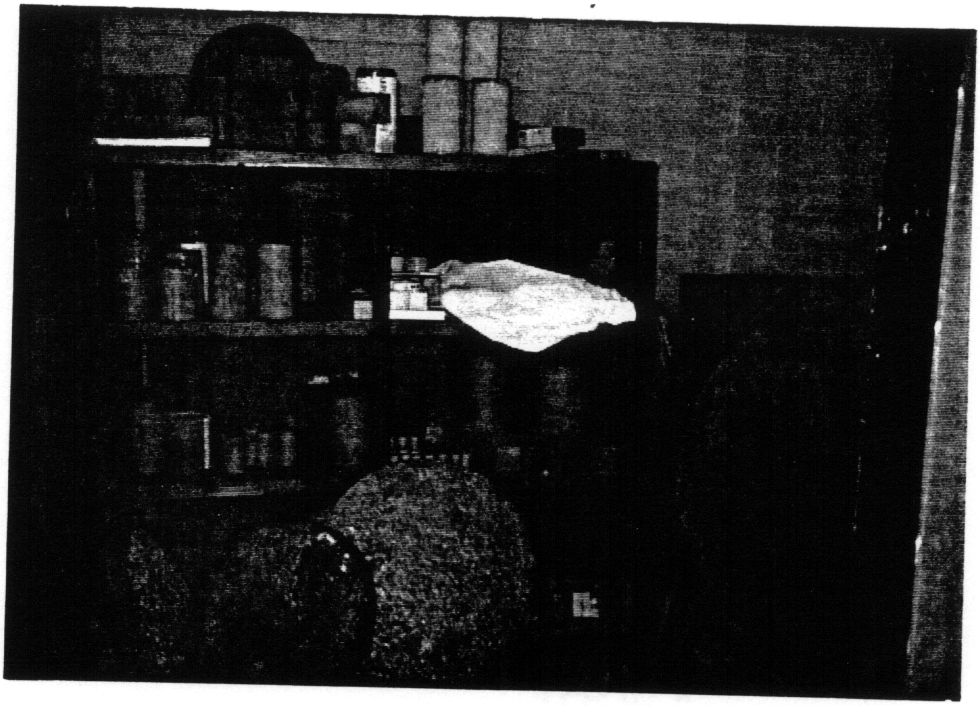

Photo 10. The samples are placed in this curing room which meets ASTM standards.

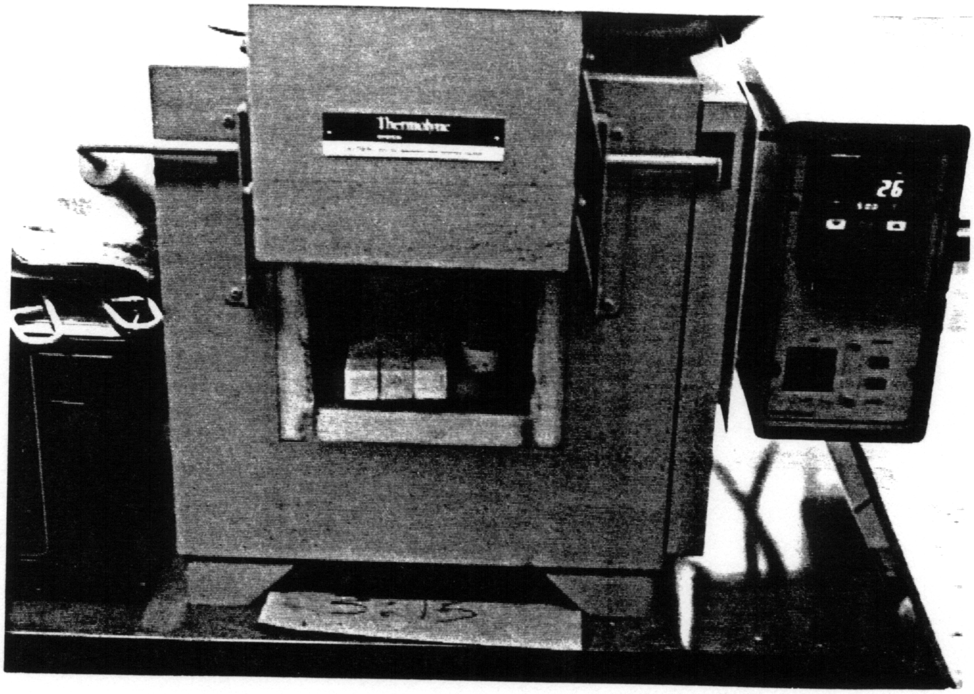

Photo 11. Some of the samples are heat treated in a furnace to melt the wax and release the chemical.

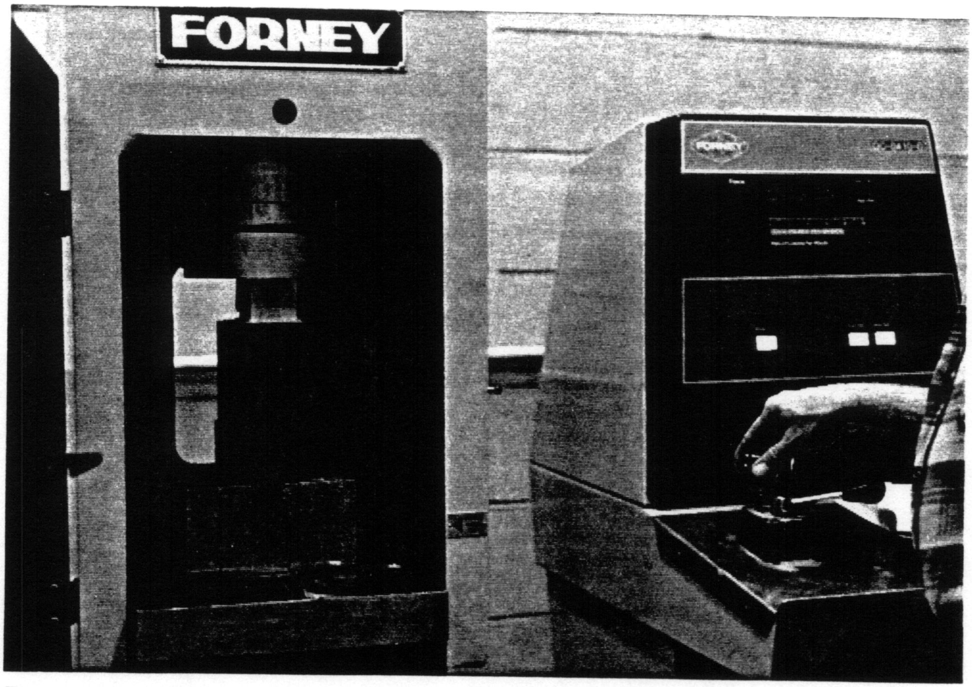

Photo 12. The sample is being tested for compressive strength.

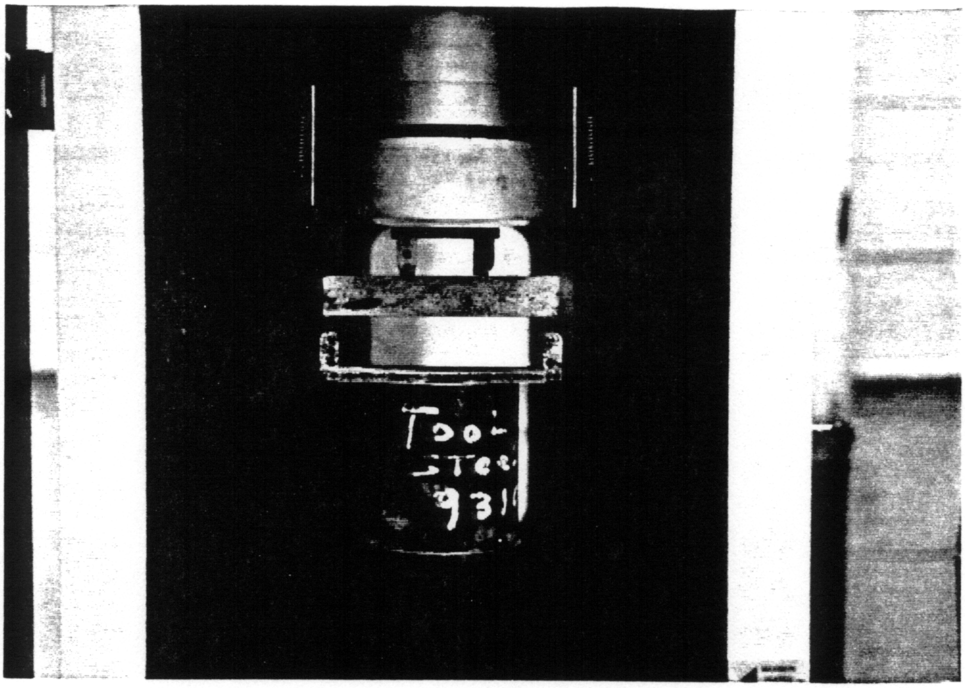

Photo 13. The sample is being tested for strength in flexure.

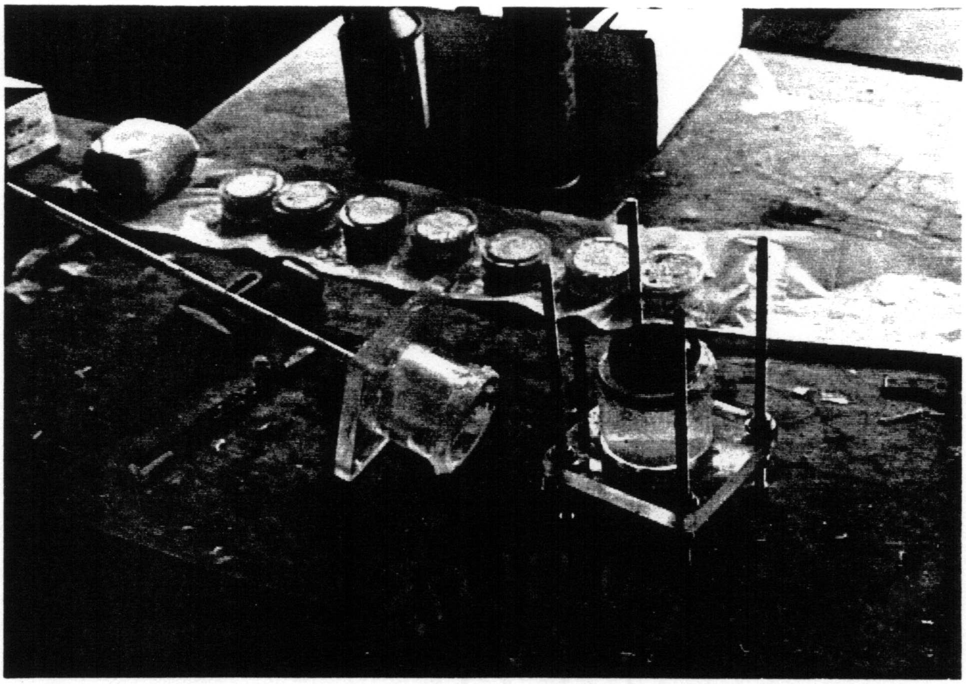

Photo 14. The gravity flow permeability apparatus is being set up.

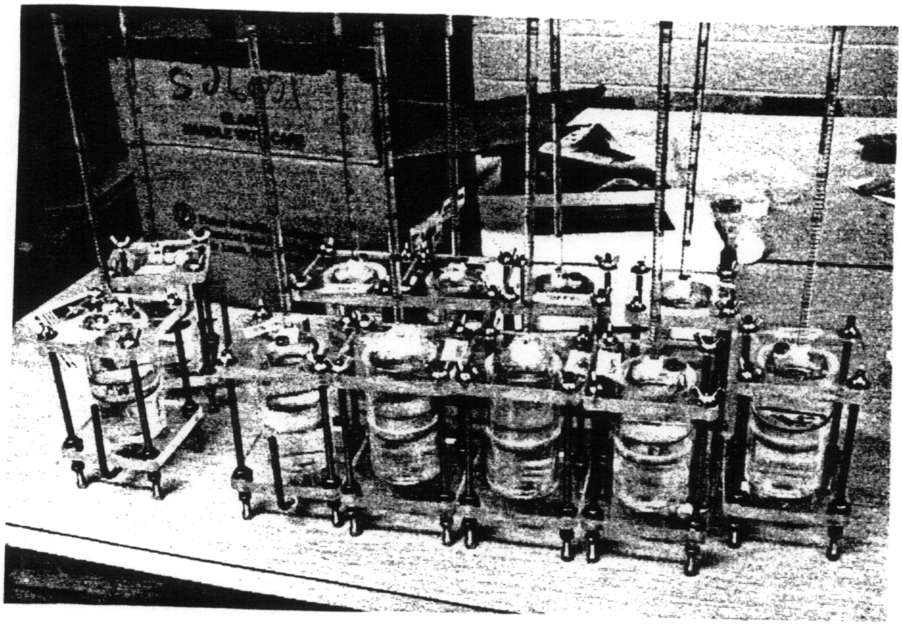

Photo 15. This permeability test equipment is used for the gravity flow test.

Photo 16. Samples are tested for freeze/thaw damage in the Logan machine.

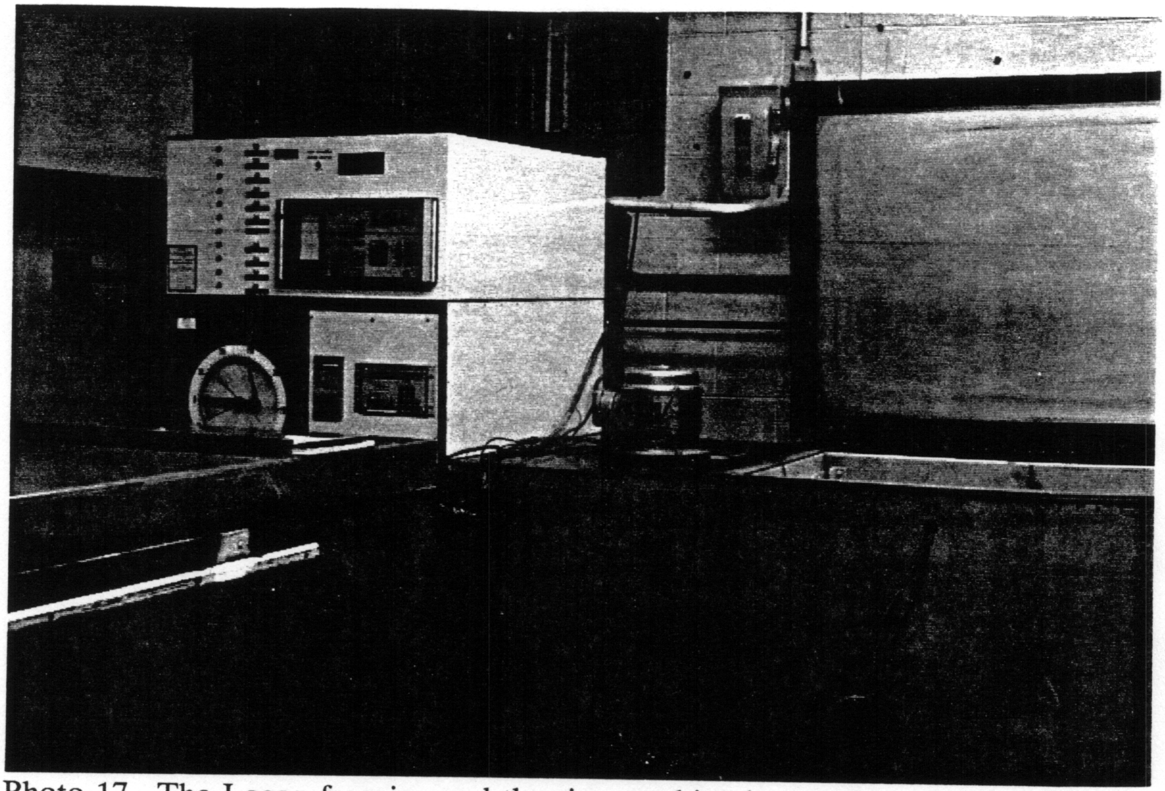

Photo 17. The Logan freezing and thawing machine is used for tests in which samples are cycled 300 times to fulfill ASTM test C666.

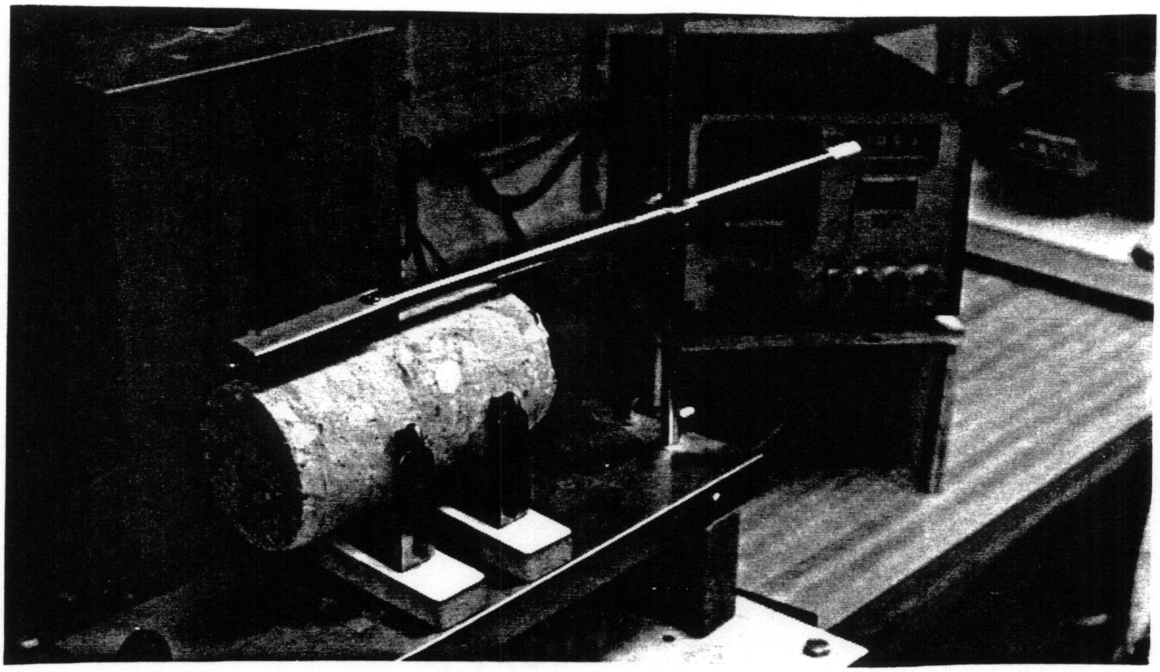

Photo 18. The freeze/thaw samples are tested for damage in dynamic modulus of elasticity in a sonic apparatus.

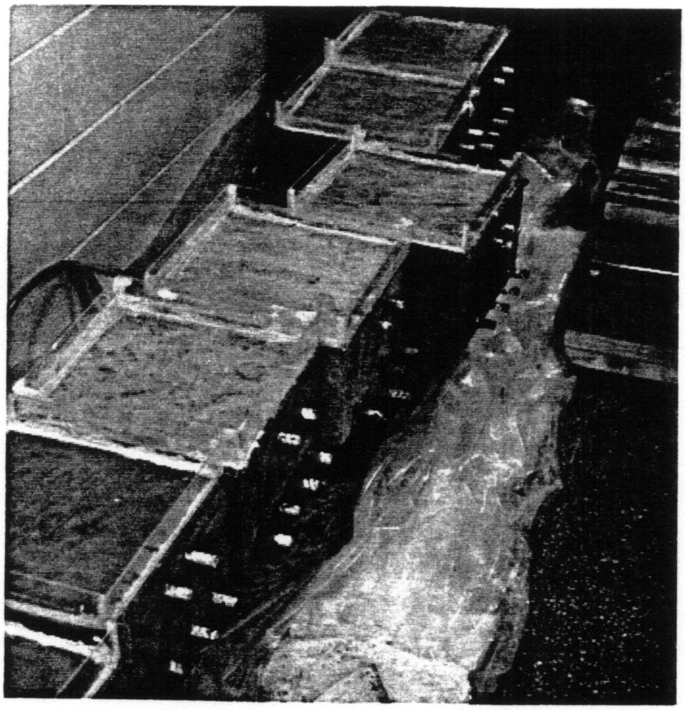

Photo 19. The test specimens are tested for corrosion and chloride ion intrusion (these long-term tests are ongoing).

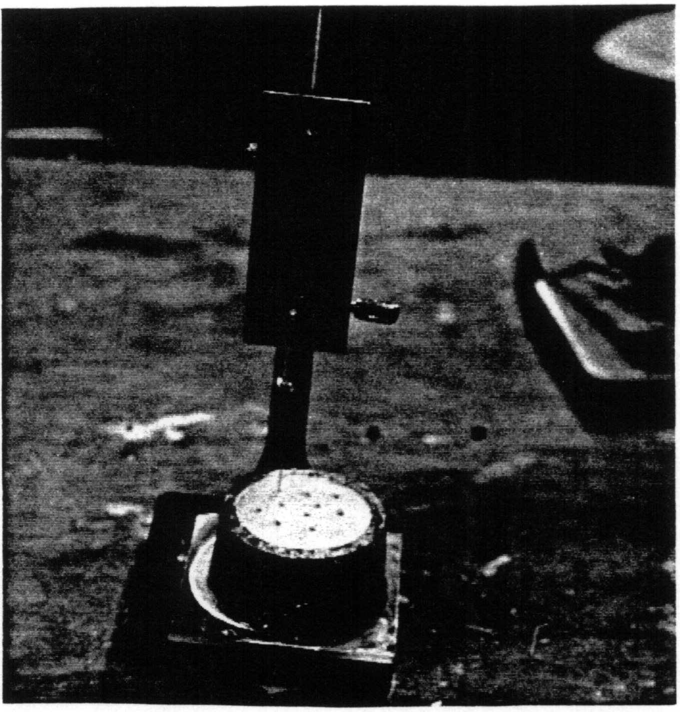

Photo 20. Set time experiments are done with a Vicat needle.

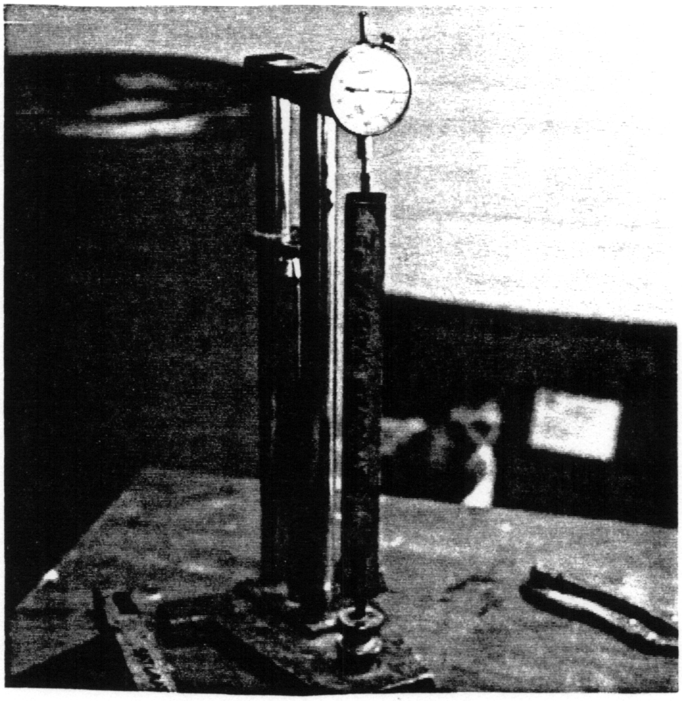

Photo 21. Shrinkage tests are performed using a comparator.

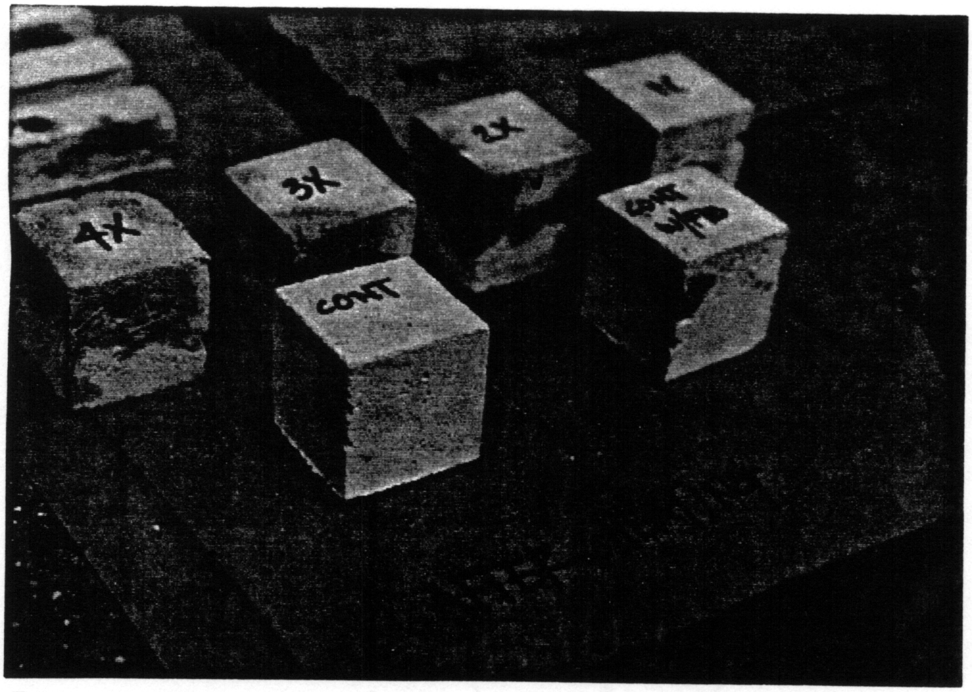

Photo 22. Release of red dyed chemical from fibers into white cement matrix allows visual inspection.

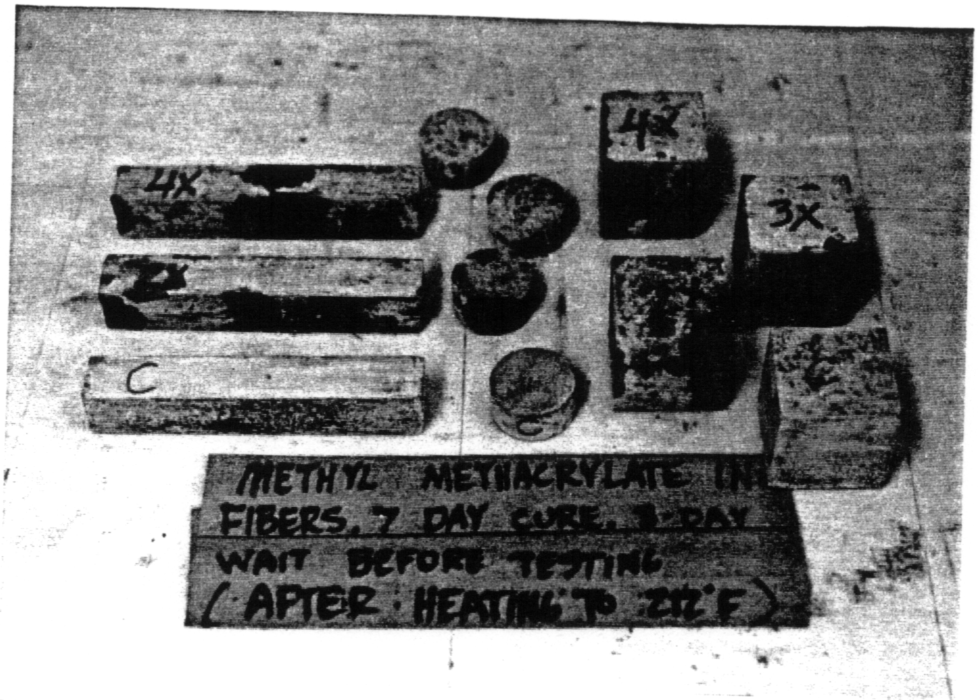

Photo 23. Samples show external amount of methyl methacrylate and wax released from inside portland cement that migrated to surfaces during, 7 day cure, 3-day wait--after heating to 212° F.

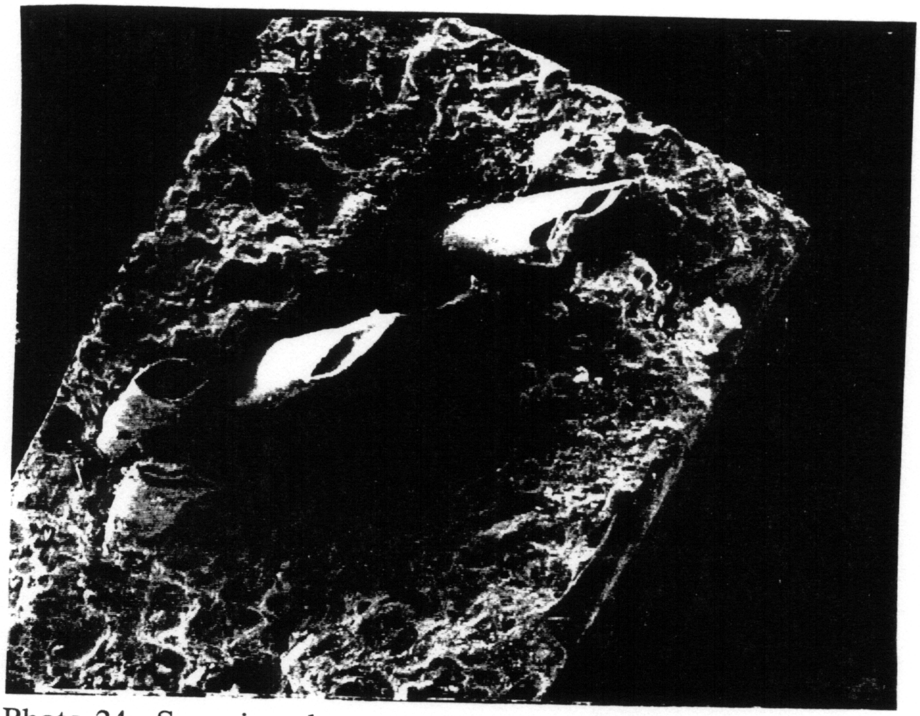

Photo 24. Scanning electron microscope photograph shows the area around a fiber into which chemical was released.

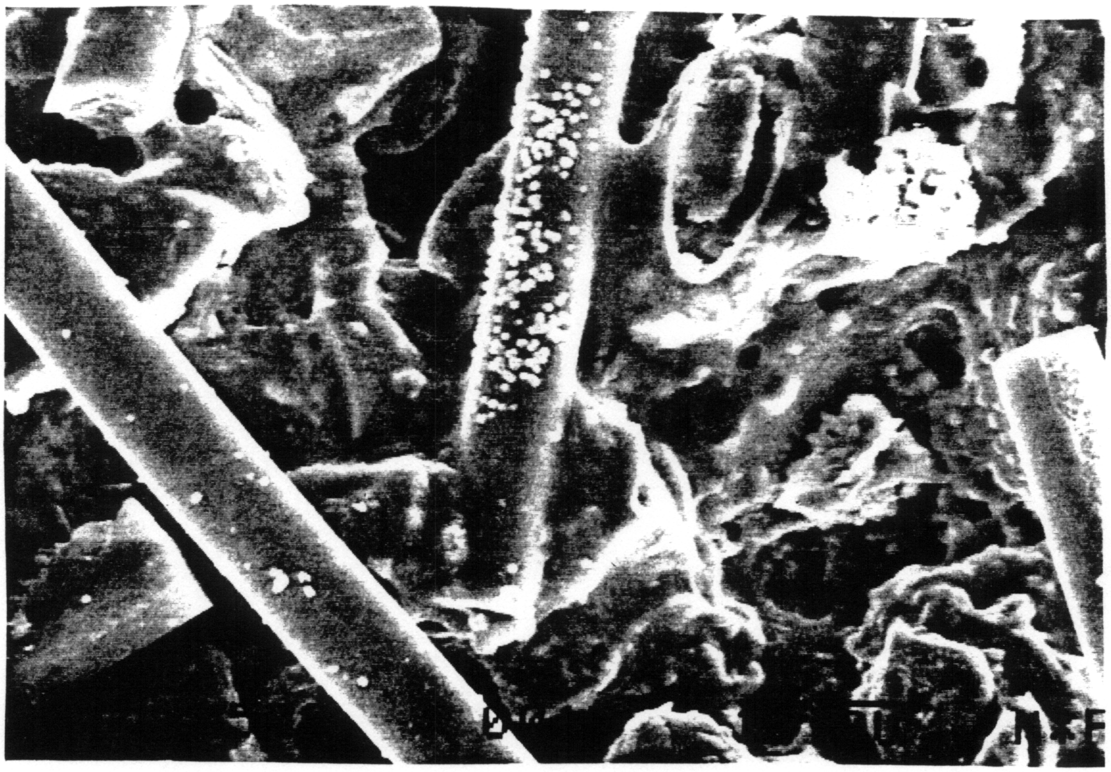

Photo 25. Scanning electron microscope photograph shows porous fibers releasing their chemical.

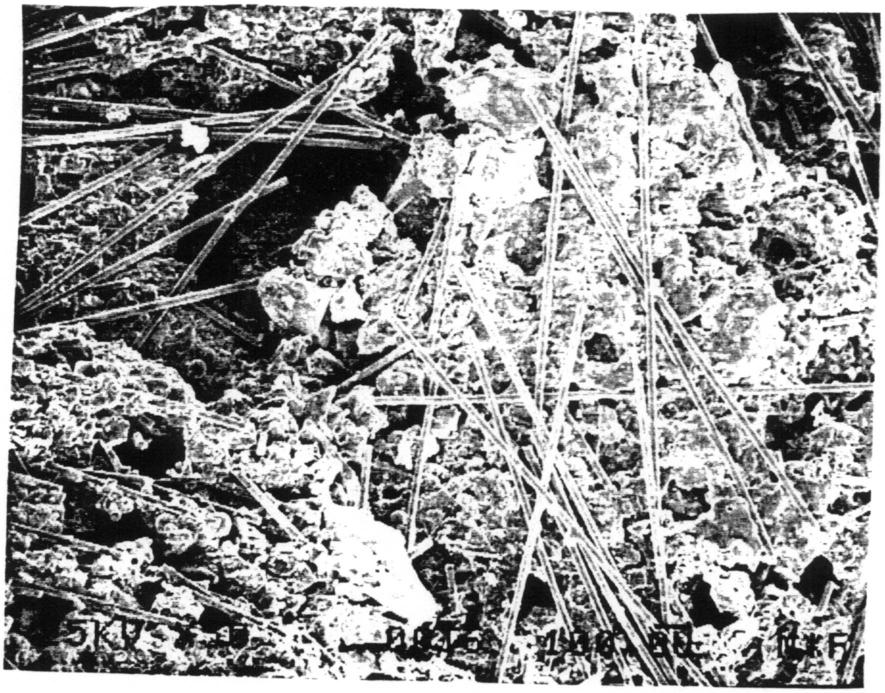

Photo 26. Scanning electronic miscroscope photo shows sintered phosphate bonded bottom ash material with fibers.

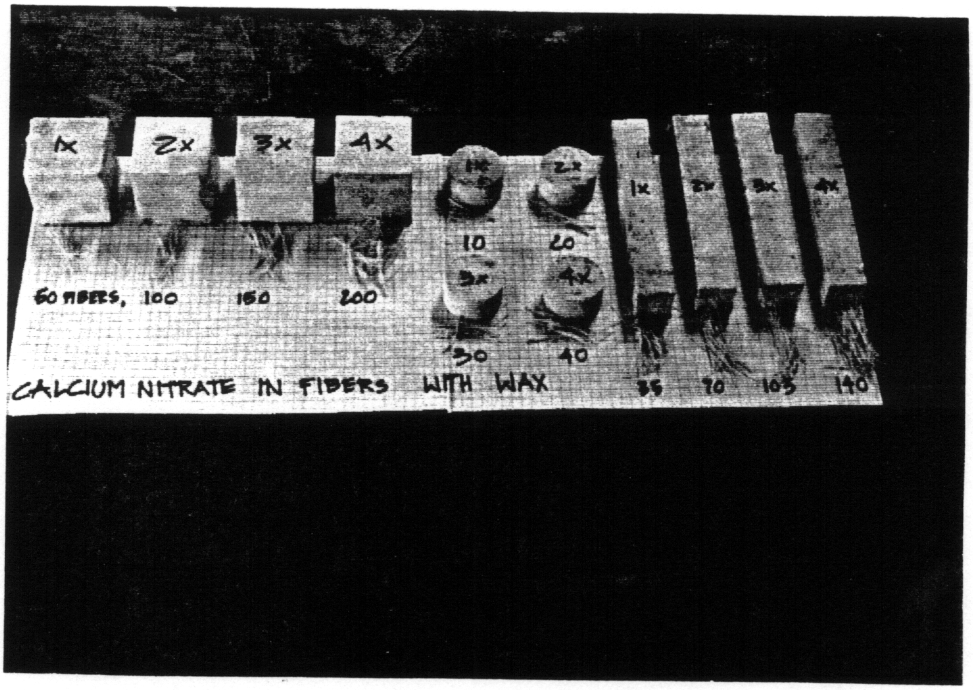

Photo 27. This is the volume of fibers used in samples containing calcium nitrite or methyl methacrylate in polypropylene fibers.

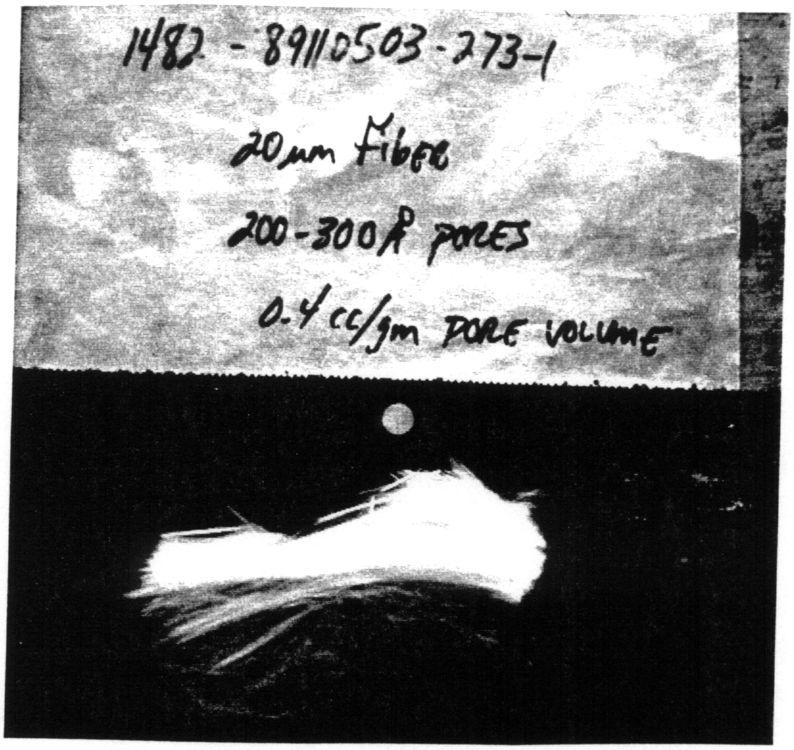

Photo 28. This is a full-scale picture of hollow porous fiberglass fibers used.

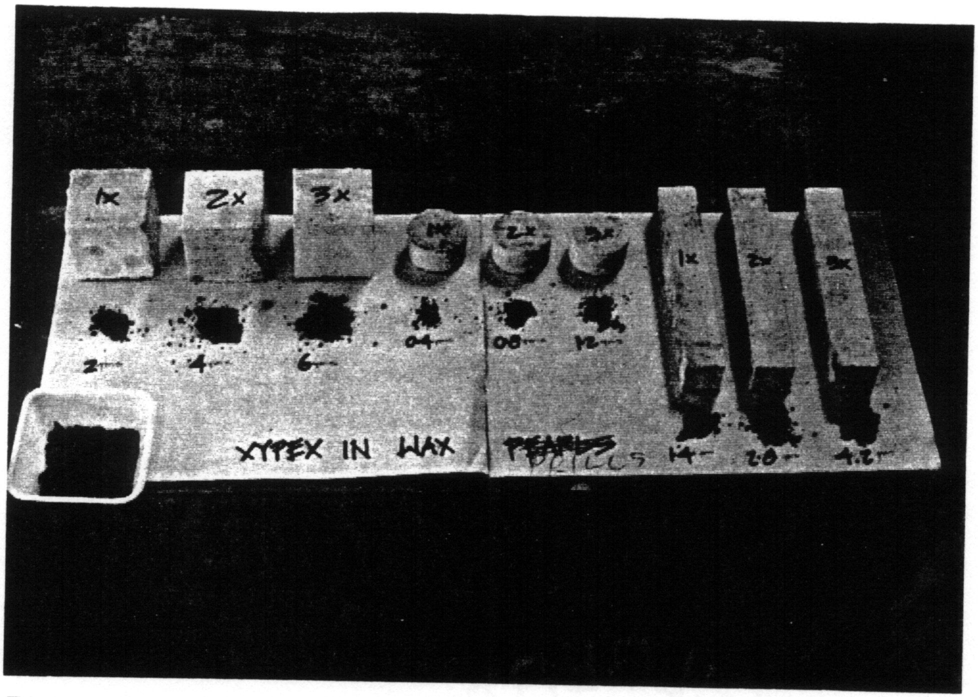

Photo 29. This is the volume of Xypex/wax prills used in samples.

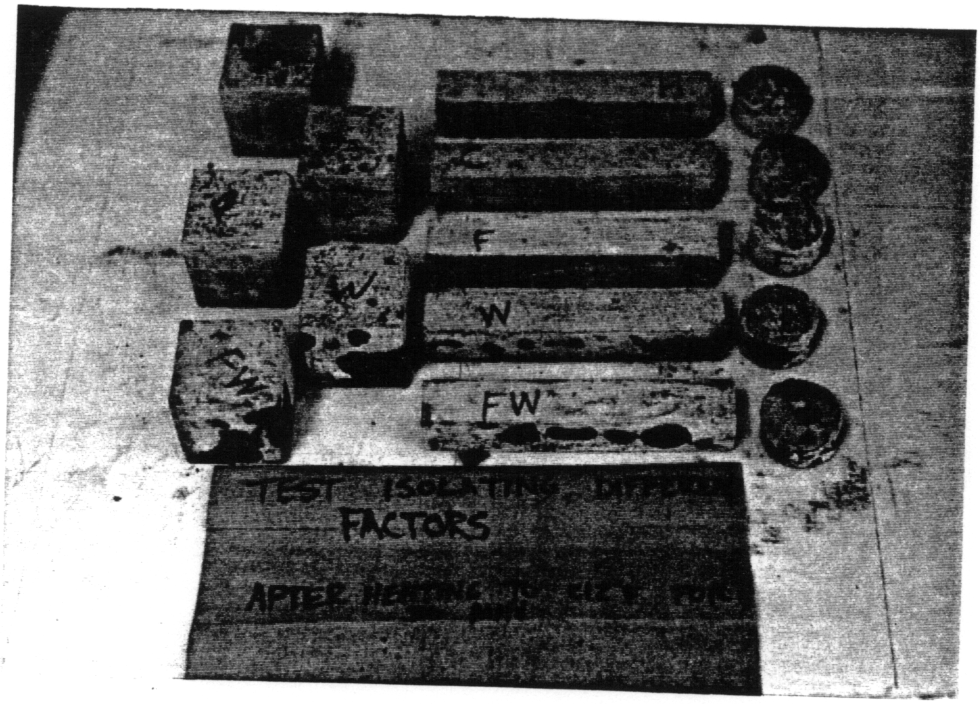

Photo 30. These are samples in which various factors as wax/chemical/fibers were isolated in portland cement, cured for 3 days, heated to 212° F.

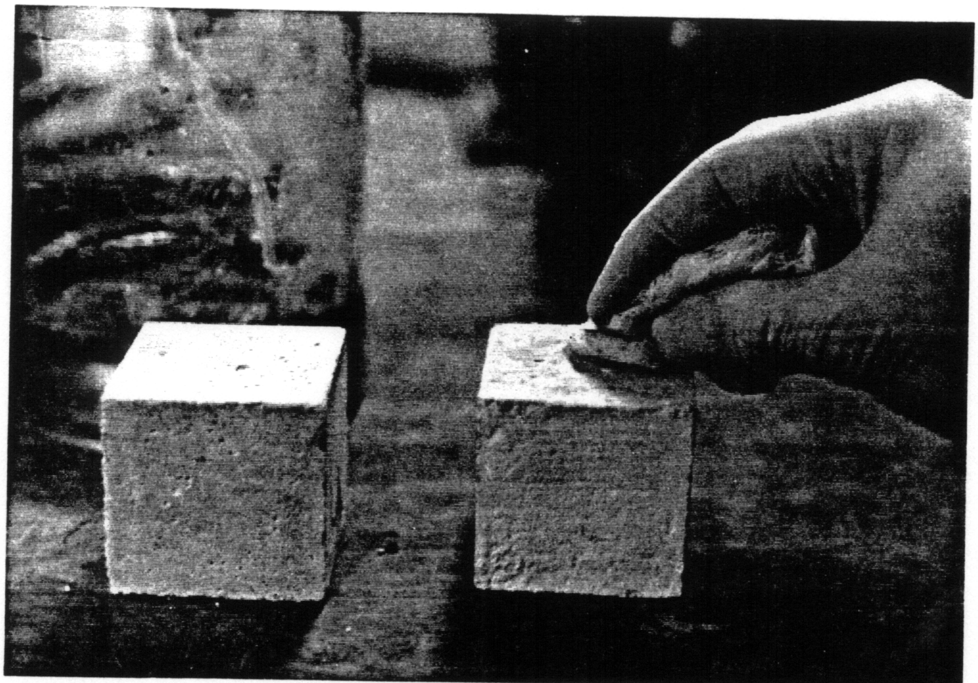

Photo 31. These are samples showing methyl methacrylate on top surface to simulate conventional application method.

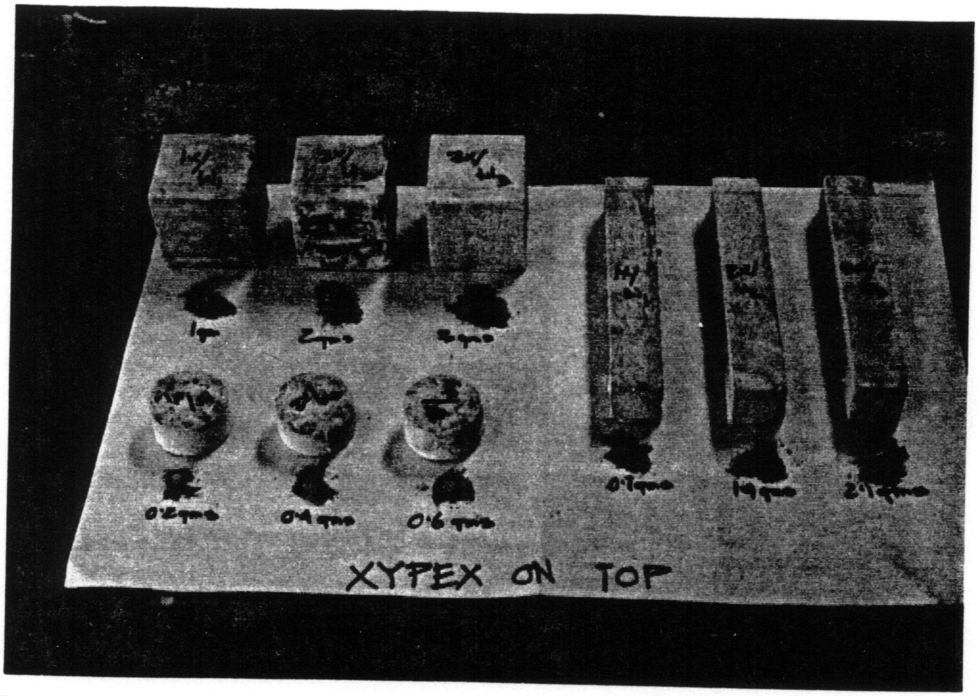

Photo 32. These are samples showing Xypex being put on top of samples to simulate conventional top surface application method.

Photo 33. Storage tests were used to determine long-term effects of storing filled fibers. Here, they are stored in a refrigerated environment.

Photo 34. Insulation bed was used in which samples are placed--heating on the top exposed surface only.

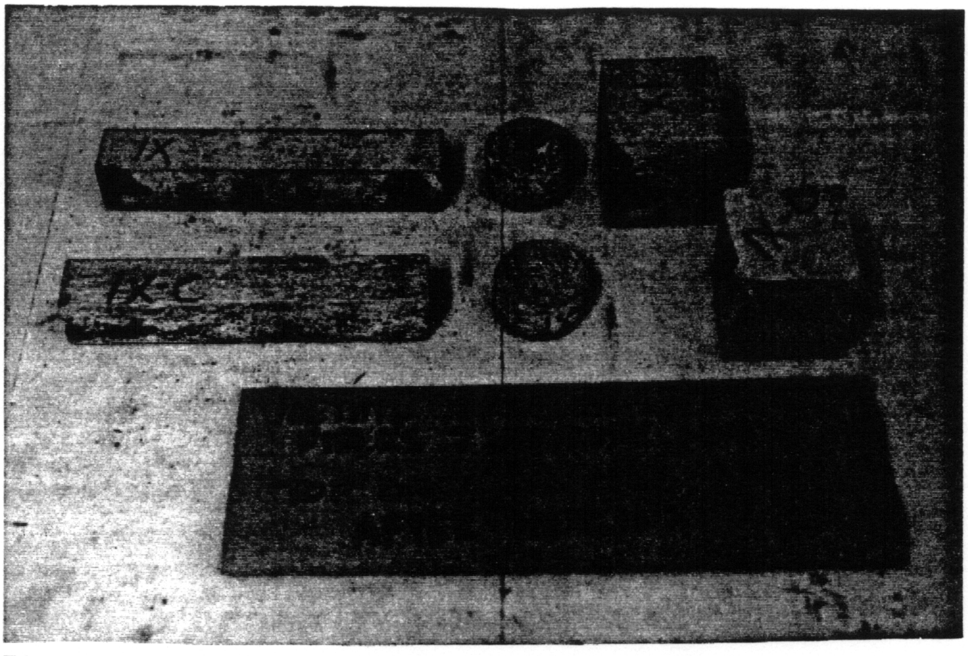

Photo 35. These are portland cement samples containing methyl methacrylate in which only the top surface is exposed to heat of 212° F. The other surfaces are buried in insulation.

VITA

CAROLYN MINETTA DRY
Birthdate: February 22, 1942
1605 Parkhaven Dr., Champaign, IL 61821

EDUCATION

PhD in Environmental Design and Planning	Virginia Polytechnic Institute and State University	1991
Master of Architecture	Texas A & M University	1976
Bachelor of Architecture (with distinction)	University of Minnesota	1970
Architecture, Graduate School of Fine Arts	University of Pennsylvania	1968
Architecture	Rhode Island School of Design	1965
Fine Arts and Art History	Columbia University	1964
Bachelor of Arts (in Philosophy)	Carleton College	1964

REGISTRATION

Architectural Registration	Texas, USA	1974

HONORS ACADEMIC/PROFESSIONAL

Oak Ridge National Lab, Metals & Ceramics Div.	University Fellow	Summer 1987
	Nominted for excellence in teaching award by students	1987
NASA	Faculty Fellow	Summer 1984
	Faculty Fellow	Summer 1983
University of Illinois Urbana-Champaign, IL	Listed as teacher who is excellent by students	1983
NEA	Faculty Fellow	Summer 1980

TEACHING

1987-90	Associate Professor	University of Illinois

PROFESSIONAL EXPERIENCE

1980 - Present	Natural Process Design, Inc.	Owner and President
1973 - 1974	Daytons, Inc. Minneapolis, Mn.	Design
1973	Voight and Foure St. Paul, Mn.	Design facilities for elderly and handicapped
1970 - 1972	Ellerbee Architects, Inc. St. Paul, Mn.	Design and working drawings for medical facilities
1970	Thorsen and Thorshov, Architects	

FUNDED RESEARCH PROJECTS

"Advanced Ceramics for Building Construction," 1987-90, Advanced Construction Technology Center.

"Internal Release in Concrete of Sealant Materials from Fibers," 1989-90, University of Illinois Research Board.

"Revitalization of East St. Louis, Phase 2, 1990, State of Illinois.

"Research Survey/Analysis of Structural Sandwich Wall Panels," 1989, CERL, U.S. Army.

"Technology Adoption--Survey of Industry, Government, and Vendors," 1989, CERL, U.S. Army.

"Revitalization of East St. Louis, Phase 1," 1988-1989, State of Illinois.

"Electromagnetic Pulse Shielding Attributes of Low-cost Cements Containing Various Additive Materials," 1987-1989, CERL, U.S. Army.

"Use of Delayed Release of Water from Capsules into Gypsum," 1988, CERL, U.S. Army.

"Designs for Robotic Environments," 1987, Transitions Research Co.

"Adoption of Innovative Advanced Materials for U.S. Army Purposes," 1987, CERL, U.S. Army.

"New Materials As Composites in Building Systems for Army Use," 1987, CERL, U.S. Army.

FUNDED RESEARCH PROJECTS (cont'd)

"Radiant Barriers in Hollow concrete Blocks," 1985-86, National Concrete Masonry Association.

"Building with Enhanced Indigenous Low-cost Materials in Tropical and Desert Climates," 1985-86, CERL, U.S. Army.

PUBLICATIONS

ALTERATION OF MATRIX PERMEABILITY, PORE OR CRACK STRUCTURE BY THE TIME RELEASE OF INTERNAL CHEMICALS, Carolyn Dry, Conference on Advances in Cementitious Materials, American Ceramic Society, Inc., co-sponsored by National Institute of Standards and Technology, Gaithersburg, MD., July 23-26, 1990.

PHOSPHATE BONDED AND SINTERED FLY ASH AND BOTTOM ASH FOR LIGHTWEIGHT CONSTRUCTION PANELS (abstract only), Carolyn Dry, American Ceramic Society Annual Conference, Dallas, Tx., April 22-26, 1990.

BUILDING MATERIALS WHICH EVOLVE AND ADAPT OVER TIME; USE OF ENCAPSULATION TECHNOLOGY AND DELAYED REACTIONS, Carolyn Dry, International Council for Building Research, Studies and Documentation (CIB), Conference, Paris, France, June 19-23, 1989.

PHOSPHATE CEMENT STRUCTURAL PANELS USING INDUSTRIAL WASTE (abstract only), Carolyn Dry, American Ceramics Society Annual Conference, Indianapolis, Indiana, April 1989.

BUILDING MATERIALS, WHICH EVOLVE AND ADAPT OVER TIME--USE OF ENCAPSULATION TECHNOLOGY AND DELAYED REACTIONS, Carolyn Dry, proceedings of the 1st International Architectural Research Centers Consortium Conference/ARCC '88, Urbana-Champaign, IL, November 13-15, 1988.

SUMMARY OF MATERIALS RESEARCH, Carolyn Dry, Architectural Research Centers Consortium (ARCC) Conference, November 13-15, 1988.

THE ORGANIZATION OF ACADEMIC BUILDING RESEARCH, Carolyn Dry, International Council for Building Research, Studies and Documentation (CIB), Bartlett School of Architecture & Planning, London, England, Oct. 26-28, 1988.

CHANGEABLE PROPERTIES OF THE BUILDING ENVELOPE--ADAPTABILITY TO CHANGING PERFORMANCE REQUIREMENTS, C. Dry, B. Givoni, W. Kroner, Proceedings of the International Congress on Building Energy Management, Lucerne, Switzerland, September 28 - October 2, 1987.

PUBLICATIONS: REFEREED (cont'd)

THE IMPACT OF DOMESTIC BUILDING INNOVATION, (ESPECIALLY HOUSING) ON INTÊRNATIONAL COMPETITIVENESS; THE ROLES OF RESEARCH CENTERS IN THE U.S. AND CHINA, Tonghi University, China, 1987.

GLASS AS A BUILDING MATERIAL FOR STRUCTURES IN SPACE, ESPECIALLY IN-SITU BLOWN GLASS, C.M. Dry, Symposium '86, the Maglev and Lunar Development Symposium, Symposium Proceedings, Atlantic City, N.J., September 1986.

BUILDING WITH ENHANCED INDIGENOUS MATERIALS, C. M. Dry, International Council for Building Research Studies and Documentation, 10th CIB 86 Congress--Advancing Building Technology, Congress Proceedings, Washington, D. C., September 1986.

THE DESIGN OF AN EXPERT SYSTEM FOR ENERGY-EFFICIENT DESIGN OF BUILDINGS, C. M. Dry, International Council for Building Research Studies Documentation, 10th CIB 86 Congress--Advancing Building Technology, Congress proceedings, Washington, D.C., September 1986.

RESEARCH REPORTS DONE FOR FUNDING AGENCY:

RESEARCH SURVEY/ANALYSIS OF STRUCTURAL SANDWICH WALL PANELS, Carolyn Dry, Construction Engineering Research Laboratory (CERL), U.S. Army, 1989.

TECHNOLOGY ADOPTION--SURVEY OF GOVERNMENT AGENCIES, FACILITIES, INDUSTRY FACILITIES, AND VENDORS, Carolyn Dry, Construction Engineering Research Laboratory (CERL), U.S. Army, 1989.

ELECTROMAGNETIC PULSE SHIELDING ATTRIBUTES OF LOW-COST CEMENTS CONTAINING VARIOUS ADDITIVE MATERIALS, Carolyn Dry, Construction Engineering Research Laboratory (CERL), U.S. Army, 1988-89.

USE OF DELAYED RELEASE OF WATER FROM CAPSULES INTO GYPSUM, Carolyn Dry, Construction Engineering Research Laboratory (CERL), U.S. Army, 1988.

PROVIDE ESTABLISHMENT OF BASELINE KNOWLEDGE REGARDING ADOPTION OF NEW TECHNOLOGIES, Carolyn Dry, Construction Engineering Research Laboratory (CERL), U.S. Army, 1988.

RESEARCH REPORTS DONE FOR FUNDING AGENCY: (cont'd)

REVIEW OF TECHNOLOGY ADOPTION INDEX FOR THE ARMY, Carolyn Dry, Georgia Institute of Technology, 1988.

NEW MATERIALS COMPOSITES AND BUILDING SYSTEMS FOR ARMY USE, Carolyn Dry, Construction Engineering Research Laboratory (CERL), U. S. Army, 1987.

DESIGNS OF ROBOTIC ENVIRONMENTS, Carolyn Dry, Transitions Research Company, 1987.

PROFESSIONAL AFFILIATIONS

Architecture Research Centers Consortium (ARCC).
International Council for Building Research and Documentation (CIB).
Advanced Construction Technology Center (ACTC).

PROFESSIONAL COMMITTEES

National:

Head of International Council for Building Research and Documentation (CIB) Committee W89 on Education and Research.
Organizing meeting on CIB Education and Research for Moscow '91 conference.
President, Architectural Research Centers Consortium, 2 terms, December 1988 - Present, (elected twice).
Architecture Research Center Consortium, Executive Board Member, 1988 - Present.
Chairperson, Architectural Research Centers Consortium, membership drive, 1990.
Co-chairperson of Long-term Planning Committee, Architectural Research Centers Consortium, 1989-90.
Chairperson of the Materials Research Network, Architectural Research Centers Consortium, 1989 - Present.
Directed Architecture Research Centers Consortium (ARCC) '89 Conference, Radisson Park Terrace Hotel, Washington, D.C., November 19-21, 1989.
Member of PhD Committee and of the Architectural Research Centers Consortium, 1988 - 1989.
Coordinated and hosted International Conference on Architecture Research/ARCC '88, Architecture School, University of Illinois, Champaign-Urbana, Illinois, November 1988.
Chairperson of International Council for Building Research and Documentation (CIB) '89 Conference W89 Committee, workshop coordinator, "Research in Academic Settings," Paris, France, 1989.
Chairperson of working group on "Local Technologies," Council on Tall Buildings, 1986.
U.S. Editor of Architecture and Design, New Delhi, India, 1986 - 1987.
Invited reviewer, sponsored research, Space Station Human Factors Project, NASA AMES, 1986.

State:

Project Investigator--Organized and coordinated service and research project on East St. Louis consisting of approximately 18 students and 6 faculty participating. Also lobbied for ongoing legislative funding for that effort and obtained it, 1989 - 1991.

UNIVERSITY COMMITTEES

School:

ARCC Representative, University of Illinois, 1987-91.
Committee on PhD, 1989-91.
Search Committee, 1988-91.
Chair, Committee on Research, School of Architecture, University of Illinois, 1987-89.
Coordinating efforts on design of East St. Louis project, 1987-1990.
Obtained funding for 26 graduate research assistants, 1 student fellowship.

Carolyn Minnetta Day