**DEVELOPMENT OF HIGH TEMPERATURE, CORROSION RESISTANT POLYMER
CONCRETE FOR USE IN THE STEAM DISTRIBUTION SYSTEM OF THE
CONSOLIDATED EDISON COMPANY OF NEW YORK - FINAL REPORT**

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ABSTRACT

The results of a research program conducted by Brookhaven National Laboratory (BNL) to evaluate and develop polymer concrete (PC) materials, which can be used as an alternative material of construction to conventional steel-reinforced portland cement concrete (PCC) within the steam distribution system of Consolidated Edison Company of New York (Con Ed), are presented. Three fiber-reinforced PC systems were identified and evaluated in a series of laboratory and in situ field tests. Based upon the results of these tests preliminary design studies were performed by BNL and the Con Ed Civil Design Division to determine the necessary floor slab, wall and roof thicknesses required to replace a typical steel reinforced PCC manhole with a fiber-reinforced PC manhole.

EXECUTIVE SUMMARY

The Consolidated Edison Company of New York (Con Ed) operates and maintains a large steam distribution system under the streets of New York City. Over the years several materials related-problems have been encountered with the steel-reinforced portland cement concrete (PCC) manholes used to house the system's valves and fittings. The high ambient temperature and humidity within the manholes create an environment which eventually leads to the corrosion of the reinforcing steel in the concrete. The by-products of the corrosion process increase the volume of the reinforcing steel, creating tensile stresses in the surrounding concrete. As these stresses exceed the tensile strength of the concrete, cracks develop in the concrete which eventually lead to delaminations and/or spalls in the concrete. In addition, condensate leaking from the valves and/or piping system attacks the cement matrix of the concrete which weakens the surface of the concrete thereby making it susceptible to further deterioration. Consequently, many of the manholes in the system are severely deteriorated and need to be replaced.

The manholes are presently being rebuilt using conventional PCC. Since the manholes are located beneath the streets and sidewalks, there is a great emphasis to minimize the time involved in rebuilding the manhole to prevent excessive disruption of traffic. As a result, the manholes are often cast around existing steam mains and are then immediately placed into service. The concrete is therefore only a few days old when it is subjected to the harsh environment of the manholes. In addition, by placing the manhole into service so quickly the concrete is not allowed to fully develop the strength and physical characteristics that it normally would obtain under ideal curing conditions. This can result in the development of a substandard quality of concrete. The combination of quickly casting and placing the new PCC manhole into service and the severe operating conditions to which the manholes are exposed has resulted in a shorter than desired service life.

With the development in recent years of more advanced materials of construction, such as polymer concrete (PC), it may be possible to cast manholes that have a longer service life resulting from the improved physical and mechanical properties of these materials.

The Process Materials Group of the Energy Efficiency and Conservation Division, Department of Applied Science at Brookhaven National Laboratory (BNL), Upton, NY has developed numerous PC formulations that display a wide range of physical and mechanical properties. Some of these materials are currently being used in

commercial applications while others are still undergoing development and evaluation. Based on this experience BNL carried out a program for Con Ed entitled "Development of High Temperature, Corrosion Resistant Polymer Concrete for Use in the Steam Distribution System of the Consolidated Edison Company of New York." The results of this program are described in this report.

The primary objective of the program was to develop a PC system suitable for use as a construction material for steam-valve manholes. Alternate methods of construction would be investigated and the PC formulations would be tailored to meet the needs of the different construction technologies under consideration. During the laboratory-phase of the program a private contractor familiar with the field application of PC systems would be consulted to ensure that the systems under development were adaptable to field installations.

The original program plan called for the development of a PC system which could be used to (a) make precast panels or (b) fabricate cast-in-place manholes. The precast panels would be used as protective stay-in-place forms against which conventional PCC could be cast or they would be used to replace the PCC in its entirety.

The exposure conditions within a typical steam-valve manhole required that any PC system being considered for use exhibit the following characteristics: (a) it should be thermally stable at temperatures up to 275°F, (b) it should have good strength and stiffness at temperatures up to 275°F, (c) it should be impermeable to moisture penetration, and (d) it should have good resistance to possible chemical attack.

Evaluation of the candidate systems would be based upon the results of tests done to determine the physical and mechanical properties over a temperature range of 40° to 275°F. Properties to be evaluated included: water absorption, shrinkage, compressive strength, flexure strength, tensile strength, and thermal coefficient of expansion. The tests would primarily be done under laboratory conditions. Based upon the results of these tests one or more PC systems would be selected for full-scale evaluation in the field. This work would be done in Phase Two and was beyond the scope of work for this phase of the program.

Before starting the laboratory test program a survey was performed to verify the range of ambient air temperatures typically encountered within the steam-valve manholes. Seven operating manholes were selected at random and surveyed by Con Ed personnel. The results indicated that air temperatures within the manholes varied between 214° and 349°F and averaged 297°F. In addition, it was determined that the temperature of the steam within a steam main is $\approx$ 380°F. Based upon this information, Con Ed asked that the design service temperature of the PC systems be raised from the

originally specified value of 275° to a value of 400°F. This would ensure that the PC systems were thermally compatible with the range of temperatures found within the steam-valve manholes and it would also ensure that the PC systems would not thermally degrade in the event of a steam main rupture.

The scope of work for the program was revised to reflect the fact that the design service temperature was raised to 400°F. In addition, it was expanded to include small-scale field testing of the candidate PC systems. These tests were added in order to determine the effects of exposure to actual field conditions on the physical and mechanical properties of PC and PCC systems.

To meet the objectives of the program four tasks were developed to serve as guidelines. They were:

- A. Identification and evaluation of candidate PC systems.
- B. Laboratory-scale evaluation.
- C. Field evaluation.
- D. Preliminary design of a typical steam-valve manhole.

The results of the work performed in these tasks are summarized below.

In Task A three PC systems were developed and evaluated. Each system consisted of four components: a polymer binder system, a blended fine aggregate system, a graded coarse aggregate system, and a fiber reinforcement. The fiber reinforcement was added to the PC mix design to improve the strength and ductility of the systems. The primary difference between each system was the monomer/resin system used as the binder. Three binder systems were evaluated: (1) a styrene-trimethylolpropane trimethacrylate (TMPTMA) [ST]-based monomer system, (2) a vinyl ester-TMPTMA [VET]-based monomer system, and (3) a phenol formaldehyde [PF] resin system.

One and one-half inch long corrugated, carbon steel fibers were initially selected for use as the reinforcing system. Synthetic fibers, such as graphite and Kevlar aramid fibers, also were evaluated, but the carbon steel fibers were found to provide the best load carrying capacity and ductility. Stainless steel fibers were later evaluated when results of the in situ field tests indicated that corrosion of some of the carbon steel fibers exposed at the surface of the samples was causing some of the PC systems to deteriorate.

Preliminary evaluation of the three candidate systems (Task B) was based upon the results of a series of laboratory-scale tests designed to (a) determine the physical and mechanical properties of each system over a temperature range of 72° to 400°F and (b) determine if exposure to simulated field conditions adversely affected these properties.

The results of the laboratory-scale tests indicated that the strength properties of each system decreased with increasing temperature. The strength reductions were due to a softening of the polymer binder systems, and not to any physical deterioration of the PC systems. Compressive strengths for the three systems generally varied between 12,220 and 14,270 psi at 72°F and between 4,730 and 9,415 psi at 400°F. The flexural yield strength generally varied between 2,145 and 2,865 psi at 72°F and 930 and 1,440 psi at 400°F. The highest strength values were exhibited by the VET PC system. By comparison, fiber-reinforced portland cement concrete, which had been cast and cured at room temperature conditions, was found to have a compressive strength of 5115 psi and a flexure strength of 960 psi at 72°F.

Results of small-scale, short-term, load-deflection tests indicated that the VET PC system was the most rigid system and the ST PC system the most flexible. The test results also indicated that each of the three systems would creep at room temperature conditions under a sustained load.

The coefficients of thermal expansion for the PC systems were found to vary between 6.2 and 10.2×10^{-6} in./in./°F over a temperature range of 75° to 425°F. The coefficient of thermal expansion for conventional PCC normally varies between 4.0 and 7.0×10^{-6} in./in./°F and has an average value of 5.5×10^{-6} in./in./°F. The coefficients for each system varied slightly depending upon the binder and also tended to vary with temperature, generally increasing slightly with increases in temperature. The coefficients of thermal conductivity for the PC systems were found to be within the range of values associated with conventional PCC, i.e. they varied between 0.8 and 2.1 BTU/hr/ft/°F. Thermal conductivity values were found to vary with the type of binder and with temperature.

Water absorption values for the PC systems were found to be significantly less than those of conventional PCC, which normally varies between 5 and 7 wt%. The PC systems had average water absorption values varying between 0.41 and 1.86 wt%.

Small-scale laboratory tests were done on PC mortar samples under simulated field conditions in an autoclave to evaluate how each system might perform in the field. The tests showed that 12 wk of exposure to simulated field conditions resulted in a slight decrease in compressive strength for the PF system, while the strengths of the VET and ST systems remained relatively constant. Visual examinations of the samples throughout the tests indicated no significant deterioration due to autoclaving. The results suggested that each of the PC systems should perform well in the field.

When the laboratory-scale tests were completed; in situ field tests (Task C) were started. The objectives of the field tests

were: (a) to evaluate the effects of exposure to actual field conditions on the physical and mechanical properties of PC and PCC systems, (b) to determine if the heat generated within a typical manhole could be used to post-cure a PC system, and (c) to evaluate the long-term creep characteristics of a PC beam under load.

Samples were tested in situ in three operational steam-valve manholes for up to 18 mo. The manholes (MH) used in the tests were MH7498, MH7500, and MH15105. The average air temperature within each manhole was as follows: MH7498 - 177°F, MH7500 - 160°F, and MH15105 - 194°F. Three PC systems and two PCC systems were tested in situ. The PC systems were the ST, VET, and PF systems. The PCC systems were a non-reinforced system and a fiber-reinforced system. The specimen placed in test included 2- by 2- by 12-in. long beams and 3-in. diameter by 6-in. long cylinders.

In general, most of the samples removed within the first 12 mo. of testing were in good physical condition; i.e. no significant deterioration of the surfaces was noted. The exceptions were the ST, PF, and VET samples removed from MH7498 after 6 to 8 mo. of exposure. These samples were beginning to show signs of scaling caused by the rusting of some of the carbon steel fibers located near the surfaces of the samples. An examination of these samples after testing indicated that the rusted fibers were present only in that region located near the surface of the samples and that the rusting had not progressed to the fibers located in the interior of the samples. Analysis of the polymer binders after exposure indicated no evidence of thermal degradation.

Results of the splitting tensile strength and flexure strength tests showed that each of the PC systems exhibited some reduction in strength as a result of exposure to the environment within the manholes. These reductions in strength had been predicted by the results of the laboratory-scale autoclave tests. After 6 to 9 mo. of exposure in the manholes, the flexural yield strength of the PC systems varied between 1590 and 1710 psi at 160°F, 890 and 1770 psi at 180°F, and 1410 and 1870 psi at 200°F; with the VET PC system always exhibiting the highest strengths.

As previously indicated the program plan called for the development of a PC system which could be used to (a) make precast panels or (b) fabricate cast-in-place manholes. Shortly after the start of the field tests a decision was made by Con Ed and BNL to concentrate on the development of a system which could be used in cast-in-place applications. Tests were therefore done to determine the ease with which the PC systems could be cast into formwork. Tests were also done to determine if the heat generated within a manhole could be used to post-cure the PC manhole after it had been put into service.

Results of in situ exposure tests done on ST and VET PC beams and cylinders cast and cured at room temperature indicated that the

heat generated within the steam-valve manholes can be used to post-cure these PC systems. The flexural yield strength of the VET PC system was found to increase 12 percent after 3 mo. of exposure in MH15105.

As a result of the problems associated with the rusting of the carbon steel fibers, a series of tests were done to evaluate the use of 430 stainless steel fibers as a replacement for carbon steel fibers. The results of these tests indicated that at 200°F the strength properties of the samples made with the stainless steel fibers were very similar to values measured for samples made with the carbon steel fibers. In addition, the stainless steel fibers did not deteriorate. In situ testing of individual fibers in MH15105 indicated that carbon steel fibers began to rust within 1 mo. of being placed in test while the 430 stainless steel fibers exhibited no evidence of rusting after 11 mo. of exposure.

In situ load-deflection (creep) tests were done in MH15105 (at an ambient temperature of $\approx 196^\circ\text{F}$) using a 2-in. by 8-in. by 6.25 ft. long fiber-reinforced VET PC beam cast at room temperature to determine how the system would behave under a sustained load. When tested for 54 wk at 84 percent of its theoretical design load, the beam was found to deflect approximately 0.748 in. at midspan. The rate of creep was calculated over the duration of the test to be approximately 0.010 in./wk.

A second beam was tested to determine if the creep could be controlled with the addition of conventional reinforcing bars. The results of laboratory and in situ load-deflection tests indicated that at 200°F the VET PC system continued to creep under a sustained load, i.e. the conventional reinforcing bars did not help control the creep exhibited by the system. In addition, the rebar did not reduce the magnitude of the deflections.

Tests were done on non-reinforced and fiber-reinforced PCC samples to determine the effects of elevated temperatures on the development of strength properties. Results of tests done on fiber-reinforced PCC samples cast for use in the in situ exposure tests showed that the strength properties of concrete cast and cured at elevated temperatures were significantly less than those for concrete cast and cured at room temperature. When tested at 200°F, there was an average reduction in compressive strength (f_c) of 36 percent for the samples cast and cured at elevated temperatures ($f_c = 3225$ psi) as compared to the samples cast and cured at room temperature ($f_c = 4890$ psi). Reductions in flexure strength values also were noted.

In situ test results for non-reinforced and fiber-reinforced PCC samples after 3 mo. of exposure in MH15105 indicated that the samples were in good condition and that the strength properties had increased slightly. The most significant change noted in either of the PCC systems was that both systems exhibited a loss in weight.

The weight loss was most likely due to a loss of moisture from the samples and not to any physical deterioration. The continued loss of moisture from the samples may at some point adversely affect the strength development of the system by reducing the rate at which the cement in the matrix hydrates.

A preliminary design study was made by BNL (Task D) to determine the necessary floor slab, wall, and roof thicknesses required to replace a typical reinforced PCC manhole with a cast-in-place, fiber-reinforced PC manhole. The design approach used classical plate theory by considering the manhole to be a series of plates subjected to loads resulting from soil pressures, highway loading, and dead weight. Designs were performed at two service temperatures, 285° and 400°F, for each of the three PC systems under evaluation. The preliminary design analysis indicated that the required wall thicknesses varied between 4.35 and 6.50 in., depending upon the PC system used and the required design temperature. The required thickness of the roof slab varied between 7.80 and 11.70 in. A preliminary design study by the Con Ed Civil Design Division produced similar results.

Polymer Construction Specialties, Inc. of Syosset, NY performed a preliminary cost analysis for BNL to provide a rough estimate of the costs associated with the placement of a 8 ft by 5 ft by 7 ft high cast-in-place PC manhole made with the VET PC system. A comparative estimate also was done for a manhole cast with conventional PCC. The estimates showed that the cost of the cast-in-place PC manhole would be approximately \$32,316, compared to \$20,800 for the PCC manhole. It should be noted that the analysis included only the cost of materials and those costs associated with the placement of a PC or PCC manhole. It did not include the cost for excavating and removing the existing manhole or the cost for backfilling the new manhole and replacement of the pavement surface. The analysis also assumed that the PCC floor of the existing manhole was in good condition and that it could be used as the base slab for the new PC or PCC manhole.

The cost of placing a PC manhole was estimated to be ~50 percent higher than that for placing a conventional PCC manhole. However, the increased service life of a PC manhole should offset the initial increase in investment.

In general, the results of the laboratory and in situ field tests indicate that the physical and mechanical properties and the corrosion resistance characteristics of the vinyl ester-TMPTMA (VET) PC system are superior to those of the other PC systems evaluated. However, the suitability of using the VET PC system as a structural material in the construction of underground, steam-valve manholes would, at present, appear to be limited by several factors which influence the performance of the system at elevated temperatures. As a result, the program was not carried beyond the design stage and full-scale testing of a PC manhole was not

performed. The factors influencing this decision included the following:

(a) The VET PC system exhibits outstanding strength properties at 72°F, e.g. the system has a compressive strength of 14,270 psi and a flexural yield strength of 2,865 psi. However, test results have shown that the strength properties decrease significantly with increases in temperature. When compared to values measured at 72°F, the VET PC system exhibits a 20 to 25 percent decrease in strength at 240°F and a 50 percent decrease in strength at 400°F.

(b) Long-term field tests performed on beams made with and without conventional reinforcing bars have indicated that the system exhibits an excessive amount of creep when loaded at 84 percent of its theoretical design capacity. Efforts to solve this problem have, to date, been unsuccessful.

(c) The lack of established design methods makes it difficult to accurately predict how the system will perform in the field, particularly at elevated temperatures. Conventional reinforced concrete design theory was used in the design studies performed in this program. It was also used to design the in situ creep tests. The results of the creep indicate that the assumptions made during the design of the experiments did not adequately predict the results which were obtained.

Based upon the results presented in this report it is concluded that the PC systems evaluated in this program are not, at this time, ready for use as a construction material for steam-valve manholes. Additional work will need to be done to address the limitations of the materials at elevated temperatures before they are ready for use in the field. Suggested areas of research include the following:

(a) Because the use of PC as a structural material is still relatively new there are, at present, no established design standards which will accurately predict actual field performance, particularly at elevated temperatures. As a result, additional laboratory and field tests need to be done to completely define the behavior of PC at ambient and elevated temperature conditions. One area in particular which needs to be addressed is creep. Tests results have shown that under the presently selected design loads the creep exhibited by the system is excessive. A more extensive series of load tests needs to be done to fully define the creep characteristics and to identify acceptable design limitations.

(b) Before a full-scale steam-valve manhole is built and put into service, at least one small-scale (one-quarter or

one-half scale) model should be load tested to verify the analysis used in the design of the manhole.

(c) Long-term in situ testing of PC samples should be done to gather as much information as possible about the performance and durability of the PC systems under actual field conditions.

(d) The VET PC system may be best suited for use in applications in which the maximum ambient temperature is less than 150°F. When compared to values measured at 72°F, the VET PC system exhibits only a 5 to 9 percent reduction in strength at 150°F as compared to a 20 to 25 percent decrease in strength at 240°F and a 50 percent decrease in strength at 400°F. Work should be done to more fully define the physical and mechanical properties of the VET PC system at temperatures of 150°F, or less.

**DEVELOPMENT OF HIGH TEMPERATURE, CORROSION RESISTANT
POLYMER CONCRETE FOR USE IN THE STEAM DISTRIBUTION
SYSTEM OF CONSOLIDATED EDISON COMPANY OF NY**

1.0 INTRODUCTION

1.1 Background.

The Consolidated Edison (Con Ed) Company of New York operates and maintains a large steam distribution system under the streets of New York City. Over the years several materials related problems have been encountered with the steel-reinforced portland cement concrete (PCC) manholes used to house the system's valves and fittings. The high ambient temperature and humidity within the manholes create an environment which eventually leads to the corrosion of the reinforcing steel in the concrete. The by-products of the corrosion process increase the volume of the reinforcing steel, creating tensile stresses in the surrounding concrete. As these stresses exceed the tensile strength of the concrete, cracks develop in the concrete which eventually lead to delaminations and/or spalls in the concrete. In addition, condensate from steam leaks in the valves and/or piping system attacks the cement matrix of the concrete which weakens the surface of the concrete thereby making it susceptible to further deterioration. Consequently, many of the manholes in the system are severely deteriorated and need to be replaced (Figures 1 and 2).

The manholes are being rebuilt using conventional PCC. Since the manholes are located beneath the streets and sidewalks, there is a great emphasis to minimize the time involved in rebuilding the manhole to prevent excessive disruption of traffic. As a result, the manholes are often cast around live steam mains and are immediately placed into service. The concrete is therefore only a few days old when it is subjected to the harsh environment of the manholes. In addition, by placing the manhole into service so quickly the concrete is not allowed to fully develop the strength and physical characteristics that it normally would obtain under ideal curing conditions. This can result in the development of a substandard quality of concrete. The combination of quickly pouring and placing the newly cast PCC manhole into service and the severe operating conditions to which the manholes are exposed invariably results in a shorter than desired service life.

With the development in recent years of more advanced materials of construction, such as polymer concrete (PC), it may be possible to cast manholes that have a longer maintenance-free

(a)

(b)

Figure 1. Interior views of two Con Ed steam manholes, from the street level, illustrating the extent to which the concrete walls in some of the manholes have deteriorated.

Figure 2. Interior view of Manhole (MH) 7500 (looking north) illustrating the extent of deterioration present in some of the concrete manholes. Note that the cover over the reinforcing steel in the ceiling has fallen off exposing the steel, which has begun to rust. The end wall is also severely cracked.

service life resulting from the improved physical and mechanical properties of these materials^[1].

The Process Materials Group of the Energy Efficiency and Conservation Division, Department of Applied Science at Brookhaven National Laboratory (BNL), Upton, NY has developed numerous PC formulations that display a wide range of physical and mechanical properties^[2-4]. Some of these materials are being used in commercial applications while others still are undergoing development and evaluation. Based on this experience BNL carried out a program for Con Ed entitled "Development Of High Temperature, Corrosion Resistant Polymer Concrete For Use In The Steam Distribution System of the Consolidated Edison Company of New York".

1.2 Program Objectives.

The primary objective of the program was to develop a PC system suitable for use as a construction material for steam-valve manholes. Alternate methods of construction would be investigated and the PC formulations would be tailored to meet the needs of the different construction technologies under consideration. During the laboratory-phase of the program a private contractor familiar with the field application of PC systems would be consulted to ensure that the systems under development were adaptable to field installations.

The original program plan called for the development of a PC system which could be used to (a) make precast panels or (b) fabricate cast-in-place manholes. The precast panels would be used as protective stay-in-place forms against which conventional PCC could be cast or they would be used to replace the PCC in its entirety.

The exposure conditions within a typical steam-valve manhole required that any PC system being considered for use exhibit the following characteristics: (a) it should be thermally stable at temperatures up to 275°F, (b) it should have good strength and stiffness at temperatures up to 275°F, (c) it should be impermeable to moisture penetration, and (d) it should have good resistance to possible chemical attack.

Based upon the results of a survey performed by Con Ed personnel at the start of the program, the design service temperature which the PC systems would have to withstand was raised from the originally specified value of 275° to a value of 400°F (refer to Section 2.1). The original scope of work for the program was revised to reflect the fact that the design service temperature was raised to 400°F. In addition, it was expanded to include small-scale field testing of the candidate PC systems. These tests were added in order to determine the effects of exposure to actual

field conditions on the physical and mechanical properties of PC and PCC systems.

Evaluation of the candidate systems would be based upon the results of tests done to determine the physical and mechanical properties over a range of temperatures. Properties to be evaluated included: water absorption, shrinkage, compressive strength, flexure strength, tensile strength, and thermal coefficient of expansion. Based upon the results of the laboratory and field tests one or more PC systems would be selected for full-scale evaluation in the field. This work would be done in Phase Two and was beyond the scope of work for this phase of the program.

To meet the objectives of the program, the following series of tasks were developed to serve as guidelines:

- A. Identification and evaluation of candidate PC systems.
- B. Laboratory-scale evaluation.
- C. Field evaluation.
- D. Preliminary design of a typical manhole.

2.0 IDENTIFICATION AND EVALUATION OF CANDIDATE PC SYSTEMS

2.1 Temperature Requirements.

Before starting the laboratory test program a survey was performed to verify the range of ambient air temperatures typically encountered within the steam-valve manholes. Seven operating manholes were selected at random and surveyed by Con Ed personnel. The results, which are summarized in Table 1, indicated that air temperatures within the manholes varied between 214° and 349°F and averaged 297°F. In addition, it was determined that the temperature of the steam within a steam main is $\approx 380^\circ\text{F}$. Based upon this information, Con Ed asked that the design service temperature of the PC systems be raised from the originally specified value of 275° to a value of 400°F. This would ensure that the PC systems were thermally compatible with the range of temperatures found within the steam-valve manholes and it would also ensure that the PC systems would not thermally degrade in the event of a steam main rupture.

2.2 Binder System Selection.

In general, polymer concrete (PC) is a composite material formed by polymerizing a monomer/resin system with an aggregate system. The monomer/resin system acts as the binder for the composite. The PC systems developed for this program consist of four components: a binder system, a blended fine aggregate system, a graded coarse aggregate system, and a fiber reinforcement.

The procedure used to cast the PC samples was as follows. The PC was mixed by first blending the fine and coarse aggregates together in a mixer. The binder system, which is a liquid, was then added to the mix. Finally the fiber reinforcement was added. After the mix was completely blended, it was poured into the molds or formwork and consolidated by vibration. The binder systems used were formulated such that they would allow the mix to initially cure, i.e. harden, at room temperature. After the PC had cured the cast section was demolded, and then post-cured in a constant temperature oven to fully develop the strength properties of the system and to ensure that the binder system had been completely reacted.

The primary difference between the PC systems developed for evaluation was the monomer/resin system used for the binder. Three monomer/resin systems were selected for evaluation: a styrene-trimethylolpropane trimethacrylate (TMPTMA) [ST] based monomer system, a vinyl ester resin-TMPTMA [VET] based system, and a phenol

Table 1. Ambient air temperatures within various
Con Ed steam manholes.

MANHOLE NO.	LOCATION	AMBIENT AIR TEMPERATURE, °F
15105	41st Street & 1st Avenue	349
7887	44th Street & Lexington Ave.	299
8603	Madison Ave. between 47th and 48th Streets	320
8120	Madison Ave. so. of 59th St.	272
6185	5th Ave. south of 75th St.	214
7039	7th Avenue & 49th Street	332
7301	43rd St. west of Broadway	290

formaldehyde [PF] resin system. The mix formulations of each binder system are summarized in Table 2.

The ST based system is a low viscosity monomer system that was developed by BNL, which, when polymerized produces a polymer which has very good stability at temperatures up to 572°F. Much of the work done with the ST based system was done using the version of the system developed by BNL. However, the ST based system was later modified by adding poly(methyl methacrylate) (PMMA) to the system. The PMMA in the styrene-TMPTMA-PMMA (STP) system helps improve the film forming characteristics of the system by reducing the rate of evaporation of monomer from the surface before polymerization. The improved film resulted in a harder finish to the surface of the PC and also helped to reduce the water absorption characteristics of the system.

The base resin used in the VET system is a vinyl ester resin manufactured by Dow Chemical Co. called Derakane 470-45. According to Dow Chemical's "Chemical Resistance and Engineering Guide," this resin "combines good corrosion resistance characteristics with superior retention of properties at high temperatures, superior oxidation resistance, and resistance to mixtures of chemicals." The resin system was modified by adding TMPTMA to improve the strength properties of the resin at temperatures above 300°F.

The PF resin system is a developmental resin manufactured by Borden Chemical Co. called Durite SL-618A. According to Borden, the cured phenolic system has excellent resistance to heat, hydrolysis, strong acids, and organic solvents.

Thermogravimetric analysis (TGA) data for each polymer system, show that each system is thermally stable at 400°F (Figures 3-6).

Table 2. Formulations of the Binder Systems

A. Styrene-TMPTMA (ST) monomer system.

54.0 wt% styrene monomer
 4.5 wt% polystyrene beads
 39.0 wt% TMPTMA monomer
 1.0 wt% A-174 silane coupling agent
 1.0 wt% dimethyl aniline (DMA) promoter
 0.5 wt% di-tert-butyl peroxide (DTBP) initiator
 with 4.0 wt% BFF-50 benzoyl peroxide (BPO) initiator

B. Styrene-TMPTMA-PMMA (STP) monomer system.

53.0 wt% styrene monomer
 4.3 wt% polystyrene beads
 38.2 wt% TMPTMA monomer
 2.0 wt% poly(methyl methacrylate)
 1.0 wt% A-174 silane coupling agent
 1.0 wt% DMA promoter
 0.5 wt% DTBP initiator
 with 4.0 wt% BPO initiator

C. Vinyl ester-TMPTMA (VET) resin system.

78.2 wt% Derakane 470-45 vinyl ester resin
 20.0 wt% TMPTMA monomer
 1.0 wt% A-174 silane coupling agent
 0.1 wt% DMA promoter
 0.5 wt% DTBP initiator
 with 4.0 wt% BPO initiator

D. Phenol formaldehyde (PF) resin system.

71.0 wt% Durite SL-618A phenol formaldehyde resin
 1.0 wt% methanol
 1.0 wt% A-187 silane coupling agent
 1.1 wt% 10 wt% aqueous solution of ammonium
 bifluoride
 8.1 wt% water
 17.8 wt% Durite RC-204A hardener
 with 8.7 wt% Durite RC-495A activator
 (blended in with the fine aggregate)

Figure 3. TGA data for the VET monomer system.

Figure 4. TGA data for the ST mortar system.

Figure 5. TGA data for the PF mortar system.

Figure 6. TGA data for the STP PC system.

2.3 Aggregate System Selection.

2.3.1 Fine aggregate system. The fine aggregate system for the ST, STP, and VET systems consists of dry, blended silica sand, flour sand, Type III portland cement, and a liquid surfactant (Surfynol S-440). Table 3 presents the formulation of the fine aggregate system. The Type III cement is added to the system to improve the hydrothermal stability of the PC system by improving the chemical bonding between the monomer and aggregate systems. The surfactant is added to the system to improve the wetting characteristics of the aggregate and to help limit the amount of dust generated during mixing. Table 4 shows a sieve analysis of the blended silica sand and the flour sand.

The fine aggregate system for the PF system consists of dry, blended silica sand, flour sand, and a powdered activator (Durite RC-495A).

2.3.2 Coarse aggregate system. The coarse aggregate used in all PC systems was a washed and dried, 3/8-in. crushed siliceous gravel. Table 4 presents a sieve analysis.

2.4 Fiber Reinforcement System.

Research performed by BNL has shown that the ductility of PC composites can be improved by adding steel fibers to the mix^[5]. Therefore tests were done to evaluate the flexure strength of steel fiber-reinforced PC. Synthetic fibers, such as graphite and Kevlar aramid fibers, also were evaluated because they are less likely to be subjected to corrosion in humid environments than are the steel fibers. Chopped stainless steel fibers also were evaluated.

Table 3. Formulations of the fine aggregate systems.

A. Fine aggregate system for the ST, STP, and VET PC systems.

71.5 wt% blended silica sand
8.0 wt% silica flour sand
20.0 wt% Type III portland cement
0.5 wt% Surfynol 440 surfactant

B. Fine aggregate system for the PF PC system.

81.0 wt% blended silica sand
17.0 wt% silica flour sand
2.0 wt% Durite RC-495A activator

Table 4. Sieve analysis data.

A. Typical sieve analysis of blended silica sand.
(J. S. Morie & Sons, Inc. blend TC-4727-81)

U.S. Standard Sieve Size	Percent Passing (cumulative)
No. 6	100
No. 12	100
No. 20	60
No. 30	48
No. 40	28
No. 50	26
No. 70	15
No. 100	3
No. 140	1
No. 200	<1

B. Typical sieve analysis of silica flour sand.

U.S. Standard Sieve Size	Percent Passing (cumulative)
No. 120	100
No. 140	96
No. 200	90
No. 270	82
No. 325	73

C. Typical sieve analysis of the siliceous gravel.

U.S. Standard Sieve Size	Percent Passing (cumulative)
1/2-in.	99
3/8-in.	88
No. 4	8
No. 8	1
No. 16	<1

Note: This grading is very close to the No. 8
Grading specified in ASTM D 448-86.

A preliminary series of flexure strength tests were done to compare the performance of the various types of fibers under consideration. The tests were performed using 2- by 2- by 12-in. long beams and were done in accordance with test method C78-84 of the American Society for Testing and Materials (ASTM).

Five types of fibers were evaluated:

- 1.5 in. long corrugated carbon steel fibers (Novocon International)
- 1.50 in. long Kevlar 49 aramid fibers (DuPont)
- 1.00 in. long Kevlar 49 aramid fibers (DuPont)
- 0.25 in. long Magnamite AS graphite fibers (Hercules)
- 0.30 in. long TD-700 304 stainless steel fibers (Brunswick)

Samples were cast using the ST and VET systems and tested in flexure at room temperature (72°F). For comparison, non-reinforced beams cast with the VET system also were tested. The results are shown in Figures 7 and 8. The greatest improvements in load carrying capacity and ductility were obtained using the 1.5 in. long corrugated steel fibers. Based upon these results, all subsequent work was done using the steel fiber reinforced PC systems.

2.5 PC Mix Design Formulations.

Table 5 gives formulations for the ST, STP, VET and PF polymer concrete systems.

Table 5. PC mix design formulations.

A. Mix design for the ST, STP and VET PC systems.

- 52.0 wt% blended fine aggregate
- 34.5 wt% coarse aggregate
- 6.5 wt% binder system
- 7.0 wt% corrugated steel fibers

B. Mix design for the PF PC system.

- 49.5 wt% blended fine aggregate
- 32.5 wt% coarse aggregate
- 11.5 wt% phenol formaldehyde resin
- 6.5 wt% corrugated steel fibers

Figure 7. Flexure load vs. deflection data for the ST PC system made with various types of fibers.

Figure 8. Flexure load vs. deflection data for the VET PC system made with various types of fibers.

3.0 LABORATORY TEST PROGRAM

3.1 Objectives.

The primary objectives of the laboratory tests were: (a) to experimentally determine the physical and mechanical properties of the PC systems over a temperature range of 40° to 400°F and (b) to determine if exposure to simulated field conditions deteriorated these properties.

3.2 Test Methods.

The physical and mechanical properties measured included compressive strength, splitting tensile strength, flexure strength, flexural modulus of elasticity, shear strength, coefficient of thermal expansion, coefficient of thermal conductivity, and water absorption values. The strength properties were measured at 40°, 72°, 150°, 240°, 320° and 400°F. The test methods used to evaluate each property are discussed below.

3.2.1 Compressive strength. Compressive strengths were determined in accordance with ASTM test method C 39-86 "Compressive Strength of Cylindrical Concrete Specimens" using 3-in. diameter by 6-in. long cylinders. Compressive strength tests on PC mortars were done using 1-in. diameter by 2-in. long cylinders.

3.2.2 Splitting tensile strength. Splitting tensile strengths were determined in accordance with ASTM test method C 496-90 "Splitting Tensile Strengths of Cylindrical Concrete Specimens" using 3-in. diameter by 6-in. long cylinders.

3.2.3 Flexure strength and flexural modulus of elasticity. Flexural properties were determined in accordance with ASTM test method C 78-84 "Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)" using 2- by 2- by 12-in. long beams.

3.2.4 Shear strength. Shear strengths were determined using a guillotine shear test developed by BNL. The tests were done using 3-in. diameter by 6-in. long cylinders.

3.2.5 Coefficient of thermal expansion. The coefficients of thermal expansion were measured using 2- by 2- by 12-in. long beams and were done using ASTM test method C 531-85 "Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, and Monolithic Surfaces" as a guide.

3.2.6 Coefficient of thermal conductivity. The coefficients of thermal conductivity were measured using a Shotherm QTM Thermal

Conductivity Meter. The tests were done using 2- by 8- by 7-in. plaques.

3.2.7 Water absorption. The water absorption characteristics of the PC systems were measured using 2-in. cubes cut from the flexure tests beams after they had been tested to failure. The tests were done using ASTM test method C 20-87 "Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water" as a guide.

3.2.8 Creep characteristics. The behavior of the PC systems under sustained loading was evaluated by applying a concentrated load at the centerpoint of a simply supported beam. Deflection measurements were taken at the quarterpoints of the span length. The tests were done using 1-in. high by 3-in. wide by 30-in. long beams.

3.2.9 Bond of conventional reinforcing steel to PC. The bond strength of conventional reinforcing steel to PC was determined in accordance with ASTM C 234-86 "Comparing Concretes on the Basis of the Bond Developed with Reinforced Steel."

3.3 Laboratory Test Results.

3.3.1 Physical and mechanical properties. Tables 6 - 8 summarize the mechanical properties of ST, VET and PF PC systems at 72°, 150°, 240°, 320°, and 400°F. Test data for the VET PC system at 40°F also is included in Table 7. The data show that the mechanical strength of each system decreases with increasing temperature. However, this trend is not unexpected because the polymer binders of each system soften with increasing temperature. As previously noted, the softening of the polymers should not be considered detrimental, because the decomposition temperatures of the polymers are above 482°F.

The properties of the PC systems that will be primarily used in the structural design of a manhole are the flexural yield strength (FYS) and the ductility of the material when subjected to flexural loads (see Section 5.3). Figure 9 shows a comparison of the FYS values for each PC system. The VET system exhibits the highest FYS values over the range of 72° to 400°F. However, this system also shows the greatest reduction in strength over this range of temperature. The PF system shows the least reduction in strength over this range.

A comparison of the splitting tensile and flexure strength data shows that it may be possible to use splitting tensile strength test data to predict the flexural yield strength of the PC systems under evaluation.

Table 6. Strength properties of the ST PC system.

Property	Test Temperature, °F				
	72	150	240	320	400
Compressive Strength, psi	12,220	11,790	9,305	7,020	4,730
Splitting Tensile Strength, psi	2,150	2,035	1,775	1,280	965
Flexural Yield Strength, psi	2,145	2,020	1,720	1,545	930
Ultimate Flexure Strength, psi	2,690	2,800	2,670	1,950	1,100
Flexural Modulus of Elasticity, psi x 10 ⁶	3.43	3.04	1.86	1.30	0.64
Shear Strength, psi	3,370	2,640	2,410	1,595	1,275

Table 7. Strength properties of the VET PC system.

Property	Test Temperature, °F					
	40	72	150	240	320	400
Compressive Strength, psi	15,870	14,270	13,570	11,220	8,740	6,530
Splitting Tensile Strength, psi	2,490	2,585	2,450	2,170	1,695	1,385
Flexural Yield Strength, psi	2,760	2,865	2,745	2,205	1,965	1,440
Ultimate Flexure Strength, psi	2,920	3,335	3,035	3,035	2,745	1,795
Flexural Modulus of Elasticity, psi x 10 ⁶	4.43	4.07	3.50	2.54	1.74	0.88
Shear Strength, psi	2,610	4,515	3,870	3,210	2,735	2,570

Table 8. Strength properties of the PF PC system.

Property	Test Temperature, °F				
	72	150	240	320	400
Compressive Strength, psi	13,410	11,025	11,045	10,270	9,415
Splitting Tensile Strength, psi	2,165	1,850	1,745	1,535	1,505
Flexural Yield Strength, psi	2,175	1,805	1,665	1,580	1,390
Ultimate Flexure Strength, psi	2,290	2,395	2,040	1,900	1,830
Flexural Modulus of Elasticity, psi x 10 ⁶	2.66	2.17	1.64	1.30	1.19
Shear Strength, psi	3,925	4,040	3,425	3,090	2,875

Figure 9. Variation of the flexural yield strength with temperature for the VET, ST, and PF PC systems.

Figures 10 - 12 illustrate the flexure load vs. deflection characteristics of each PC system over a temperature range of 72° to 400°F. The data show that the FYS (the stress corresponding to the load at the end of the linear portion of the load vs deflection curve) and the ultimate flexure strength (the stress corresponding to the maximum load) decrease with increasing temperature.

Deflection tests done on simply supported beams at room temperature indicate that the VET PC system is the most rigid system and that the ST PC system is the most flexible (Figure 13). The VET PC system deflected 0.013 in. upon initial loading, while the ST PC system deflected 0.030 in. Deflection vs. time (i.e. creep) tests indicate that each system will creep under sustained loading. After 5 weeks under load, the midspan deflection of the VET system increased to 0.023 in., and the midspan deflection of the ST system increased to 0.046 in.

Results of the laboratory tests done to evaluate the bond strength developed between conventional reinforcing steel and the VET PC system at 72°, 200°, and 400°F are summarized in Table 9. Reference data for portland cement concrete (PCC) is included for comparison.

In general, the results indicate that the pullout strength decreased with increasing temperature. At 72°F the VET PC system had a pullout strength of 44,500 lb while at 400°F the system had a pullout strength of 26,600 lb.

Figure 10. Variation of flexure load vs deflection characteristics with temperature for the VET PC system.

Figure 11. Variation of flexure load vs deflection characteristics with temperature for the ST PC system.

Figure 12. Variation of flexure load vs deflection characteristics with temperature for the PF PC system.

Figure 13. Comparison of deflection test data for the VET, ST, and PF PC systems.

Table 9. Rebar Pullout Test Results.

System	Temperature	Compressive Strength	Pullout Strength	Failure Mode
VET PC	72°F	14,270 psi	44,500 lb	Rebar
VET PC	200°F	12,875 psi	37,675 lb	Rebar & PC
VET PC	400°F	6,530 psi	28,705 lb	PC
PCC	72°F	9,830 psi	26,600 lb	PCC

An examination of the test specimen after failure indicated the failure mechanism changed with temperature. At 72°F the failure occurred completely in the rebar, i.e. the rebar failed in tension. At 200°F failure generally occurred in the rebar and occasionally in the PC, indicating that the ability of the PC to bond to the rebar was beginning to decrease. At 400°F the failure occurred at the interface between the steel and the PC, indicating

that the bond between the PC and the steel was not sufficient to fully develop the load carry capacity of the rebar.

Published data indicates that at room temperature conditions PCC, with a compressive strength of 9,830 psi, has a pullout strength of 26,600 lb and that the failure mechanism is at the interface between the PCC and the rebar.^[5]

Figures 14 and 15 illustrate the variation in the coefficients of thermal expansion and thermal conductivity for each PC system over a range of temperatures.

The coefficient of thermal expansion for each of the PC systems is higher than that for conventional PCC, which normally varies between 4.0 and 7.0×10^{-6} in./in./°F and averages 5.5×10^{-6} in./in./°F. The coefficients for each system vary slightly depending upon the polymeric binder used in the system. The PF system exhibits the lowest range of values: 6.2 to 8.3×10^{-6} in./in./°F. The ST and VET systems exhibit very similar values: 8.4 to 10.2×10^{-6} in./in./°F. The coefficients also were found to vary with temperature, generally increasing slightly with increases in temperature.

The coefficients of thermal conductivity are within the range of values associated with conventional PCC, the thermal conductivity of which generally ranges between 0.8 and 2.1 BTU/hr/ft/°F depending upon its composition and moisture content. The values measured for the PC system varied between 1.40 and 2.03 BTU/hr/ft/°F. The thermal conductivity varies slightly with the type of polymer binder, with the PF system showing the lowest values and the VET system showing the highest values. The conductivity values for each were found to vary slightly with temperature. The conductivity appears to remain relatively constant up to about 246°F beyond which it decreases slightly with increasing temperature.

The water absorption values for the PC systems are well below those of conventional PCC. PCC normally has a water absorption value varying between 5 and 7 wt%. The water absorption values measured for the PC systems are summarized in Table 10.

Table 10. Water Absorption Test Results.

PC System	Water Absorption Value, wt%	
	Range	Average
ST	1.00 - 1.83	1.36
VET	0.19 - 0.71	0.41
PF	1.57 - 2.15	1.86

Figure 14. Variation in the coefficient of thermal expansion with temperature for the VET, ST, and PF PC systems.

Figure 15. Variation in the coefficient of thermal conductivity with temperature for the VET, ST, and PF PC systems.

3.3.2 Autoclave exposure tests. Tests were done under simulated field conditions in an autoclave to evaluate how each PC system might perform in the field. Due to space limitations in the autoclave, the tests were done using 1-in. diameter by 2-in. long PC mortar cylinders. The evaluation of each system was based upon visual examinations, and the results of compressive strength tests done after 1, 2, 4, 8 and 12 wk of exposure to steam at 400°F. Figure 16 summarizes compressive strength test results for each PC mortar system.

The data indicates that the compressive strength of the ST and VET mortars, measured at 400°F, remained relatively constant during the test. However, the strength of the PF mortar decreased significantly after one week of exposure, after which the strength remained relatively constant. Visual examinations of the samples throughout the test showed no significant deterioration due to the autoclaving.

The test results suggest that each of the PC systems, particularly the ST and VET systems, should perform well in the field. However, it should be emphasized that the results can only be used to get an indication of how each system might perform in the field. Because the tests were done with mortars, the results do not accurately show how the total composite system containing coarse aggregate and steel fibers might perform.

Figure 16. Variation of compressive strength with autoclave exposure time for the VET, ST, and PF mortar systems.

4.0 IN SITU FIELD TEST PROGRAM

4.1 Objectives.

As previously noted, the results of the laboratory-scale autoclave tests suggested that each of the PC systems might perform well in the field. To verify these results, in situ field tests were made.

The objectives of the in situ field tests were: (a) to evaluate the effects of exposure to actual field conditions on the physical and mechanical properties of PC and PCC systems, (b) to determine if the heat generated within a typical manhole could be used to post-cure a PC system, and (c) to evaluate the long term creep characteristics of a PC beam under load.

4.2 Field Test Locations.

Six proposed test sites were inspected and evaluated; three sites were selected for the in situ exposure tests. Selection was primarily based upon the ambient air temperature within the manhole and the amount of area within the manhole available for placing test specimen. These three manholes are described below.

Manhole (MH) 7498 -- an expansion joint manhole located beneath the sidewalk on the north corner of 85th Street and Central Park West. The manhole is approximately 10 ft by 6.5 ft by 6.5 ft in height and contains a 24-in. diameter, insulated steam main. Air temperature within the manhole was measured at 183°F. An internal inspection of the manhole found it to be in fair condition. The walls were cracked in a few locations, but were intact. Most of the concrete cover over the reinforcing steel in the ceiling had delaminated and fallen onto the floor of the manhole (Figure 17). The exposed reinforcing steel was severely deteriorated, and in many cases had fallen from the ceiling onto the floor. The rest of the ceiling was intact.

MH7500 -- a main valve manhole located beneath the sidewalk on the south corner of 86th Street and Central Park West. The manhole is approximately 18.5 ft by 8 ft by 9 ft in height and contains a 24-in. diameter, insulated main and a 3-in. diameter, insulated bypass line. Air temperature within the manhole was measured to be between 159° and 164°F. An internal inspection of the manhole found it to be in a condition similar to that of MH7498, i.e. the walls of the manhole were cracked but intact and the concrete cover over the reinforcing steel in the ceiling had delaminated, and in some cases had fallen to the floor (see Figure 2). At the time of the inspection there was about 1 ft of standing

(a)

(b)

Figure 17. Interior views of MH7498 showing the extensive deterioration of the concrete walls (a) and ceiling (b). Note the exposed reinforcing in the ceiling.

water on the floor of the manhole. The water disappeared by the time the in situ tests were started.

MH15105 -- a main valve manhole located beneath the sidewalk at 41st Street and 1st Avenue. The manhole is approximately 25 ft by 20 ft by 7 ft in height and contains two 30-in. diameter, insulated mains. The manhole was generally in good condition. Some cracking was evident in the walls (Figure 18), but the ceiling was in good condition and appeared to have been cast within the last few years. Air temperature within the manhole was measured to be about 205°F.

Profiles of the air temperature in MH7498, MH7500, and MH15105 over the duration of the field tests are shown in Figure 19. Monitoring of sample temperatures within MH15105 indicated that the temperatures of the samples were generally higher than the air temperature measured within the manhole, and that the sample temperatures increased as the distance from the floor of the manhole increased. For example, over a four month period the average air temperature in MH15105 was measured to be $\approx 194^{\circ}\text{F}$. The internal temperature of samples placed on the floor of the manhole averaged 179°F . Samples placed approximately four feet above the

Figure 18. Interior view of MH15105 showing the cracking present in the south wall of the manhole.

Figure 19. Profiles of the ambient air temperature in each manhole and the outside air temperature.

floor of the manhole had an average internal temperature of $\approx 200^{\circ}\text{F}$, and samples placed at ceiling height (7 ft above the floor) had an average internal temperature of 206°F .

4.3 Test Program.

The ST, STP, VET and PF PC systems (refer to Section 2.2) and two PCC systems (a non-reinforced portland cement concrete system and a fiber-reinforced portland cement concrete system) were tested in situ. A summary of the systems tested in each manhole is presented below.

Manhole No.	Systems in test in manhole
7498	ST, VET, and PF PC systems.
7500	ST, VET, and PF PC systems.
15105	ST, STP, VET, and PF PC systems. Non-reinforced and fiber-reinforced PCC systems.

The in situ tests were started in MH7498 and MH7500 on October 3, 1991 and in MH15105 on October 31, 1991. A selected number of beams and cylinders were removed from each manhole after 1, 2, 3, and 6 mo. of exposure and brought back to BNL for testing. This testing schedule was later revised to permit the 6 mo. samples to be left in test for longer time if the samples showed no signs of deterioration. Laboratory evaluation of each system was based upon the results of splitting tensile strength, flexure strength, water absorption, and dimensional stability tests.

The testing of samples in MH7498 and MH7500 was stopped on June 11, 1992 due to renovation of the manholes by Con Ed. The testing of samples run in MH15105 was stopped on September 14, 1993 with the completion of the program.

4.4 In Situ Test Results.

4.4.1 Effects of field exposure on the properties of the PC systems. Table 11 summarizes the results obtained from the laboratory tests done on the in situ test specimen brought back to BNL for evaluation. Flexural yield strength test data for the VET, ST, and PF PC systems is presented graphically in Figures 20 - 22.

In general, most of the samples removed within the first 12 months of testing were in good physical condition; i.e. no significant deterioration of the surfaces was noted (Figure 23). The only noticeable change was a discoloration of the PC. The exceptions to this were the ST, VET, and PF samples removed from MH7498. These samples, particularly the cylinders, began to show significant deterioration due to spalling after about 6 months of exposure (Figure 24).

A close visual examination of these samples indicated that the spalling was most likely due to the deterioration of the carbon steel fibers located at the surface of the samples. These fibers began to rust as a result of exposure to the environment within the manhole. The corrosion by-products resulted in an increase in the volume of the fibers, creating tensile stresses in the PC mortar around the fibers. As these stresses increased, cracks developed in the sample which eventually lead to spalling of the surface. A visual examination of the sample cross-sections, after testing, indicated that the fibers in the interior of the samples were not rusted. In fact, the rusted fibers were generally confined to an area within 1/8-in. of the surface of the sample.

It is believed that the high humidity within manhole MH7498 was the primary contributing factor that lead to the advanced deterioration. Spalling was also eventually noted in samples which

Table 11. In Situ Test Results

PC SYSTEM	MH No.	AVERAGE MANHOLE AIR TEMP., (deg.)	EXPOSURE TIME	TEST TEMP (deg.)	FLEXURAL YIELD STRENGTH, psi	ULTIMATE FLEXURE STRENGTH, psi	SPLITTING TENSILE STRENGTH, psi	WATER ABSORPTION, wt% IN SITU	LAB TEST
VET	Ctrl	--	--	160 F	2050	2620	2000	--	0.40
				180 F	2035	2490	1935	--	"
				200 F	1680	2190	1870	--	"
	7498	177 F	1 mo.	180 F	1755	2290	2080	0.16	0.56
			2 mo.	"	1830	2380	1960	0.16	0.24
			3 mo.	"	1600	1898	1848	0.41	0.31
			8 mo.	"	1770	2995	1760	0.23	0.08
	7500	160 F	1 mo.	160 F	1580	2435	2095	0.05	0.58
			2 mo.	"	1755	2730	2335	0.05	0.59
			3 mo.	"	1590	2245	2115	0.01	0.60
			8 mo.	"	1710	2455	1920	-0.06	0.60
	15105	196 F	1 mo.	200 F	1420	1930	1900	0.21	0.49
			2 mo.	"	1530	2035	1855	0.21	0.59
			3 mo.	"	1460	2185	1855	0.18	0.60
			6 mo.	"	1870	2030	1710	0.29	0.39
			18 mo.	"	1725	1945	1545	0.56	0.75
VETrt (RT Cure)	Ctrl	--	--	200 F	2005	2550	1785	--	0.17
				400 F	1000	1130	765	--	--
	15105	196 F	1 mo.	200 F	2270	2595	2075	0.05	0.11
			2 mo.	"	1645	2680	1970	0.04	0.09
			3 mo.	"	2360	2650	1860	0.04	0.11
			6 mo.	"	2000	2500	--	0.10	0.15
			12 mo.	"	1810	2860	--	0.08	0.27
			3 mo.	400 F	965	1060	745	--	--
			6 mo.	"	840	1200	--	--	--
PF	Ctrl	--	--	160 F	1780	1965	1525	--	1.86
				180 F	1525	2325	1585	--	"
				200 F	1480	1715	1660	--	"
	7498	177 F	1 mo.	180 F	1560	1830	1750	1.11	1.60
			2 mo.	"	1175	2175	1475	1.29	2.18
			3 mo.	"	1235	1450	1645	1.30	2.03
			7 mo.	"	890	1565	1150	1.68	1.63
	7500	160 F	1 mo.	160 F	1585	1825	1625	0.17	2.18
			2 mo.	"	1645	2050	--	0.36	1.81
			3 mo.	"	1525	1870	1730	0.31	2.15
			8 mo.	"	1590	2345	1920	-0.37	1.94
	15105	196 F	1 mo.	200 F	1335	1590	1335	1.40	1.51
			2 mo.	"	1330	1595	1515	0.92	1.87
			3 mo.	"	1215	1625	1590	0.68	1.98
			9 mo.	"	1410	1515	1165	0.63	2.10
ST	Ctrl	--	--	160 F	1310	1665	1795	--	1.34
				180 F	1440	1650	1670	--	"
				200 F	1045	1255	1565	--	"
	7498	177 F	1 mo.	180 F	1690	2420	1640	0.12	1.08
			2 mo.	"	1580	1900	1695	0.25	1.07
			3 mo.	"	1525	1755	1735	0.25	0.96
			6 mo.	"	1490	1825	1570	0.47	0.72
	7500	160 F	1 mo.	160 F	1415	1665	1675	0.05	1.10
			2 mo.	"	1635	2390	1750	0.05	1.02
			3 mo.	"	1590	2005	1605	0	1.00
			8 mo.	"	1660	2360	1730	-0.10	0.99
	15105	196 F	1 mo.	200 F	1335	1505	1585	0.13	0.44
			2 mo.	"	1670	2315	1685	0.19	0.47
			3 mo.	"	1455	2070	1775	0.14	0.44
			18 mo.	"	1585	1870	1405	0.61	0.85
STP	Ctrl	--	--	200 F	1695	2175	1214	--	1.05
	15105	196 F	1 mo.	200 F	1680	2100	--	0.10	1.05
			2 mo.	"	1980	2560	--	0.17	0.81
			3 mo.	"	1570	2150	1160	0.23	0.93

All values are an average of a minimum of 3 test specimens.

The flexural modulus of rupture is defined as that stress corresponding to the end of the linear portion of the load vs. deflection curve.

Figure 20. Variation of the flexural yield strength with time of exposure in MH7500 for the ST, VET and PF PC systems.

Figure 21. Variation of the flexural yield strength with time of exposure in MH7498 for the ST, VET and PF PC systems.

Figure 22. Variation of the flexural yield strength with time of exposure in MH15105 for the ST, VET and PF PC systems.

Figure 23. VET PC samples after 8 mo. of exposure in MH7500.

Figure 24. A ST PC sample after 6 mo. exposure in MH7498. Rusting of fibers located near the surface has resulted in deterioration due to spalling.

had been in test for 18 months in MH15105. The humidity in MH15105, however, was not as high as that in MH7498 and as a result the fibers did not rust as quickly.

A comparison of TGA data for polymer samples taken from laboratory controls and from beams and cylinders which had exhibited significant deterioration due to spalling indicated that there was no degradation of the polymer binders.

The test data shows that, in general, each of the ST, VET, and PF PC systems exhibited reductions in strength as a result of exposure to the environment within the manholes. After 6 to 9 mo. of exposure in the manholes, the FYS values for the VET, ST, and PF PC systems, measured at 160° to 200°F, may be summarized as follows:

PC System	Flexural Yield Strength
VET	1710 to 1870 psi
ST	1490 to 1660 psi
PF	890 to 1590 psi

These ranges represent a decrease in the FYS for the VET and PF systems and an increase in the FYS the ST system, when compared to their respective control values. The data also indicates that the VET system exhibits the highest range of FYS values of the three systems. Results of the tests done to evaluate the physical properties of the VET and ST systems after 18 mo. of exposure in MH15105 indicate that the FYS for the VET system, measured at 200°F, decreased about 1.4 percent when compared to the control values for the system. The FYS for the ST system, measured at 200°F, decreased about 24 percent.

The tendency of the systems to absorb moisture also increased as a result of the exposure. This is indicated by a comparison of the water absorption values measured in situ and in the laboratory. The increase in the tendency of the PC systems to absorb moisture may have also contributed to the rusting of the carbon steel fibers and the resultant spalling.

The overall changes in the flexural characteristics of the PC systems can be seen by examining the load versus deflection versus time of exposure curves for the ST, VET and PF PC systems. These curves are presented in Appendix A.

In situ tests to evaluate the STP PC system were done in MH15105. This system was tested to evaluate if the addition of PMMA to the system would improve the field performance of the styrene-based system. The test results are summarized in Table 11. Figures 25 and 26 show the comparison of the results from splitting tensile and flexure strength tests for ST and STP systems.

Figure 25 shows that the STP system has higher FYS values and lower splitting tensile strength values than the ST system when measured at 200°F. Figure 26 shows the load versus deflection curves for both systems after 3 mo. of exposure in MH15105. Both systems show similar behavior in flexure; however, the STP system has a slightly higher E value and a higher ultimate flexure strength. The load versus deflection versus time of exposure curves for the STP system are presented in Appendix A.

4.4.2 In situ post-curing of a PC system. BNL had assumed that any PC system used to cast a manhole would be completely post-cured before the manhole was placed into service. Consequently, all samples used in the laboratory-scaled and in situ field tests were post-cured when fabricated. Subsequent discussions with Con Ed engineers indicated that there was no assurance that a manhole, which had been cast-in-place using PC, would be fully post-cured before being put into service. Therefore, tests were done to determine if the heat generated within a manhole could be used to post-cure the ST and VET PC systems.

The tests were done using 1-in. diameter PC mortar cylinders. The cylinders were cast in the lab and cured only at room

Figure 25. Comparison of in situ test data for the ST and STP PC systems.

Figure 26. Comparison of the load vs. deflection characteristics for the ST and STP PC systems after 3 mo. exposure in MH15105.

temperature. The VET cylinders were tested in MH7500 (ambient temp. = 160°F) and MH15105 (ambient temp. = 189°F), and the ST cylinders were tested in MH15105. Samples were removed after 1, 2, 3, and 6 months of exposure and brought back to BNL for compressive strength tests. The results, summarized in Figures 27 and 28, show that the compressive strengths of both systems increased after exposure to the elevated temperatures of the manholes, demonstrating that the heat within the manholes can be used to post-cure the PC systems as presently formulated.

Based upon these results, a series of tests were done to further evaluate the strength properties of the VET PC system, which had been post-cured, using the heat within MH15105. The tests were done using 3-in. diameter by 6-in. long cylinders and 2 by 2 by 12-in. long beams. The test specimens were exposed to the heat within MH15105 for 3 months. Samples were removed after 1, 2, and 3 months of exposure and then brought back to BNL for testing.

Figure 29 shows an overall increase in the flexure and splitting tensile strengths of the VET system with time as a result of the post-curing of the system. Improvements in the flexural strength properties are shown in Figure 30. The load carrying capability of the system increases with the time of exposure and is most likely due to the post-curing of the system by the heat generated within the manhole.

4.4.3 In situ testing of samples made with stainless steel fibers. As a result of the problems associated with the rusting of the carbon steel fibers, a series of tests were done to evaluate the use of 1.5-in. long, corrugated, 430 stainless steel fibers as a replacement for carbon steel fibers. The stainless steel fibers, known as Xorex steel fibers, are manufactured by Novocon International, Inc. This is the same company which manufactures the carbon steel fibers. The cost of the 430 stainless steel fibers is approximately 4 times greater than that of the carbon steel fibers.

Preliminary tests were done in the laboratory to compare the flexural characteristics of PC beams made with the stainless steel fibers to PC beams made with the carbon steel fibers. The tests were done at 72° and 200°F using beams made with the VETrt PC system. The test results are illustrated in Figures 31 and 32. In general, the results indicate that at 72°F: (a) the FYS of the beams made with the stainless steel fibers is approximately 30 percent higher than the FYS of the beams made with the carbon steel fibers, (b) the ultimate flexure strength of the beams made with the stainless steel fibers is approximately 6 percent higher than that measured for the beams made with the carbon steel fibers, and (c) the deflection, at ultimate strength, of the beams made with the stainless steel fibers is approximately 37 percent lower than that measured for the beams made with the carbon steel fibers. When tested at 200°F the beams made with the stainless steel fibers

Figure 27. Compressive strength of VET mortars post-cured in situ.

Figure 28. Compressive strength of ST mortars post-cured in situ.

Figure 29. Variation of strength properties with in situ time of exposure for the ambient temperature-cured VET PC system.

Figure 30. Variation of load vs. deflection characteristics with in situ time of exposure in MH15105 for the ambient temperature-cured VET PC system.

Figure 31. Load-deflection characteristics, at 72°F, of VETrt PC beams made with carbon steel and 430 stainless steel fibers.

Figure 32. Load-deflection characteristics, at 200°F, of VETrt PC beams made with carbon steel and 430 stainless steel fibers.

continue to exhibit higher FYS and ultimate strength values. However, the ductility of the beams made with the stainless steel fibers increases and is similar to that for the beams made with the carbon steel fibers.

Upon completion of the laboratory tests, VETrt PC beams and cylinders made with the stainless steel fibers were placed into test in MH15105. Test results for samples removed after 1, 3, and 12 mo. of exposure are summarized in Table 12. Test results for samples made with carbon steel fibers are included for comparison. Flexural characteristics for samples removed 3 and 12 mo. of exposure are illustrated in Figure 33.

The results indicate that at 200°F the strength properties of the samples made with the stainless steel fibers are very similar to those measured for the samples made with the carbon steel fibers. Figure 33 illustrates that after 3 mo. of exposure the load-deflection characteristics of both systems are almost identical. After 12 mo. of exposure the FYS of the beams made with stainless steel fibers has decreased slightly and the system has become more ductile. It should be noted that after 12 mo. of exposure there was no evidence of any rust or spalling on those samples made with the stainless steel fibers. After 3 mo. of exposure, some rust stains were noted on those samples made with carbon steel fibers. However, no spalling was evident.

To further evaluate the corrosion resistance of the 430 stainless steel fibers, open-topped jars containing an equal number of carbon steel and stainless steel fibers were placed in MH15105 for a period of 11 months. The fibers are visually examined on a monthly basis to determine the extent of corrosion of each type of fiber. The carbon steel fibers began to rust within 1 mo. of being placed in test while the stainless steel fibers exhibited no evidence of rusting after 11 months of exposure (Figure 34).

Table 12. Properties of the VETrt PC system made with carbon steel and 430 stainless steel fibers.

PC SYSTEM	MH NO.	AVERAGE MANHOLE AIR TEMP., (deg.)	EXPOSURE TIME	TEST TEMP (deg.)	FLEXURAL YIELD STRENGTH, psi	ULTIMATE FLEXURE STRENGTH, psi	SPLITTING TENSILE STRENGTH, psi	WATER ABSORPTION, wt%	
								IN SITU	LAB TEST
VETrt w/CS Fbrs	Control	--	--	200 F	2095	2580	1785	--	0.17
	15105	196 F	1 mo.	200 F	2200	2570	2075	0.05	0.11
			3 mo.	"	2360	2650	1890	0.04	0.11
			12 mo.	"	1810	2880	--	0.08	.027
VETrt w/SS Fbrs	Control	--	--	200 F	2180	2600	--	--	0.20
	15105	196 F	1 mo.	200 F	2210	2750	2070	0.02	0.12
			3 mo.	"	2140	2685	--	0.08	0.24
			12 mo.	"	2330	2770	2110	0.12	0.11

NOTES: All values are an average of a minimum of 3 test specimens.
VETrt = vinyl ester-TMPTMA system, cured at room temperature conditions.
w/CS fbrs = the PC system is made with carbon steel fibers.
w/SS fbrs = the PC system is made with 430 stainless steel fibers.

Figure 33. Load-deflection characteristics, at 200°F, of VETrt PC beams made with carbon steel and 430 stainless steel fibers after 3 and 12 mo. exposure in MH15105.

Figure 34. 430 stainless steel and carbon steel fibers after 11 mo. exposure in MH15105.

4.4.4 In situ load testing of VETrt PC beams. In situ load-deflection tests were done in MH15105 to evaluate the creep characteristics of the fiber-reinforced VETrt PC system. The tests were done using 2-in. by 8-in. by 6.25-ft long beams (Figure 35) which were cast in the laboratory at room temperature conditions. The beams were not post-cured.

The beams were set up as a simply supported beams loaded with a concentrated load of 250 lb at the midpoint of the span. This loading produced a computed maximum bending stress of 844 psi. Assuming that the maximum permitted design stress is 50 percent of the flexural yield strength (FYS = 2005 psi at 200°F, see Table 11), the loading produces a computed maximum bending stress which is 84 percent of the allowable design stress.

The deflection characteristics of the beams were monitored by measuring the deflection at the quarterpoints with dial gauges (Figure 36). Initial deflection data was collected when the beams were placed into test and at subsequent intervals of approximately 3 to 5 weeks.

Figure 35. In situ creep test beam in place in MH15105.

Figure 36. Dial gauge used to measure deflections.

The in situ testing of the fiber-reinforced VETrt PC beam was stopped after 54 weeks. A visual inspection of the beam, after removal from the manhole, indicated no significant deterioration of the PC. The beam had been slightly discolored while in test and some of the carbon steel fibers exposed at the surface of the beam had begun to rust. However, with the exception of one small area of approximately 1 sq in., there was no scaling of the surface of the beam due to the rusting of the fibers.

The deflection data, which is presented in Figure 37, indicates that after 54 weeks the midspan deflection was measured to be approximately 0.748 in. The data also illustrates that the beam continued to creep throughout the duration of the test. In addition, there was a noticeable (7 percent) increase in deflections measured after the 24th and 28th weeks of the test. This large increase in deflection may, in part, have been due to the increase in the air temperature in the manhole. Over the first 17 weeks of the test the air temperature varied between 179° and 192°F and averaged 186°F. Over the last 30 weeks the air temperature varied between 200° and 208°F and averaged 204°F. This represents an increase in the average air temperature of the manhole of 10 percent. It should also be noted that the rate of creep, before and after the increase in the manhole air temperature, remained relatively constant at approximately 0.010 in./wk.

Figure 37. In situ creep test results for the fiber-reinforced VETrt PC beam tested in MH15105.

Based upon these results, it was hypothesized that conventional steel reinforcing bars (rebars) could be used to help control the creep being exhibited by the VETrt PC system. To verify this hypothesis, a fiber-reinforced VETrt PC beam containing steel rebars was placed in test in MH15105 for a period of approximately 21 weeks.

The dimensions of the new beam placed into test were identical to those of the beam which had been removed from the manhole, i.e. 2 in. thick by 8 in. wide by 6.25 ft long. The beam was analyzed using a working stress analysis to determine the amount of reinforcing required to support a concentrated load of 250 lb located at the midpoint of the span. Based on this analysis three No. 3 reinforcing bars were placed on 2 in. centers at a distance of 1.25 in. from the top of the beam.

The test results, which are illustrated in Figure 38, indicate that the rebar did not reduce the deflections exhibited by the VETrt PC system nor did it reduce the rate of creep. In fact the deflections measured for the beam containing the rebar (Beam No. 2046) were greater than those measured for the beam which had no rebar (Beam No. 1573) and the rate of creep measured for Beam No. 2046 was almost identical to that measured for Beam No. 1573.

Figure 38. In situ creep test results for VETrt PC beams made with and without conventional reinforcing steel.

An explanation for the increased deflections exhibited by Beam No. 2046 was not readily apparent. With one exception, the conditions under which the two beams were tested were identical. The only difference between the two tests being that the ambient air temperature in MH15105 was on average 14 degrees higher during the time that Beam No. 2046 was in test. While this may have accounted for some of the increase noted in the deflections it is unlikely that it was the sole cause for the increase. It was therefore decided that tests would be done under controlled, laboratory conditions to evaluate the creep characteristics of fiber-reinforced VETrt PC beams made with and without steel rebar.

The laboratory creep tests were done in a walk-in oven using two 2-in. thick by 8-in. wide by 6.25-ft. long beams made with the fiber-reinforced VETrt PC system. One of the beams contained three No. 3 bars placed 2-in. on center at a distance of 1.25-in. from the top surface of the beam. These beams were identical to those tested in situ in MH15105.

As in the field, the beams were set up as simply supported beams with a concentrated load of 250 lb located at the midpoint of the span, Figure 39. This loading produced a computed maximum bending stress of approximately 844 psi. The deflection

Figure 39. Set-up for the laboratory-scale creep tests, with Beam No. 2036 in the foreground and Beam No. 2037 in the back right.

characteristics of the beams were monitored by measuring the deflections at the quarterpoints and midpoint of the span.

Prior to loading, the beams were subjected to a range of temperatures intended to simulate the conditions which are likely to exist in the field during placement of a typical PC manhole. The beams, which were cast at room temperature conditions (i.e. 75°F), were first heated for 4 days at 145°F to simulate the temperature within the manhole during placement of the PC. This segment of the preheating cycle was to have been run at 120°F but problems with the oven's control panel resulted in the beams being heated to 145°F. The beams were then heated for 2 days at 208°F to simulate the temperature conditions within an enclosed manhole which has been placed in service but has not yet been loaded, i.e. soil and pavement loads have not been applied to the roof of the manhole. The beams were then loaded.

The beams were load tested for a period of 8 wk. With the exception of a 3 day period during the third week, the beams were tested for 7 wk at an average temperature of approximately 218°F. (It was necessary to shut down the oven for 3 days during the test.

The loads were left in place during the shutdown and the temperature averaged 78°F.) After 7 wk, the test temperature was raised to 400°F, to simulate the temperature conditions within a manhole during a large steam leak. The temperature was maintained at 400°F for 48 hr, after which it was returned to 218°F and the tests were stopped. The deflection measurements obtained for each beam are graphically summarized in Figures 40 and 41.

Figure 40 illustrates that, as in the field tests, the deflections exhibited by the beam containing the rebar (Beam No. 2037) are greater than those exhibited by the beam without the rebar (Beam No. 2036). After 7 wk the midpoint deflection for Beam No. 2037 was measured to be 0.294 in. This is approximately 25 percent greater than that measured for Beam No. 2036.

A comparison of the deflections measured for the in situ and laboratory test beams, after 1 wk in test, indicate that if the PC is allowed to post-cure in situ prior to being loaded, the deflection of the system can be reduced. After 1 wk, the deflections measured for the beams being tested in the laboratory were significantly less than those measured for the beams tested in situ. The midspan deflection of Beam No. 2037 is 45 percent less than that measured for Beam No. 2046. The beams tested in situ were cast at room temperature conditions but were not "heat treated" prior to being loaded.

Figure 41 illustrates the affects of increasing the ambient temperature, from 200° to 400°F, on the load-deflection behavior of the beams. In general, both beams failed, refer to Figure 39. Beam No. 2036 failed catastrophically, i.e. it collapsed, while Beam No. 2037 was able to continue to support the applied load. However, the midspan deflection of Beam No. 2037 increased from 0.294 in., when measured at 200°F, to 1.254 in., when measured at 400°F. In addition, an examination of Beam No. 2037 indicated that there were numerous cracks in the tension face of the beam and that these cracks extended atleast halfway into the thickness of the beam. Deflection measurements made after the beam had been unloaded and allowed to cool to room temperature indicated the beam rebounded about 10 percent.

Results of tests done to determine the flexural properties of VETrt PC beams which had been placed in test in MH15105 indicated that the creep test beams might possibly fail under the imposed loading when the temperature was increased to 400°F, see Figure 42. The figure illustrates that the ultimate flexure strength of the VETrt PC system increased from 850 to 940 psi after 3 mo. of exposure in MH15105. However, these strength values were very close to the calculated stress of 844 psi imposed by the test load. Obviously there was not enough reserve strength in the PC system to prevent it from failing when the ambient temperature was raised to 400°F.

Figure 40. Laboratory and in situ creep test results for VETrt PC beams made with and without conventional steel reinforcing bars.

Figure 41. Load vs. deflection characteristics, measured at 200° and 400°F, for VETrt PC beams made with and without conventional steel reinforcing bars.

Figure 42. Variation of flexure load vs deflection characteristics, at 200° and 400°F, for the VETrt PC system after 3 mo. in MH15105.

4.4.5 Effects of field exposure on the properties of portland cement concrete systems. In situ testing of conventional portland cement concrete (PCC) was done using non-reinforced and fiber-reinforced PCC. The tests were done using 3-in. diameter by 6-in. long cylinders and 2- by 2- by 12-in. long beams. All samples were cast and stored at room temperature until they were placed into test seven to ten days after being cast. Table 12 summarizes the mix designs.

The tests were done in MH15105 and the results are presented in Table 13. The effect of elevated temperatures on the compressive strength is illustrated by comparing the 28-day compressive strength values measured for each mix at 72° and 200°F. Both mixes show a significant decrease in compressive strength as a result of being tested at an elevated temperature. The compressive strength of the non-reinforced PCC decreased from 4,045 to 2,030 psi and the compressive strength of the fiber-reinforced PCC decreased from 4,670 to 2,830 psi.

In general, all samples removed from test appeared to be in good condition with no visible deterioration. Compressive and flexure strength values for both PCC systems, measured at 200°F,

Table 12. Portland cement concrete (PCC) mix designs.

A. Non-reinforced PCC.

<u>Mix Component</u>	<u>Batch Wt Ratio</u>
Type I portland cement	1.00
3/8-in. crushed gravel	1.65
Blended silica sand	2.00
Mix water	0.42
Air entraining agent	2.5 fl. oz.

Slump $\approx$ 2.5 in. Entrained air content $\approx$ 6 percent.

B. Fiber-reinforced PCC.

<u>Mix Component</u>	<u>Batch Wt Ratio</u>
Type I portland cement	1.00
3/8-in. crushed gravel	2.50
Blended silica sand	1.50
Mix water	0.43
1.5-in. steel fibers	0.092
Air entraining agent	2.5 fl. oz

increased after 3 mo. of exposure. Changes in the sample weight and water absorption characteristics of both mixes also were noted. Of particular interest is the data regarding weight change. Both PCC systems exhibited reductions in weight. The weight loss is most likely due to a loss of moisture from the samples, not from any physical deterioration. The continued loss of moisture from the samples may, at some point, adversely affect the strength development of the systems by reducing the rate at which the cement in the matrix hydrates.

Con Ed indicated to BNL, after the start of the tests, that it would have been more representative of actual field placement conditions if the PCC samples had been cast and cured at an ambient temperature of 100° to 125°F. In general, this is the temperature range at which the concrete for a steam-valve manhole is normally placed. Subsequently, a second group of fiber-reinforced PCC cylinders and beams were cast and put into test in MH15105.

The samples were cast under three different sets of conditions to determine the effect of placement conditions on the strength properties of PCC. One series of beams and cylinders were cast at room temperature and moist cured in the molds for seven days. They were then demolded and stored at room temperature until tested. The second series of samples were cast at an ambient temperature of 110°F and cured in the molds at this temperature for 24 hours. The

Table 13. In Situ test results for non-reinforced and fiber-reinforced portland cement concrete.

Property	Non-Reinforced Concrete	Fiber-Reinforced Concrete
Compressive Strength, psi		
Initial 28-Day Strength		
at 72°F	4,045	4,670
at 200°F	2,030	2,830
After 1 mo. Exposure		
at 200°F	3,385	3,850
After 3 mo. Exposure		
at 200°F	3,510	4,155
Flexure Strength, psi		
Initial 28-Day Strength		
at 200°F	715	730
After 1 mo. Exposure		
at 200°F	670	730
After 2 mo. Exposure		
at 200°F	828	---
After 3 mo. Exposure		
at 200°F	765	815
Water Absorption, wt%		
Initial 28-Day Samples	6.13	7.17
After 1 mo. Exposure	6.10	7.61
After 2 mo. Exposure	6.27	--
After 3 mo. Exposure	6.55	6.75
Weight Change, wt%		
After 1 mo. Exposure	-3.95	-3.91
After 2 mo. Exposure	-3.10	--
After 3 mo. Exposure	-3.60	-2.94

samples were then demolded and stored in a laboratory oven at 190°F until tested. The third series of samples also were cast at an ambient temperature of 110°F and cured in the molds at this temperature for 24 hours. The samples were then demolded and placed into test in MH15105, the average ambient temperature of which was approximately 190°F. The results of the tests done to evaluate the properties of this group of samples is summarized in Table 14.

This data shows that the strength properties of the concrete cast and cured at elevated temperatures are significantly less than that of the concrete cast and moist cured at room temperature. When tested at 200°F, there was an average reduction in compressive

strength of 36 percent for the samples cast and cured at the elevated temperatures as compared to the samples cured at room temperature. Reductions in flexure strength values were also noted.

Table 14. Strength properties of fiber-reinforced PCC cast and cured at elevated temperatures.

<u>Casting/Curing Conditions</u>	<u>Test Temperature</u>	<u>Compressive Strength, psi</u>	<u>Ult. Flexure Strength, psi</u>
Cast, cured & stored at 72°F.	72°F	5,115	960
Cast, cured & stored at 72°F	200°F	4,180	610
Cast at 110°F, cured and stored in oven at 190°F.	200°F	3,225	405
Cast at 110°F, placed in test in MH15105.	200°F	3,930	640

Note: All strength data are 32-day strengths.

5.0 PRELIMINARY DESIGN OF A MANHOLE MADE WITH FIBER-REINFORCED POLYMER CONCRETE

5.1 Introduction.

A design study was made to replace a typical reinforced portland cement concrete manhole with a cast-in-place, fiber-reinforced polymer concrete (FPC) manhole.

The procedure used for the design was to consider the manhole as a series of plates: roof, sidewall, and foundation slab. Each plate was subjected to loads resulting from soil pressure, highway loading, and dead weight and was analyzed using classical plate theory. A similar design approach was used by BNL in the design and development of precast FPC natural gas vaults^[6].

This chapter discusses the loadings, material properties, and stress evaluations used in the design of manholes for the Con Ed steam distribution system.

5.2 Loading Conditions.

The loading acting on the manhole shall contain three components:

- (1) The dead weight of the manhole.
- (2) The effect of soil pressure on the manhole (unless a specified value is available use 110 lb/cu ft).
- (3) A live load component that shall be taken as one of the following (Note: the design criteria for a particular application should specify which of these is to be considered):

- (a) A uniform vertical load of 600 psf (such as required by the NYC building code).
- (b) The HS-20 AASHTO loading, which consists of the more severe of a uniform lane load of 640 lb/ft distributed over a 10 ft lane width, or two concentrated wheel loads of 20,800 lb each (including a 30 percent impact factor) spaced at 5 ft.
- (c) A 15 cubic yard concrete truck; the rear wheels of this truck produce four loads of 20,250 lb spaced at 5 ft in one direction and 6 ft in the other direction.

The forces acting on each element of the box by these loadings are discussed below.

5.2.1 Forces on the roof. The roof will be loaded with the dead weight of the roof slab plus any soil overburden placed as a uniform load on the cover plate. Because the roof will generally be close to the surface (the roof is usually about one foot below the ground surface), the highway loading is placed directly on the roof. The roof should be designed for either a uniform live load of 600 psf or a single wheel load of 20,800 lb placed at the center of the roof. For manholes that have plan dimensions greater than 10 ft, consideration should be given to placing the two or four wheel loads (depending on whether the box is designed for HS-20 or the 15 cu yd concrete truck) on the roof in a position leading to the highest bending moments.

5.2.2 Forces on the sidewalls. The loading on the sidewalls, which are in contact with the soil, is taken as the soil pressure (resulting from soil weight and highway loading) component that is normal to the surface of the plate (i.e., the loading on the vertical plates is equal to the horizontal soil pressure at the depth of interest). In all cases, the horizontal soil pressure is taken as one-half of the vertical pressure. While the actual loading on the wall will vary over the depth of the wall, it is recommended that the wall be designed for a uniform pressure equal to the average loading applied to the wall.

The loading component of the soil pressure due to its own weight (p_s) is:

$$P_s = \gamma z / 2 \quad (\text{Eq. 1})$$

where, γ = soil density, lb/cu ft
 z = depth below the surface, ft
 P_s = pressure, psf

The loading component for the 15 cu yd concrete truck is computed by converting the four wheel loads to a uniform loading over an area of 5 ft by 6 ft, and spreading the load by 45 degrees as depth from the surface increases. The pressure acting on the sidewall is one-half of the vertical component of the soil pressure. Therefore, the pressure acting on the sidewall is:

$$p_{ct} = 81,000 / [(2)(5+2z)(6+2z)] \quad (\text{Eq. 2})$$

The loading component for the HS-20 loading will be critical for the two wheel loads. The loading is taken to act on an area of 6 ft by 1 ft on the surface and to spread out at a 45 degree angle with depth. Therefore, the pressure acting on the sidewall is:

$$p_{HS} = 20,800 / [(2)(6+2z)(1+2z)] \quad (\text{Eq. 3})$$

The uniform pressure of 600 psf is not attenuated with depth so that the resulting load on the sidewall is:

$$P_{NYC} = 600/2 = 300 \text{ psf} \quad (\text{Eq. 4})$$

This pressure must be less than the allowable soil bearing pressure. If it is not, the plan dimensions of the manhole must be increased.

The actual loading on the sidewall will vary linearly over the depth of the wall. An average uniform loading will be used so that the design process may be expedited. Any errors which may result are well within the reliability within which the loads are known.

5.2.3 Forces on the foundation slab. The forces on the foundation slab shall be taken as a uniform pressure equal to the weight of the manhole plus the weight of the soil over the roof plus the total highway load acting on the roof divided by the area of the slab. Therefore,

$$P_{FS} = \gamma h + (W_B + W_H)/A \quad (\text{Eq. 5})$$

where, h = depth of the soil over the roof, ft
 W_B = weight of the manhole, lb
 W_H = 81,000 lb for the concrete truck
 = 41,600 lb for the HS-20 loading
 = 600 psf x A for the NYC building code
 A = plan area of the foundation slab, sq ft
 γ = soil density of 110 lb/cu ft

5.3 Material Properties.

The properties of FPC can be adjusted by the proper selection of resin type, resin content, and fiber characteristics. The most significant properties of the FPC that are used for design are the flexure strength of the mix and the ductility of the material when subjected to flexural loads. The flexure strength should be determined by a modulus of rupture test. The test should be continued to failure and the flexural yield strength (f_r) should be determined as the stress corresponding to the load at the end of the linear portion of the load vs. deflection curve. The design is based on an allowable flexural stress of $f_r/2$. The material used to construct the manholes should have sufficient ductility such that the area under the load vs. deflection curve between the end of the linear portion of the curve (the point defining f_r) and the failure load be at least ten times the area under the linear portion of the curve.

Other strength properties of interest include the shear strength of the material (v_f) and the modulus of elasticity (E). The modulus of elasticity can be found from the modulus of rupture test used to determine f_r .

A punching shear test should be run to evaluate the shear strength. The allowable shear stress in the manhole should be limited to $v_f/3$.

FPC composite materials have a density of ≈ 150 lb/cu ft.

5.4 Stress Evaluations.

The manhole consists of six plate elements. Classical plate theory was used to evaluate the bending stresses. The loading on the sidewalls and foundation slab will be uniform as discussed in Sections 5.2.2 and 5.2.3. The loading on the roof may be either uniform or a point load at the center of the plate as discussed in Section 5.2.1.

Because the manholes are cast monolithically (or in some cases sections of the manholes are connected with joints having strengths equivalent to a monolithic pour), it is recommended that the boundary conditions of adjoining plates be taken as fixed. Therefore, all foundation slabs can be designed as having fixed boundary conditions. Sidewalls will have three sides fixed and the edge adjoining the roof will be fixed, if a FPC roof is adequately joined to the sidewall, and free, if not. The roof will be fixed if the sidewall-cover joint is adequate. If not, the edges of the cover will be simply supported.

Solutions for these load cases are given in tabular form by Szilard [7].

5.5 Preliminary Design Calculations.

5.5.1 Design assumptions. The following assumptions have been used for the design:

- (1) The design includes the effect of temperature on material properties but does not include thermal expansion loads acting on the manhole. The thickness of the sidewalls are likely to increase by as much as 50 percent if the expansion loads are to be resisted by these walls.
- (2) The primary load on the manhole is that arising from a 15 cu yd concrete truck placed near the manhole.
- (3) The top of the manhole is placed with 1 ft of soil on the roof.
- (4) The ductility of the material is assumed to satisfy the requirements discussed in Section 5.3, i.e. the total area under the load vs. deflection curve be at least ten times the area under the curve up to the point used to define the flexural yield strength (end of the linear portion of the load-deflection curve).

5.5.2 Preliminary design. Preliminary designs were developed for a manhole to be constructed using each of the three PC systems under evaluation, i.e. the VET system, the ST system, and the PF system.

Two design temperatures were considered, 285° and 400°F. As stated in Section 5.3, the design of the manhole will be governed by the flexural properties of each system. Table 15 summarizes the typical properties of each PC system at 285° and 400°F.

The flexural yield strength of each system at 285° and 400°F is as follows:

FPC System	Flexural Yield Strength, psi	
	285°F	400°F
VET	2070	1440
ST	1625	930
PF	1620	1390

One half of each of these values was used for design purposes.

The dimensions of the manhole are assumed to be 10 by 12 ft in plan and 8 ft high (Figure 43). The design follows the procedures outlined in Section 5.2.

Table 15. Typical properties of the candidate PC systems at 285° and 400°F.

PC SYSTEM	FLEXURAL YIELD STRENGTH, psi	FLEXURAL MODULUS of ELASTICITY, psi	SPLITTING TENSILE STRENGTH, psi	COEFFICIENT of THERMAL EXPANSION, in./in./deg F	COEFFICIENT of THERMAL CONDUCTIVITY, BTU/hr/ft/deg F
VET					
@ 285 deg F	2070	2.09 x E+6	1900	9.3 x E-6	1.79
@ 400 deg F	1440	0.88 x E+6	1385	10.2 x E-6	1.70
ST					
@ 285 deg F	1625	1.54 x E+6	1495	9.7 x E-6	1.75
@ 400 deg F	930	0.64 x E+6	965	9.3 x E-6	1.55
PF					
@ 285 deg F	1620	1.45 x E+6	1630	8.2 x E-6	1.42
@ 400 deg F	1390	1.19 x E+6	1505	7.2 x E-6	1.42

NOTE: Drawing not to scale.

Figure 43. Layout of a typical Con Ed steam-valve manhole.

5.5.2.1 Sidewall design.

The load on the 8 by 12 ft sidewall consists of the soil pressure (Eq. 1) and the concrete truck (Eq. 2). The resulting pressures to the top of the wall ($z = 1$ ft), the bottom of the wall ($z = 9$ ft), and the average are as given below.

Load on the sidewall.

Load	Pressure, psf		
	Top	Bottom	Average
Soil	55	495	
Concrete Truck	723	73	
TOTAL	778	578	678

The maximum bending moment is calculated assuming that the plate is fixed at the four boundaries (Szilard, Case 80). The moment is:

$$M_{\max} = 0.075p_oL^2 = 0.075 \times 678 \times 8^2 = 3254 \text{ ft lb/ft}$$

The required thickness (t) is:

$$t = [6M_{\max}/f_{\text{allow}}]^{1/2}$$

The required thicknesses (t_w of Fig. 32) of the sidewalls for each of the PC systems are as follows:

FPC System	Required sidewall thickness (t_w), in.	
	Design Temperature, °F	
	285°	400°
VET	4.35	5.20
ST	4.90	6.50
PF	4.90	5.30

5.5.2.2 Foundation slab design.

The foundation slab is designed to carry the combined weight of the box (estimated to be 61,800 lb), overburden soil (estimated to be 13,200 lb), and the concrete truck (81,000 lb). Using Eq. 5 this results in a plate bearing pressure of 1300 psf. The maximum bending moment is calculated assuming that the slab is fixed at the four boundaries (Szilard, Case 80). The moment is:

$$M_{\max} = 0.064p_oL^2 = 0.064 \times 1300 \times 10^2 = 8320 \text{ ft lb/ft}$$

This moment requires the following slab thicknesses (t_f):

FPC System	Required foundation thickness (t_f), in.	
	Design Temperature, °F	
	285°	400°
VET	6.90	8.30
ST	7.80	10.40
PF	7.80	8.50

5.5.2.3 Roof slab.

The roof slab was designed to carry the weight of the slab itself (conservatively estimated at 150 psf), one foot of overburden soil (110 psf), and the total weight of the concrete truck distributed uniformly over the roof ($81000/120 = 675$ psf). The moments are computed from Case 80 of Szilard. The maximum moment is:

$$M_{\max} = 0.064p_oL^2 = 0.064 \times (150+11+675) \times 10^2 = 5984 \text{ ft lb/ft}$$

The required thickness is increased to account for the manhole cutouts. If area replacement is used to account for the cutouts the thickness should be increased by a factor of $[11/(11-2.75) = 1.33]$. The required thicknesses are determined from the following equation:

$$t = 1.33[6M_{\max}/f_{\text{allow}}]^{1/2}$$

The following slab thicknesses (t_r) are required:

FPC System	Required roof thickness (t_r), in.	
	Design Temperature, °F	
	285°	400°
VET	7.80	9.40
ST	8.80	11.70
PF	8.90	9.60

5.5.3 Design Summary.

A summary of the required design thicknesses for each of the components of the manhole is presented below.

FPC System	Required design thickness, in.		
	t_w	t_f	t_r
VET @ 285°F	4.35	6.90	7.80
@ 400°F	5.20	8.30	9.40
ST @ 285°F	4.90	7.80	8.80
@ 400°F	6.50	10.40	11.70
PF @ 285°F	4.90	7.80	8.90
@ 400°F	5.30	8.50	9.60

Note: t_w = thickness of the walls, t_f = thickness of the floor, and t_r = thickness of the roof.

5.6 Preliminary Design of a Full-Scale, Steam-Valve Manhole by Con Ed.

A preliminary design of a VET PC steam-valve manhole was also performed by the Con Ed Civil Design Division. In general, the Con Ed design utilized a working stress design approach to analyze and design the manhole. The roof support system was designed as a series of beams; B1, B2, and B3 (see Figure 44). B1 and B2 are the support beams around the openings in the roof and B3 is the "slab" which spans the center of the roof between the openings. To help control deflections and creep conventional reinforcing steel was added to the beams (B1 and B2) around the openings in the roof. The walls were considered to be one large beam.

The design assumed the manhole was located 3 ft below street level and that it had the following interior dimensions:

Length = 9 ft (clear).

Width = 6 ft 4 in. (clear).

Floor to ceiling height = 6 ft 8.5 in. (clear).

The design also assumed that the PCC floor system was intact and in good condition and would not need to be replaced. Dowels would be used to anchor the walls to the PCC floor slab.

The manhole was designed for a service temperature of 240°F. At this temperature the VET PC system has the following properties:

Flexural yield strength	1,805 psi
Flexural modulus of elasticity	1.67 x E+6 psi
Compressive strength	10,395 psi

In summary, the design required that the sidewalls have a minimum thickness of 4.5 in. and that the roof beams have a minimum thickness of 8.0 in. The design calculations are presented in Appendix B.

Plan View

Elevation

NOTE: Drawing not to scale.

Figure 44. Plan of the VET PC steam-valve manhole designed by the Con Ed Design Civil Division.

6.0 PRELIMINARY COST ANALYSIS

The following analysis provides a preliminary estimate of the costs associated with the field placement of a steam-valve manhole consisting of a PCC floor slab and PC walls and roof. The estimate was provided by Polymer Construction Specialties (PCS), Inc. of Patchogue, NY. PCS Inc. is a construction company located on Long Island that specializes in projects involving polymer concrete materials.

The estimate includes the cost for fabricating and placing all necessary formwork, mixing and placement of the PCC floor, and mixing and placement of the PC wall and roof systems. The estimate does not include the cost of excavating and removing the existing manhole structure nor does it include the cost for backfilling the new manhole and replacing the pavement.

The cost estimate was based on the following assumptions.

Manhole size = 8 ft long by 5 ft wide by 7 ft high.

Floor thickness = 12 in., cast using conventional PCC.

Wall thickness = 5 in.

Roof thickness = 6.5 in., with two 2.75 ft by 2.75 ft openings for the manhole rings to be located diagonally opposite each other.

The walls and roof will be cast using the fiber-reinforced VET PC system. The materials cost of this system was estimated to be approximately \$80/cu ft.

PCS Inc. also provided a comparative estimate for a manhole cast completely of conventional PCC. The walls of the manhole were assumed to have a minimum thickness of 10 in. and the roof a minimum thickness of 12 in. Table 16 summarizes the cost estimates made by PCS.

The estimates indicate that the cost of the cast-in-place PC manhole is approximately \$32,316 compared to a cost of \$20,800 for the PCC manhole. It should be noted that while the cost of a PC manhole is approximately 50 percent higher than that of a conventional PCC manhole the increased service life of a PC manhole will offset the initial increase in investment.

Table 16. Comparative cost estimates for the field placement of cast-in-place PC and PCC manholes.**

<u>Item</u>	<u>Labor</u>	<u>Materials</u>	<u>Equipment</u>	<u>PC Mix</u>	<u>Total</u>
A. Cost estimate for the PC manhole.					
Slab*	\$1,500	\$ 750	\$ 250	\$ 200	\$ 2,700
Walls	9,875	2,090	3,000	5,680	20,645
Roof	5,150	1,525	1,000	1,296	8,971
Totals	\$16,525	\$4,365	\$4,250	\$7,176	\$32,316
* The slab is to be cast using conventional concrete.					
B. Cost estimate for a conventional PCC manhole.					
Slab	\$1,500	\$ 750	\$ 250	\$ 200	\$ 2,700
Walls	8,000	2,000	1,500	500	12,000
Roof	4,250	1,000	750	100	6,100
Totals	\$13,750	\$3,750	\$2,500	\$ 800	\$20,800*
* The total cost may not include the cost of the steel reinforcing.					

**Cost estimate by PCS Inc.

7.0 SUMMARY AND RECOMMENDATIONS

7.1 Summary.

Deteriorated steam manholes in the steam distribution system of the Consolidated Edison Company of New York, Inc. (Con Ed) are being rebuilt using conventional portland cement concrete (PCC). Because the manholes are located beneath the streets and sidewalks of New York City, there is a great emphasis to minimize the time involved in rebuilding the manhole. Therefore, the manholes are often cast and placed into service very quickly. Consequently, the concrete is often only a few days old when it is subjected to the harsh environment of the manholes. In addition, by placing the manhole into service so quickly the concrete is not allowed to fully develop the strength and physical characteristics that it would normally attain under ideal curing conditions. This can sometimes result in the development of a substandard quality of concrete. The combination of quickly pouring and placing the newly cast PCC manhole into service and the severe operating conditions to which the manholes are exposed invariably result in a shorter than desired service life.

With the development in recent years of more advanced materials of construction, such as polymer concrete (PC), it may be possible to cast manholes that have a longer maintenance-free service life resulting from the improved physical and mechanical properties of these materials.

The Process Materials Group of the Energy Efficiency and Conservation Division, Department of Applied Science at Brookhaven National Laboratory (BNL) conducted a research program for Con Ed regarding the development of high temperature, corrosion resistant polymer concretes for use as construction materials in its underground steam distribution system. The results of this program are described in this report.

The primary objective of the program was to develop and experimentally evaluate PC materials that could be used as an alternative construction material to steel-reinforced PCC. The exposure conditions within a typical steam-valve manhole required that any PC system being considered for use exhibit the following characteristics: (a) it should be thermally stable at temperatures up to 400°F, (b) it should have good strength and stiffness at temperatures up to 400°F, (c) it should be impermeable to moisture penetration, and (d) it should have good resistance to possible chemical attack. The PC system should also lend itself to cast-in-place and/or precast applications.

Three PC systems were developed and evaluated. Each system consisted of four components: a polymer binder system, a blended fine aggregate system, a graded coarse aggregate system, and a fiber reinforcement. The primary difference between each system was the monomer/resin system used as the binder. The three binder systems evaluated were a styrene-trimethylolpropane trimethacrylate (TMPTMA) based [ST] monomer system, a vinyl ester-TMPTMA based [VET] monomer system, and a phenol formaldehyde [PF] resin system. Each binder system is thermally stable at 400°F.

One and one-half inch long corrugated, carbon steel fibers were selected for use as the reinforcing system. Synthetic fibers, such as graphite and Kevlar aramid fibers, also were evaluated, but the carbon steel fibers were found to provide the greatest improvements in load carrying capacity and ductility. Stainless steel fibers were later evaluated when results of the in situ field tests indicated that corrosion of some of the carbon steel fibers exposed at the surface of the samples was causing some of the PC systems to deteriorate.

Preliminary evaluation of each candidate system was based upon the results of a series of laboratory-scale tests designed to (a) determine the physical and mechanical properties of the systems over a temperature range of 72° to 400°F and (b) to determine if exposure to simulated field conditions deteriorated these properties.

The results of the laboratory tests indicated that the strength properties of each system decrease with increasing temperature. Compressive strengths for the three systems generally range between 12,220 and 14,270 psi at 72°F and between 4,730 and 9,415 psi at 400°F. The flexural yield strengths vary between 2,145 and 2,865 psi at 72°F and 930 and 1,440 psi at 400°F. The highest strength values are generally exhibited by the VET PC system. The strength reductions were due to a softening of the polymer binder systems, and not to any physical deterioration of the PC systems.

Results of small-scale, short-term load-deflection tests showed that the VET PC system is the most rigid of the systems, while the ST PC system is the most flexible. Each of the three systems will creep under a sustained load.

The coefficients of thermal expansion for the PC systems are higher than those for conventional PCC, which has an average coefficient of thermal expansion of 5.5×10^{-6} in./in./°F. The coefficients for each system vary slightly depending upon the binder, and also tend to vary with temperature, generally increasing slightly with increases in temperature. The coefficients of thermal conductivity for the PC systems are within the range of values associated with conventional PCC, i.e. they varied between 0.8 and 2.1 BTU/hr/ft/°F. Thermal conductivity

values were found to vary slightly with the type of binder and also were found to vary slightly with temperature.

Water absorption values for the PC systems were found to be well below those of conventional PCC, which normally vary between 5 and 7 wt%. The PC systems had average water absorption values varying between 0.41 and 1.86 wt%.

Tests were done under simulated field conditions in an autoclave to evaluate how each system might perform in the field. The tests showed that exposure to simulated field conditions resulted in a slight decrease in compressive strength for the PF system, while the strengths of the VET and ST systems remained relatively constant. Visual examinations of the samples throughout the tests indicated no significant deterioration due to autoclaving. The results suggested that each of the PC systems should perform well in the field.

When the laboratory-scale tests were completed, in situ field tests were started. The objectives of the field tests were: (a) to evaluate the effects of exposure to actual field conditions on the physical and mechanical properties of PC and PCC systems, (b) to determine if the heat generated within a typical manhole could be used to post-cure a PC system, and (c) to evaluate the long-term creep characteristics of a PC beam under load.

Samples were tested in situ in three operational steam-valve manholes. The manholes (MH) used in the tests were MH7498, MH7500, and MH15105. The average air temperature within each manhole was as follows: MH7498 - 177°F, MH7500 - 160°F, and MH15105 - 194°F. Four PC systems and two PCC systems were tested in situ. The PC systems were the ST, STP, VET, and PF systems. The PCC systems were a non-reinforced portland cement concrete system and a fiber-reinforced portland cement system. The specimen placed in test included 2- by 2- by 12-in. long beams and 3-in. diameter by 6-in. long cylinders.

In general, most of the samples removed within the first 12 months of testing were in good physical condition; i.e. no significant deterioration of the surfaces was noted. The exceptions were the ST, PF, and VET samples removed from MH7498 after 6 to 8 months of exposure. These samples were beginning to show signs of scaling caused by the rusting of some of the steel fibers located near the surfaces of the samples. An examination of these samples after testing indicated that the rusted fibers were present only in that region located near the surface of the samples and that the rusting had not progressed to the fibers located in the interior of the samples.

Results of the splitting tensile strength and flexure strength tests showed that each of the PC systems exhibits some reduction in strength as a result of exposure to the environment within the

manholes. However, these reductions in strength had been predicted by the results of the laboratory-scale autoclave tests. After 6 to 9 months of exposure in the manholes, the flexural yield strength of the PC systems, measured at 160° to 200°F, varied between 890 and 1870 psi, with the VET PC system exhibiting the highest strengths.

Results of in situ exposure tests done on ST and VET PC beams and cylinders cast and cured at room temperature indicated that the heat generated within the steam-valve manholes can be used to post-cure the PC systems. The flexural yield strength of the VET PC system was found to increase 12 percent after 3 mo. of exposure in MH15105.

The results of tests done to evaluate the use of 430 stainless steel fibers as a replacement for carbon steel fibers indicated that at 200°F the strength properties of the samples made with the stainless steel fibers are very similar to those for samples made with the carbon steel fibers. In addition, the stainless steel fibers do not deteriorate. In situ testing of exposed fibers in MH15105 indicated that carbon steel fibers began to rust within 1 mo. of being placed in test while the 430 stainless steel fibers exhibited no evidence of rusting after 11 mo. of exposure.

In situ load testing in MH15105 (at an ambient temperature of $\approx 196^\circ\text{F}$) of a 2-in. by 8-in. by 6.25 ft. long fiber-reinforced VETrt PC beam cast at room temperature indicated that this system will creep under a sustained load. When tested for 54 weeks at 84 percent of its design capacity the beam was found to deflect approximately 0.748 in. at midspan. The rate of creep was calculated to be approximately 0.010 in./wk.

The results of laboratory and in situ load tests of fiber-reinforced VETrt PC beams containing conventional reinforcing bars indicated that at 200°F the system continues to creep under a sustained load, i.e. the addition of conventional reinforcing bar does not appear to help control the creep exhibited by this system.

Results of tests done on fiber-reinforced PCC samples cast for use in the in situ exposure tests showed that the strength properties of concrete cast and cured at elevated temperatures are significantly less than those for concrete cast and cured at room temperature. When tested at 200°F, there was an average reduction in compressive strength of 36 percent for the samples cast and cured at elevated temperatures ($f_c = 3225$ psi) as compared to the samples cast and cured at room temperature ($f_c = 4890$ psi). Reductions in flexure strength values also were noted.

In situ test results for non-reinforced and fiber-reinforced PCC samples after 3 months of exposure in MH15105 showed that the samples were in good condition and that the strength properties had increased slightly. The most significant change noted in either of

the PCC systems was that both systems showed a weight loss. This was most likely due to a loss of moisture from the samples and not to any physical deterioration. The continued loss of moisture from the samples may at some point adversely affect the strength development of the system by reducing the rate at which the cement in the matrix hydrates.

A preliminary design study was made to determine the necessary floor slab, wall, and roof thicknesses required to replace a typical reinforced PCC manhole with a cast-in-place, fiber-reinforced PC manhole. The design approach used classical plate theory by considering the manhole to be a series of plates subjected to loads resulting from soil pressures, highway loading, and dead weight. Designs were performed for each PC system under evaluation. The preliminary design analysis indicated that the required wall thicknesses will vary between 4.35 and 6.50 in. depending upon the PC system used and the required design temperature. The roof slab will vary between 7.80 and 11.70 in. A preliminary design by the Con Ed Civil Design Division produced similar results.

Polymer Construction Specialties, Inc. did a preliminary cost analysis for BNL to provide an estimate of the costs associated with the placement of a 8 ft by 5 ft by 7 ft high cast-in-place PC manhole made with the VET PC system. A comparative estimate also was done for a manhole cast with conventional PCC. The estimates showed that the cost of the cast-in-place PC manhole is approximately \$32,316, compared to \$20,800 for the PCC manhole. It should be noted that while the cost of a PC manhole is approximately 50 percent higher than that of a conventional PCC manhole the increased service life of a PC manhole will offset the initial increase in investment.

In general, the results of the laboratory and in situ field tests indicate that the physical and mechanical properties and the corrosion resistance characteristics of the vinyl ester-TMPTMA (VET) PC system are superior to those of the other PC systems evaluated. However, the suitability of using the VET PC system as a structural material in the construction of underground, steam-valve manholes would, at present, appear to be limited by several factors which influence the performance of the system at elevated temperatures. As a result, the program was not carried beyond the design stage and full-scale testing of a PC manhole was not performed. The factors influencing this decision included the following:

(a) The VET PC system exhibits outstanding strength properties at 72°F, e.g. the system has a compressive strength of 14,270 psi and a flexural yield strength of 2,865 psi. However, test results have shown that the strength properties decrease significantly with increases in temperature. When compared to values measured at 72°F, the VET PC system

exhibits a 20 to 25 percent decrease in strength at 240°F and a 50 percent decrease in strength at 400°F.

(b) Long-term field tests performed on beams made with and without conventional reinforcing bars have indicated that the system exhibits an excessive amount of creep when loaded at 84 percent of its theoretical design capacity. Efforts to solve this problem have, to date, been unsuccessful.

(c) The lack of established design methods makes it difficult to accurately predict how the system will perform in the field, particularly at elevated temperatures. Conventional reinforced concrete design theory was used in the design studies performed in this program. It was also used to design the in situ creep tests. The results of the creep indicate that the assumptions made during the design of the experiments did not adequately predict the results which were obtained.

7.2 Recommendations.

Based upon the results presented in this report it is concluded that the PC systems evaluated in this program are not, at this time, ready for use as a construction material for steam-valve manholes. Additional work will need to be done to address the limitations of the materials at elevated temperatures before they are ready for use in the field. Suggested areas of research include the following:

(a) Because the use of PC as a structural material is still relatively new there are, at present, no established design standards which will accurately predict actual field performance, particularly at elevated temperatures. As a result, additional laboratory and field tests need to be done to completely define the behavior of PC at ambient and elevated temperature conditions. One area in particular which needs to be addressed is creep. Tests results have shown that under the presently selected design loads the creep exhibited by the system is excessive. A more extensive series of load tests needs to be done to fully define the creep characteristics and to identify acceptable design limitations.

(b) Before a full-scale steam-valve manhole is built and put into service, at least one small-scale (one-quarter or one-half scale) model should be load tested to verify the analysis used in the design of the manhole.

(c) Long-term in situ testing of PC samples should be done to gather as much information as possible about the performance and durability of the PC systems under actual field conditions.

(d) The VET PC system may be best suited for use in applications in which the maximum ambient temperature is less than 150°F. When compared to values measured at 72°F, the VET PC system exhibits only a 5 to 9 percent reduction in strength at 150°F as compared to a 20 to 25 percent decrease in strength at 240°F and a 50 percent decrease in strength at 400°F. Work should be done to more fully define the physical and mechanical properties of the VET PC system at temperatures of 150°F, or less.

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APPENDIX A.

In Situ Flexure Load vs. Deflection vs. Time of Exposure Test Data

Figure A1. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH7500 for the VET PC system.

Figure A2. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH7498 for the VET PC system.

Figure A3. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH15105 for the VET PC system.

Figure A4. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH7500 for the ST PC system.

Figure A5. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH7498 for the ST PC system.

Figure A6. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH15105 for the ST PC system.

Figure A7. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH7500 for the PF PC system.

Figure A8. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH7498 for the PF PC system.

Figure A9. Variation of flexure load vs. deflection characteristics vs. time of exposure in MH15105 for the PF PC system.

Figure A10. Variation of flexure load v. deflection characteristics vs. time of exposure in MH15105 for the STP PC system.

APPENDIX B

Calculations for the Preliminary Design of a VET PC Steam-Valve Manhole by the Con Ed Design Division

B.1 Design Assumptions.

(a) The interior dimensions of the manhole are as follows (refer to Figure 44):

Length = 9 ft (clear).
Width = 6 ft 4 in. (clear).
Height = 6 ft 8.5 in. (clear).

(b) Assume the manhole is approximately 3 ft below street level and that it is located in the middle of a two lane commercial/residential street.

(c) There is a 24-in. diameter insulated, steam main which runs through the middle of the manhole and the centerline of the steam main is located 2 ft 11.5 in. above the floor of the manhole.

(d) The concrete floor will remain in place and only the walls and roof will be cast of PC. Dowels will be used to anchor the walls to the concrete floor slab.

(e) To control deflections and creep in the roof, reinforcing steel will be used in the roof slab. The minimum amount of tension reinforcement to be used should be equal to that specified for use in concrete roof slabs, i.e. one No. 6 bar at a spacing of 12 in.

(f) The manhole should be designed for a service temperature of 240°F. The properties of the VET PC system at this temperature are:

Flexural yield strength (FYS)	1,805 psi
Flexural modulus of elasticity (E_{pc})	1.67 x E+6 psi
Compressive strength (f'_c)	10,395 psi

B.2 Design Analysis Using the Working Stress Method.

B.2.1 Design Values.

Use a factor of safety (FS) of 2 for all calculations.

The allowable flexural strength (f_r) is:

$$f_r = FYS/2 = 1805/2 = 902.5 \quad \text{Use 900 psi.}$$

The allowable compressive strength (f_{pc}) is:

$$f_{pc} = f'_c/2 = 10395/2 = 5197.5 \quad \text{Use } 5200 \text{ psi.}$$

The allowable tensile strength of the reinforcing steel (f_s) is equal to 24,000 psi and the modulus of elasticity (E_s) is equal to 29,000,000 psi.

$$\eta = E_s/E_{pc} = 29,000,000/1,670,000 = 17.37 \quad \text{Use } 17.5$$

$$k = [1 + (f_s/0.45nf_{pc})]^{-1} = 0.631$$

$$J = 1 - (k/3) = 0.789$$

$$p = kf_{pc}/2f_s = 0.038$$

$$K = kJf_{pc}/2 = 582.5 \quad \text{Use } K = 583$$

B.2.2 Design of Roof Slab Beam B1.

Use a uniform dead load (dead load of the PC + soil + asphalt and concrete subbase) of 410 lb/ft over the entire span and a partially uniform live load of 5,547 lb/ft (the concentrated highway loading which is transferred through the manhole chimney to the roof slab has been converted to a partially uniform load).

$$\begin{aligned} R_1 &= w_d l/2 + w_l a(2l-a)/2l \\ &= 410(6.67)/2 + 5,547(3.75)(2[6.67] - 3.75)/(2[6.67]) \\ &= 16,321 \text{ lb} \end{aligned}$$

$$V_0 = R_1 - (w_d + w_l)\chi \quad \text{when } \chi < 3.75 \text{ ft, Solving for } \chi:$$

$$0 = 16,321 - (410 + 5,547)\chi$$

$$\chi = 2.74 \text{ ft}$$

$$\begin{aligned} M_\chi &= R_1\chi - (w_d + w_l)\chi^2/2 \\ &= 16,321(2.74) - (410 + 5,547)2.74^2/2 \\ &= 22,355 \text{ ft-lb} \quad \text{or} \quad 268,255 \text{ in.-lb} \end{aligned}$$

Determine the total depth (t) of Beam B1:

$$d = (M_x / Kb)^{0.5} \text{ and } t = d + 1.5 \text{ in. (cover) Using } b = 12 \text{ in.}$$

$$= [268,255 / (583 \times 12)]^{0.5} = 6.2 \text{ in. Use } d = 6.5 \text{ in.}$$

$$t = 6.5 + 1.5 = 8.0 \text{ in.}$$

Determine the total area of reinforcing steel (A_s) required to reinforce Beam B1.

$$A_s = M_x / f_s J d$$

$$= 268,255 / [24,000 \times 0.789 \times 6.5] = 2.18 \text{ in.}^2$$

Five No. 6 bars have a total area of $5 \times 0.44 = 2.20 \text{ in.}^2$

Check the design calculations for Beam B1 to ensure that the stresses developed in the beam are less than the allowable design stresses.

$$\rho = A_s / b d$$

$$= 2.20 / (12 \times 6.5)$$

$$= 0.03$$

$$k = [2\eta\rho + (\rho\eta)^2]^{0.5} - \rho\eta$$

$$= [(2 \times 17.5 \times 0.03) + (0.03 \times 17.5)^2]^{0.5} - (0.03 \times 17.5)$$

$$= [1.05 + 0.28]^{0.5} - 0.53$$

$$= 0.62$$

$$J = 1 - (k/3)$$

$$= 1 - (0.62/3)$$

$$= 0.79$$

$$f_s = M_x / A_s J d$$

$$= 268,255 / [2.2 \times 0.79 \times 6.5]$$

$$= 23,746 \text{ psi}$$

$$f_c = 2\rho f_s / k \leq 0.45 f_{pc} ?$$

$$= [2 \times 0.03 \times 23,746] / 0.62 \leq 0.45 \times 5,200 ?$$

$$= 2,298 \text{ psi} \leq 2,340 \text{ psi } \underline{\text{OK}}$$

B.2.3 Design of Roof Slab Beam B2.

This beam is located on the short side of the opening to the manhole chimney. Use a uniform dead load of 410 lb/ft and a uniform live load of 5,547 lb/ft (total applied load is 5,957 lb/ft).

$$\begin{aligned} R_1 &= R_2 = (w_D + w_L)l/2 \\ &= (410 + 5,547) \times 3.75/2 \\ &= 11,169 \text{ lb} \end{aligned}$$

$$\begin{aligned} M &= (w_D + w_L)l^2/8 \\ &= [(410 + 5,547)(3.75)^2]/8 \\ &= 10,471 \text{ ft-lb} \quad \text{or} \quad 125,655 \text{ in.-lb} \end{aligned}$$

Determine the total depth (t) of Beam B2:

$$\begin{aligned} d &= (M/Kb)^{0.5} \quad \text{and} \quad t = d + 1.5 \text{ in. (cover)} \quad \text{Using } b = 12 \text{ in.} \\ &= [125,655/(583 \times 12)]^{0.5} \\ &= 4.24 \text{ in.} \quad \text{Use a minimum } d \text{ of } 6.0 \text{ in.} \\ t &= 6 + 1.5 = 7.5 \text{ in.} \end{aligned}$$

Determine the total area of reinforcing steel (A_s) required to reinforce Beam B2.

$$\begin{aligned} A_s &= M/f_s Jd \\ &= 125,655/(24,000 \times 0.798 \times 6) = 1.11 \text{ in.}^2 \end{aligned}$$

Three No. 6 bars have a total area of $3 \times 0.44 = 1.32 \text{ in.}^2$

Check the design calculations for Beam B2 to ensure that the stresses developed in the beam are less than the allowable design stresses.

$$\begin{aligned} \rho &= A_s/bd \\ &= 1.32/(12 \times 6) \\ &= 0.02 \end{aligned}$$

$$\begin{aligned}
 k &= [2\eta\rho + (\rho\eta)^2]^{0.5} - \rho\eta \\
 &= [(2 \times 17.5 \times 0.02) + (0.02 \times 17.5)^2]^{0.5} - (0.02 \times 17.5) \\
 &= [0.70 + 0.12]^{0.5} - 0.35 = 0.56
 \end{aligned}$$

$$\begin{aligned}
 J &= 1 - (k/3) \\
 &= 1 - (0.56/3) \\
 &= 0.81
 \end{aligned}$$

$$\begin{aligned}
 f_s &= M/A_s J d \\
 &= 125,655 / (1.32 \times 0.81 \times 6) \\
 &= 19,587 \text{ psi}
 \end{aligned}$$

$$\begin{aligned}
 f_c &= 2\rho f_s / k \leq 0.45 f_{pc} \quad ? \\
 &= (2 \times 0.02 \times 19,587) / 0.56 \leq 0.45 \times 5,200 \quad ? \\
 &= 1,399 \text{ psi} \leq 2,340 \text{ psi} \quad \text{OK}
 \end{aligned}$$

B.2.4 Design of Roof Slab Beam B3.

This beam runs parallel to Beam B1 and spans the center section of the roof. Design the entire slab as one large beam ($b=42$ in.). Use a uniform dead load of 410 lb/ft² (1436 lb/ft) and a uniform live load of 3796 lb/ft. This section of the roof will not contain any rebars.

$$\begin{aligned}
 R_1 &= R_2 = R_d + R_L = w_d l_1 / 2 + w_L l_2 / 2 \\
 &= (1,436 \times 6.67) / 2 + (3,796 \times 5.47) / 2 \\
 &= 15,171 \text{ lb}
 \end{aligned}$$

$$\begin{aligned}
 M &= w_d l_1^2 / 8 + R_L [a + (R_L / 2w_L)] \\
 &= 1,436 (6.67)^2 / 8 + 10,382 [0.6 + (10,382 / (2 \times 3,796))] \\
 &= 7,986 + 20,426 \\
 &= 28,412 \text{ ft-lb or } 340,944 \text{ in.-lb}
 \end{aligned}$$

Determine the total depth (t) of Beam B3. Since this beam will not contain any rebar $t = d$.

$$\begin{aligned} d &= (6M/bF_T)^{0.5} \\ &= [(6 \times 340,944)/(42 \times 900)]^{0.5} \\ &= 7.36 \text{ in. Use } d = 8.0 \text{ in.} \end{aligned}$$

For $d = 8.0$ in.

$$\begin{aligned} F_T &= 6M/bd^2 \leq 900 \text{ psi ?} \\ &= (6 \times 340,944)/(42 \times 8^2) \\ &= 761 \text{ psi} \leq 900 \text{ psi } \underline{\text{OK}} \end{aligned}$$

B.2.5 Design of the Sidewalls.

The design of the walls will be controlled by the longest sidewall of the manhole. Design the wall as one large beam ($b = 9 \text{ ft} = 108 \text{ in.}$). Use a uniform load of 467 lb/ft^2 to represent the pressure applied to the wall. The walls will not contain any rebar.

$$\begin{aligned} w &= 467 \text{ lb/ft}^2 \times 9 \text{ ft} = 4,203 \text{ lb/ft} \\ M &= wl^2/8 \\ &= 4,203 \times 7^2/8 \\ &= 25,743 \text{ ft-lb or } 308,920 \text{ in.-lb} \end{aligned}$$

Determine the total depth (t) of the wall. Since this beam will not contain any rebar $t = d$.

$$\begin{aligned} d &= (6M/bF_T)^{0.5} \\ &= [(6 \times 308,920)/(108 \times 900)]^{0.5} \\ &= 4.37 \text{ in. Use } d = 4.5 \text{ in.} \end{aligned}$$

For $d = 4.5$ in.

$$\begin{aligned} F_T &= 6M/bd^2 \leq 900 \text{ psi ?} \\ &= (6 \times 308,920)/(108 \times 4.5^2) \\ &= 848 \text{ psi} \leq 900 \text{ psi } \underline{\text{OK}} \end{aligned}$$

B.3 Design Summary

In general, the design requires that the sidewalls have a minimum thickness of 4.5 in. and that the roof slab has a minimum thickness of 8.0 in. Number 6 reinforcing bars will be used around the opening to the manhole chimney to help transfer loads and to help minimize deflections and creep.