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APPLICATIONS OF HIGH-STRENGTH CONCRETE TO THE DEVELOPMENT OF THE PRESTRESSED CONCRETE REACTOR VESSEL (PCRV) DESIGN FOR AN HTGR-SC/C PLANT*

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ABSTRACT

The PCRV research and development program at ORNL consists of generic studies to provide technical support for ongoing PCRV-related studies, to contribute to the technological data base, and to provide independent review and evaluation of the relevant technology. Recent activities under this program have concentrated on the development of high-strength concrete mix designs for the PCRV of a 2240 MW(t) HTGR-SC/C plant, and the testing of models to both evaluate the behavior of high-strength concretes (plain and fibrous) and to develop model testing techniques.

A test program to develop and evaluate high-strength (≥63.4 MPa) concretes utilizing materials from four sources which are in close proximity to potential sites for an HTGR plant is currently under way. The program consists of three phases. Phase I involves an evaluation of the cement, fly ash, admixtures and aggregate materials relative to their capability to produce concretes having the desired strength properties. Phase II is concerned with the evaluation of the effects of elevated temperatures (≤316°C) on the strength properties of mixes selected for detailed evaluation. Phase III involves a determination of the creep characteristics and thermal properties of the selected mixes. An overview of each of these phases is presented as well as results obtained to date under Phase I which is approximately 75 percent completed.

Since the newer generation PCRV designs include an asymmetric cavity arrangement and offset core, existing model test data may not meet the intent of the ASME Code. In line with this two PCRV single-cavity PCRV models were fabricated to both demonstrate techniques for prestressing the models and the liner system which was developed, and to evaluate the performance of high-strength concretes. The first model was fabricated from plain concrete (79.42 MPa) and the second from a fibrous concrete (69.29 MPa). Test results are presented for the models which were hydraulically pressurized to failure.

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INTRODUCTION

The PCRV research and development program at ORNL consists of generic studies to provide technical support for ongoing PCRV-related studies, to contribute to the technological data base, and to provide independent review and evaluation of the relevant technology. Traditionally the program has involved four basic activities which are interrelated and help contribute to the development of an optimum PCRV design. These activities include: technology assessments, analysis methods development, materials, and structural component tests. Recent activities, however, have concentrated on the development of high-strength concrete mix designs for the PCRV of a 2240 MT(t) HTGR-SC/C plant, and the testing of models to both evaluate the behavior of high-strength concretes (plain and fibrous) and to develop model testing techniques.

HIGH-STRENGTH CONCRETE MIX DESIGN DEVELOPMENT

BACKGROUND

Design optimization studies by GA Technologies Inc. have indicated that a significant PCRV size reduction (≈ 1.3 m) can be effected through the use of 55 MPa concrete in conjunction with large capacity (13.3 MN) prestressing tendons [1]. This can lead to substantial cost savings (≈ $\$5.7 \times 10^6$) in both the PCRV and containment. However, the use of 55 MPa concrete for the PCRV design will involve incremental material and development costs. Despite these incremental costs (≈ 1.5×10^6), there still will be a benefit to cost ratio of about 4:1 (for a single plant) resulting from this activity. Additional benefits associated with the use of high-strength concrete include reduced concrete creep (lower prestress loss), and lower temperature rise of fresh concrete and reduced potential for alkali-aggregate reaction due to the incorporation of fly ash into the mixes as a partial replacement for cement.

OBJECTIVE AND APPROACH

The objective of the test program is to develop and evaluate high-strength concretes (≥63.4 MPa compressive strength)* utilizing materials from sources which are in close proximity to areas representing potential sites for an HTGR plant. These sites have been identified as: Florida City - Turkey Point, Florida; Port Arthur, Texas; Pennsylvania-Delaware border area; and Blythe, California area [1]. The suitability of aggregate materials from each of these sites is being evaluated. The overall program is being conducted in three phases. Phase I involves: an evaluation of the suitability of admixtures, one cement and 38.1 mm and 9.5 mm maximum size aggregate materials from each of the identified areas; development of the required high-strength concrete mix designs using fly ash as a partial replacement for cement; and determination of the strength and elastic properties at various ages and under different curing conditions. Phase II is concerned with an evaluation of the effect of elevated temperatures up to 316°C on the splitting-tensile and compressive strengths of both sealed and unsealed specimens fabricated from the mix designs developed in Phase I. Phase III involves a determination of the creep characteristics of the reference concretes when subjected to loadings representing either 30%, 45%, or 60% of their control strengths at temperatures to 71°C. Thermal properties (thermal expansion, adiabatic temperature rise, thermal diffusivity, thermal conductivity and specific heat) and the effects of thermal and stress cycling on strength and elastic properties will also be evaluated under Phase III. Reference [3] presents more details on the overall test program and reference [4] presents a detailed description of Phase I which is presently being conducted.

PHASE I TEST PROGRAM

Although the final objective of Phase I is to produce ≥63.4 MPa concrete mix designs and to develop design properties for only two of

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*Reference [1] requires that an average compressive strength at least 8.3 MPa greater than the specified strength be produced in the laboratory.

the selected sources,* there are several activities which must be conducted prior to development of the detailed design properties. These activities include: (1) materials selection and procurement, (2) admixture-cement compatability testing, (3) cement content effects testing and (4) aggregate evaluation testing.

Materials Selection and Procurement

Representative concrete making materials include Type II moderate heat of hydration and low alkali content cement, Type C fly ash, three Type D water-reducing and retarding admixtures plus an extended range water reducer (super plasticizer), and representative aggregate materials from each of the four sites selected for evaluation. Sufficient quantities of these materials have been procured for use in the first two phases of the investigation.

Admixture-Cement Compatability Testing

Six mixes were prepared in which the admixtures were evaluated for compatability with the Type II cement. The same basic mix was used for each admixture evaluated except that the water content for each mix was adjusted to produce a concrete having a slump of 89 ±13mm; that is, equal workability. Table 1 presents the basic mix designs, mix properties and compressive strength results for this series of tests. Based on its ability to provide increased workability, Type C was selected as the admixture for use in the balance of the investigation. Batch No. 10, which is the same as batch No. 8 but incorporated an extended range water reducer, demonstrates that comparable strength results can be obtained with increased workability through the use of a super plasticizing agent.

Optimum Cement Content Determinations

As noted in ref. [5], there is an optimum cement factor for concrete mixes of equal workability and the same consistency which use a specific

*After conclusion of the initial materials evaluation phase, the list of aggregate sources will be reduced to two which will be used to provide bounds on concrete properties which are achievable from a variety of aggregate sources in the United States.

aggregate of a certain maximum size. (Beyond the optimum cement factor additional cement content does not provide increased strength.) The optimum cement content for use in this study was evaluated through a series of laboratory mixes in which the cementitious materials contents (90% cement plus 10% fly ash, by weight) were varied. In the mixes for each of the two maximum size coarse aggregates (38 mm and 9.5 mm) the coarse aggregate content was held constant, the water content was adjusted to maintain the slump at 89 ±13mm, and the fine aggregate content was adjusted to account for the changing cement and water contents. Figures 1 and 2 present compressive strength results as a function of age and cementitious materials content for the 38 mm and 9.5 mm maximum size aggregate (MSA) mixes, respectively. Based on these results optimum cement contents selected for the 38 mm and 9.5 mm MSA were 10.5 and 9.5 sacks/cy yd, respectively.

Aggregate Evaluation Testing

In this series of tests each of the four aggregate sources selected are being evaluated as well as the effect of the use of fly ash as a partial replacement for cement. Utilizing results of the previous test series to establish admixture requirements and optimum cement contents, mixes utilizing aggregate materials from each of the four sources have been prepared in which from 0 to 40%, by weight, of the cement has been replaced by fly ash. Each of these mixes was designed for equal workability by adjusting the water content to maintain the slump at 89 ±13mm. Fine aggregate contents were adjusted to account for the changing volume from mix to mix of the cement, fly ash and water. Compressive strength, modulus of elasticity and Poisson's ratio results are obtained at concrete ages to 182d using both sealed and moist-cured specimens cast from each mix.

Although specimen fabrication for the aggregate evaluation test series of Phase I has been completed, the only complete compressive strength results presently available are from the Pennsylvania-Delaware border area aggregate materials. Figure 3 presents the effect of partial replacement of cement with fly ash on the strength development of the 38 mm Pennsylvania-Delaware border area aggregate material. The figure shows that cement replacement with fly ash provided improved strength and that the desired strength of 63.4 MPa at 91 d was easily achievable. Other benefits attributed to the incorporation of fly ash into the mixes include increased workability, reduced bleeding and reduced temperature rise of the fesh concrete.

Available results obtained from mixes fabricated using the Port Arthur, Texas and Blythe, California area aggregates also demonstrate that the desired strength of 63.4 MPa is easily achievable with these materials. Initial evaluations of the Florida City - Turkey Point, Florida materials indicated that they were considered marginable relative to their ability to produce the desired strengths because of their low specific gravity (2.3-2.4) and high absorption (3.8-5.8%), however based on very limited compressive strength data it is anticipated that these materials will also meet the desired strength requirement.

When more complete compressive strength results become available for the Texas, California and Florida aggregate materials the number of aggregate sources will be reduced to two and specimens fabricated to determine compressive strength, modulus of elasticity, splitting-tensile strength, drying shrinkage and linear coefficient of thermal expansion data. Tests will be conducted on both moist-cured and sealed specimens at concrete ages to 182 days. Strength and elastic properties established will serve as reference data for Phases II and III of the overall program.

TESTING OF HIGH-STRENGTH CONCRETE MODELS

BACKGROUND

Section III, Division 2 of the ASME "Code for Concrete Reactor Vessels and Containments" [2] requires a model test whenever a model of a prototype with characteristics similar to those of current design has not been constructed and tested in accordance with code provisions, or if analytical procedures to predict ultimate strength and behavior in the range approaching failure are not established. Because the newer generation PCRV designs include an asymmetric cavity arrangement and offset core, existing model test data that were developed for single-cavity and symmetric multicavity PCRV designs may not meet the intent of the above requirements. Contingency plans are therefore being developed so that a PCRV model test can be conducted in a timely manner should it be established as a requirement for licensing. In addition, as noted earlier current generation PCRV designs also incorporate the use of high-strength concrete (55 MPa) as compared 44.8 MPa concrete which was proposed for the Fulton and Summit plants.

MODEL TESTING TECHNIQUE DEVELOPMENT

Using results of a review of PCRV-related model tests [6], it was established that two model testing areas may require some development: circumferential prestressing and leaktight liner systems. A test program was therefore undertaken to establish satisfactory methods for circumferentially prestressing PCRV models ranging in size from 1:30- to 1:10-scale, and for lining the models so that they will not leak prematurely to terminate a test. Also associated with this activity was an evaluation of the performance of fibrous concrete.

Activities related to circumferentially prestressing the models were merely to identify a prestressed concrete pipe manufacturer who could apply prestress at a prescribed force level to models ranging in size from about 1- to 4-meters (3-to-13 ft) in diameter. Relative to the liner system, a design was developed which incorporated the use of ~~a~~ 12-gage AISI 1008 drawing quality steel in conjunction with a flanged head. (The flanged head eliminates the corner joint.)

DEMONSTRATION OF MODEL TESTING TECHNIQUES DEVELOPED

To demonstrate the validity of the above concepts, a ≈1:30-scale single-cavity PCRV model was fabricated using the representative high-strength concrete (78.40 MPa) mix design presented in Table 2. The model was tested by hydrauically pressurizing it until failure occurred in the head region at 24 MPa (3475 psi), Fig. 4. During the test both the liner and circumferential prestressing system functioned as designed, thus demonstrating the techniques developed. The structural capability of high-strength concrete was also demonstrated by this test. Comparing results from this test with those obtained from models having identical geometries and tested under a previous program [7, 8] indicates that the concrete compressive strength directly influences the internal failure pressure. The mode of failure for the plain concrete models also appears to be influenced by the concrete strength with the failure tending to be more of a "punching-shear" type than the cryptodome formation observed in the earlier models fabricated from lower strength concretes.

EVALUATION OF FIBROUS CONCRETE

An indication of the merit of fibrous concrete for PCRV application was also provided under this activity by fabricating and testing a second ≈1:30-scale single cavity PCRV model using fibrous concrete (Table 2) of comparable strength (70.60 MPa) to the plain concrete. The model was tested by hydraulically pressurizing it until failure occurred by rupturing twenty-three wraps of the circumferential prestressing wire near the bottom of the side-wall at 27.72 MPa (4020 psi). Even though the circumferential prestressing had failed the liner remained leaktight and continued to contain pressure. As shown in Fig. 5, the head of the fibrous concrete model remained intact and the few cracks which occurred were relatively small and closed on depressurization. These results indicate that the shear strength of fibrous concrete is at least fifteen percent greater than plain concrete at comparable strength levels, and that fibrous concrete exhibits potential as a PCRV construction material.

More details of these tests are provided in Ref. [9].

SUMMARY

Applications of high-strength concrete at ORNL to the development of the PCRV design of an HTGR-SC/C plant have been reviewed. Included in these applications are the development and evaluation of high-strength concrete mix designs using indigenous materials, and the testing of PCRV models fabricated from high-strength plain concrete and fibrous concrete. Results obtained to date indicate that achievement of the desired concrete compressive strength of $\geq$ 63.4 MPa at a 91 d age is easily obtainable with three of the four aggregate sources evaluated and will most likely be achieved using materials from the fourth source. Pressurization to failure of the two PCRV models demonstrated the effectiveness of the model testing techniques which had been developed and the merit of fibrous concrete as a potential PCRV construction material.

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Table 1. Mix Proportions and Test Results
Admixture Evaluation Test Series

Batch No.	2	3	4	8	9[a]	10
Materials (per cu. yd.)						
Cement, lb.	697	696	710	706	710	712
Fly ash, lb	77	77	79	78	79	79
Coarse aggregate, lb (SSD)[b]	1860	1858	1892	1882	1892	1898
Fine aggregate, lb (SSD)	1099	1097	1118	1112	1118	1121
Water, lb	284	282	259	258	260	257
Admixture	None	A	B	C	A	D
Mix Properties						
Slump, in.	3 3/8	3	3 1/4	4 3/8	3 3/8	9 1/4
Unit wt., lb/ft^3	148.8	148.6	150.4	149.6	150.4	150.8
Air content, %	1.30	2.70	2.65	3.00	2.45	2.70
W/C, lb/lb	0.37	0.36	0.33	0.33	0.33	0.32
Workability	good	fair	fair	good	good	very good
Compressive strength, psi						
7-day average	5830	6585	7360	7040	6895	7090
14-day average	6645	6970	7645	7790	7535	7585
28-day average	7085	7965	8045	7985	8200	8380
56-day average	7995	8700	9540	9100	9025	8860

[a] Repeat of batch no. 3 with reduced mixing time.

[b] Equal weights of no. 4 and no. 67 gradation materials.

MPa = psi x 6.894757 x 10^{-3}

Table 2. Mix Designs and Properties of Plain and Fibrous Concrete for PCRV Models

A. Mix Design

Materials	Quantity (lb/yd^3) Plain	Fibrous
Cement, Type II	892	878
Fly ash	116	115
Coarse aggregate (oven dry)[a]	1590	1565
Fine aggregate (oven dry)	1047	1031
Water[b]	403	397
Fibers (50 mm long x 0.5 mm ϕ)	0	149
Admixture	1360 mℓ	1340 mℓ

[a]19 mm maximum size for plain concrete
9.5 mm maximum size for fibrous concrete

[b]A portion of mix water was provided in form of ice to lower concrete temperature.

B. Properties

Property	Plain	Fibrous
Compressive strength, MPa	78.4	70.6
Modulus of elasticity, GPa	37.3	37.2
Poisson's ratio	0.25	0.23
Modulus of rupture, MPa	6.07	14.69
Splitting-tensile strength, MPa	4.41	9.31

SPECIMEN FABRICATION FOR DETERMINATION OF OPTIMUM CEMENT CONTENT USING 38 mm MSA HAS BEEN COMPLETED

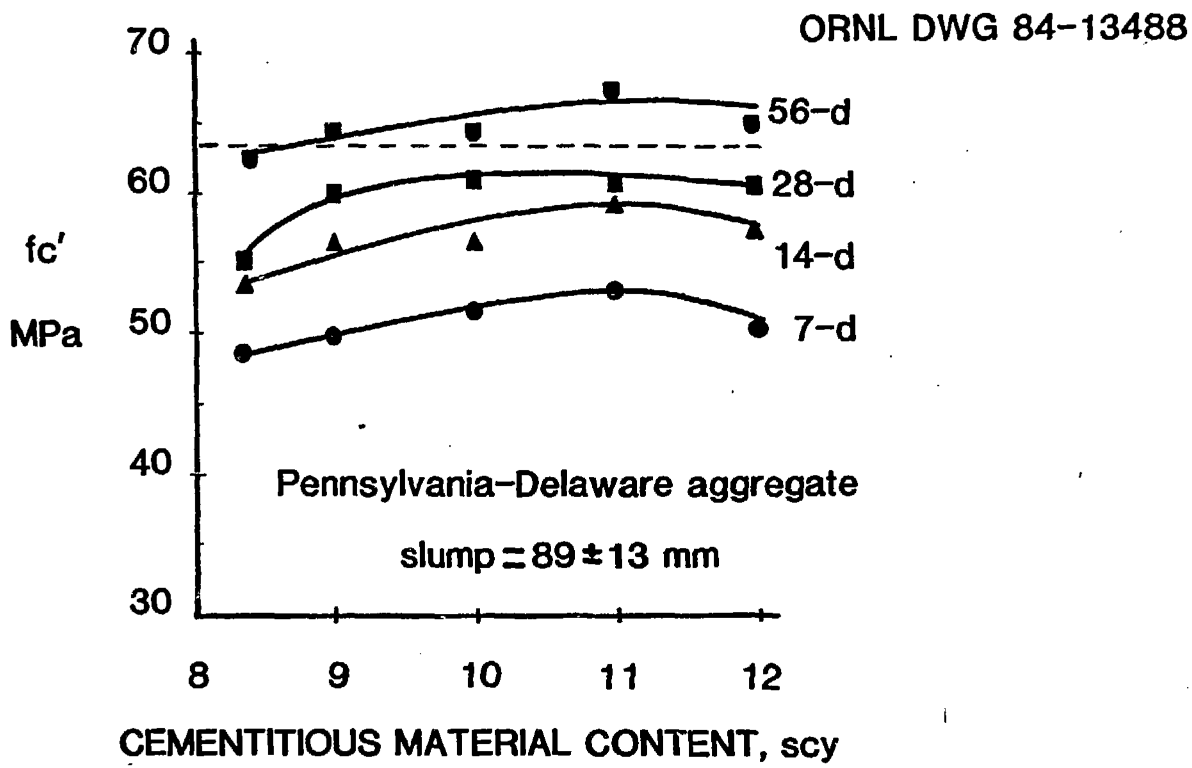

Fig. 1

SPECIMEN FABRICATION FOR DETERMINATION OF OPTIMUM CEMENT CONTENT

USING 9.5 mm MSA HAS BEEN COMPLETED

ORNL DWG 84-13489

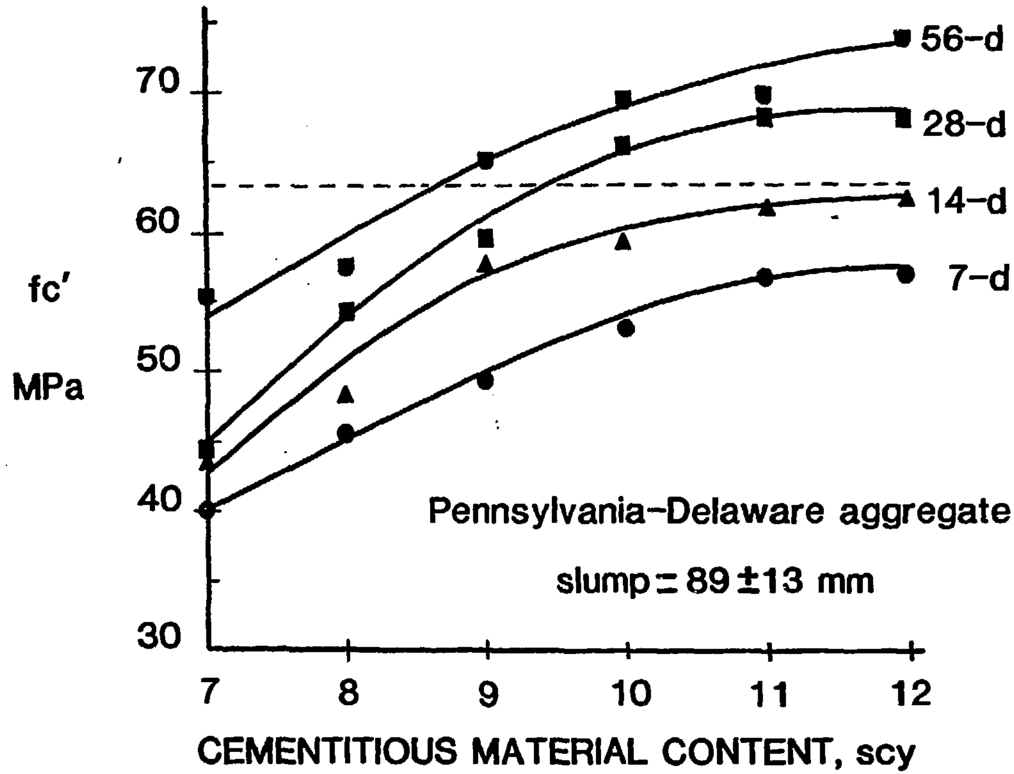

Fig. 2

PARTIAL CEMENT REPLACEMENT WITH FLY ASH PROVIDES STRENGTH BENEFITS

ORNL DWG 84-13490

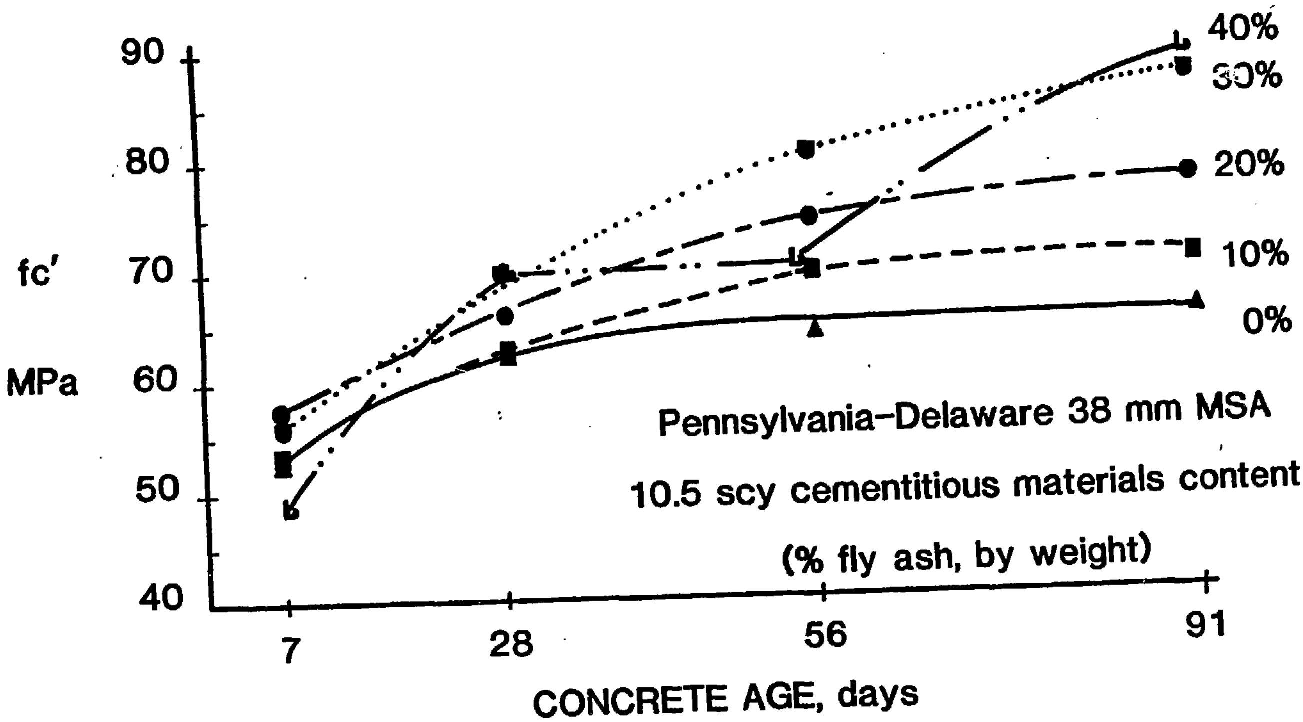

Fig. 3

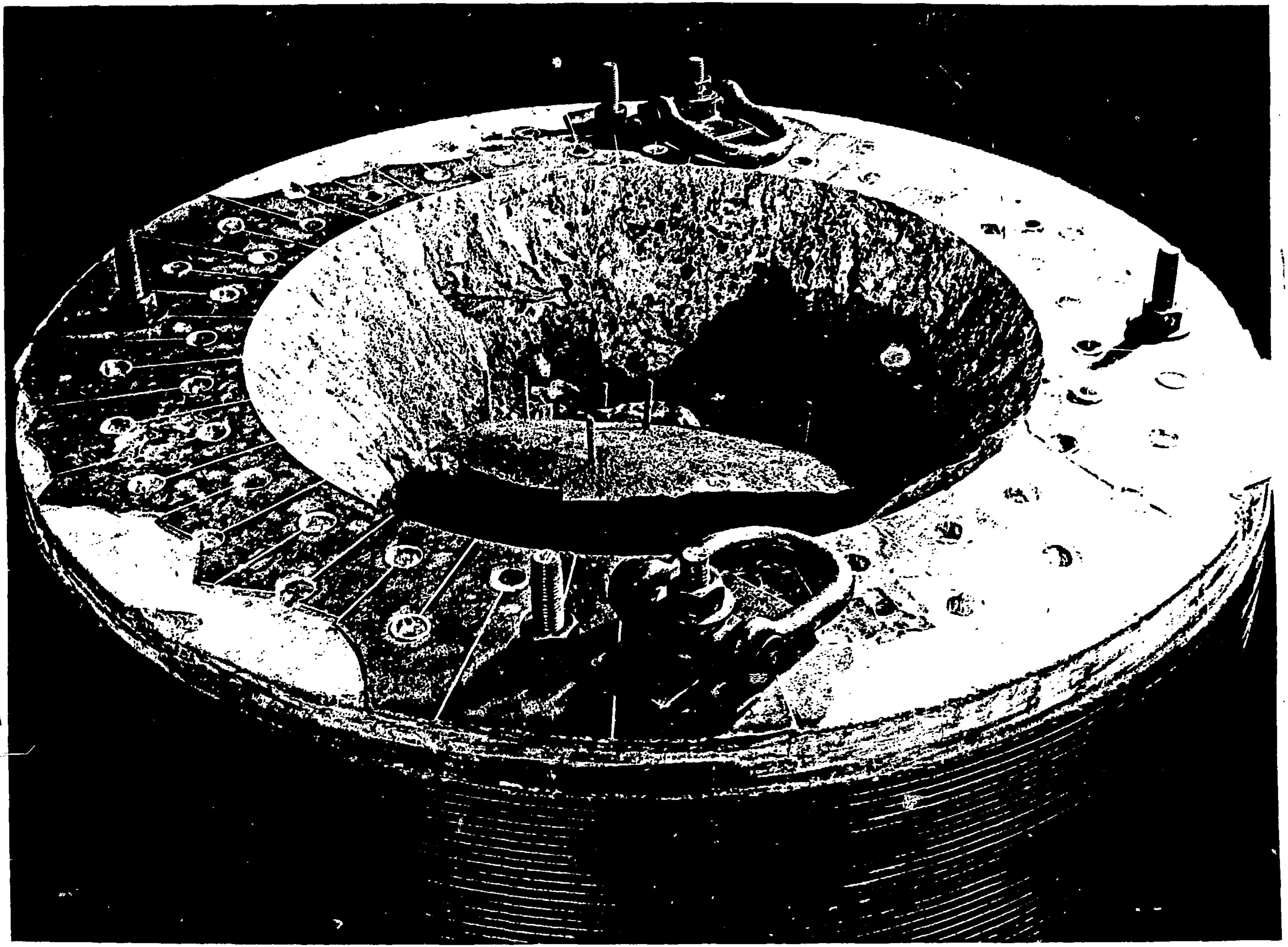

Fig. 4.

Fig. 5

Fig. 5