GYPSUM CONCRETE MODELS FOR FAILURE TEST OF PCPV

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ABSTRACT

A new technique of gypsum concrete model test for PCPV was developed for the purpose of investigating the elastic response and the mode of failure. This method, enabling the failure tests of PCPV in small scale, low pressure and short time, facilitates the study of design parameters from the viewpoint of failure mode and strength.

Mixing and property of the gypsum concrete suitable for prestressing are reported and model techniques including newly developed liner system and wire-winding device are presented.

The results of a series of tests of 1/40 scale gypsum concrete models for a proposed design are presented and the comparison with those of parallelly tested microconcrete models is made.

1. INTRODUCTION

In spite of rapid progress of the methods of numerical analysis, the model test has been an indispensable tool of predicting the mode of failure and the ultimate load factor of prestressed concrete reactor vessels. "Proof tests", which are carried out on models of usually about 1/10 scale to the prototype, have an important role of verifying the design concept and the factor of safty to be expected in a proposed design. These tests become naturally large projects of experiment which require long time and much money.

On the other hand, at the initial stage of design, it is necessary to investigate the influence of the design parameters such as configuration, prestressing, reinforcing, etc. on the modes of failure and the ultimate loads. For the purpose of this design study the method of laboratory tests on small-scaled models must be developed besides the proof test technique.

In this paper a development of the technique of small-scaled gypsum concrete model test for PCPV is reported. The prestressed gypsum concrete models of 1/40 scale made the curing unnecessary and enabled us to bring them to failure in comparatively low inner pressure, thus leading to a possibility of testing a number of different types of models in short period of time.

The main subjects involved in this research and our solution for them are as follows:

(1) Prestressing Method

The prestressing methods suitable for small models were sought for. Post-tensioning of straight rods was applied in the vertical direction. For the circumferential prestressing a self-equilibrating wire-winding device was developed, by which the single wire of 3 mm ø could be continuously wound under an accurate control of applied tension.

(2) Material of Concrete for Models

As the concrete for small model having lower strength and capable of being hardened without curing time, gypsum concrete was investigated and was proved to be applicable to prestressed specimens.

It was shown that stress-strain curve for gypsum concrete under compression is similar to that of the ordinary concrete, and also that its ultimate compressive strain takes nearly the same value to that of the latter.

(3) Lining against Inner Pressure

In order to reach the true ultimate failure of the structure, a lining method is needed which can bear the inner pressure without leakage even after the cracking of the vessel concrete. A liner system composed of double layers of an urethane rubber sheet and glass-fiber-reinforced epoxy resin sheets was developed and kept the inner pressure successfully up to the final stage of failure.

(4) Tests of Models for a Proposed Type of PCPV

As the actual application of the testing technique developed, a series of tests on 6 models of 1/40 scale was carried out.

Three versions of a proposed design containing one nonreinforced and two differently reinforced models, were tested. In each types of the model, a pair specimen in microconcrete was tested for comparison. In this series of tests, the following points were observed:

i. Before cracking, response to innerpressure shows good agreement with the results of finite element elastic analysis.
ii. The vessel has very progressive mode of failure.
iii. Load-deflection curves have tri-linear characteristics and the failure can be interpreted as a series of three different phases of elasto-plastic behaviour.
iv. Though the ultimate failure occured in shearing of the top slab, it was

observed that in many points of the vessel almost critical condition was reached until the collapse took place. Thus the well-balanced bearing capacity of the proposed design was verified.

The observation on the applicability and the similarity of the gypsum concrete in the failure test of prestressed model is given in the concluding remarks of the paper.

2. MODELS AND METHOD OF TESTS

(1) Description of Prototype and Model

The prototype was 1/40 scale reduction of the original design engineered by writers in reference to Hinkley Point "B" and Hunterston "B". Shape and dimensions thereof are given in Fig. 1 and 2. Design parameters were as given below.

i. Properties of Concrete

Compressive Strength	$Fc = 350\ kg/cm^2$
Tensile Strength	$Ft = Fc/12 = 29.2\ kg/cm^2$
Young's Modulus	$E = 3.0 \times 10^5\ kg/cm^2$
Coefficient of Expansion	$a = 8.0 \times 10^{-6}/^oC$

ii. Design Pressure — $Po = 40\ kg/cm^2$

iii. Thermal Gradient — Temperature Cross fall = 40^oC

iv. Amount of Prestressing — $Pl = 90kg/cm^2$, $Ps = 95kg/cm^2$, $Pw = 40kg/cm^2$

Finite element method program was applied on the assumption that prototype is an axi-symmetric body. Triangular mesh consisting of 443 elements and 260 nodes, (Fig. 4), were used in the calculation. For the top slab, to reflect the effect of penetrations, had the effective stiffness of hypothetic transverse isotropic axi-symmetric body with different modulus of elasticity in vertical and horizontal directions was used.

Analytical results of the principal stresses and deformation on the vertical cross section caused by internal pressure, temperature and prestressing are given in Fig. 5.

The ultimate internal pressure of this prototype was assumed to be about $150\ kg/cm^2$, and experimental difficulties associated with high pressure was expected to arise. Therefore, gypsum concrete (compressive strength of which is about 1/5 of conventional concrete) was used to reduce load level. As presently, there is little data on gypsum concrete available, explanation on the properties of gypsum concrete will be made in the next section.

FIG. 1 PLAN ON TOP SLAB AND TENDON LAYOUT

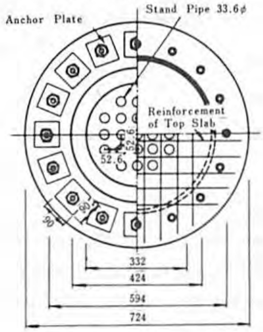


FIG. 2 VERTICAL SECTION AND TENDON LAYOUT

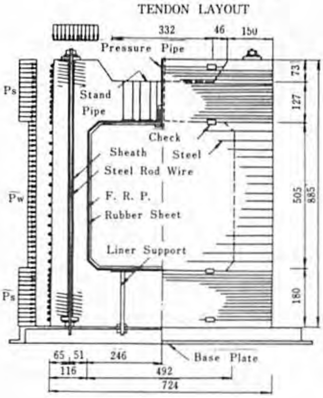


FIG. 3 PENETRATION OF TOP SLAB

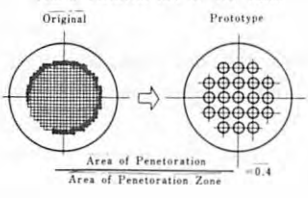


FIG. 4 FINITE ELEMENT IDEALIZATION

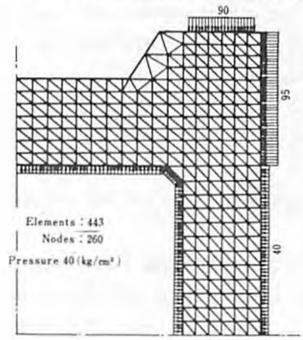


FIG. 5 (a) PRINCIPAL STRESSES AND DEFORMATION BY INTERNAL PRESSURE $P_0 = 40kg/cm^2$

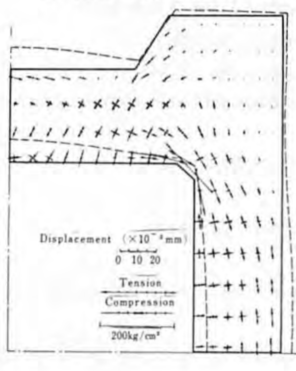


FIG. 5 (b) DISTRIBUTION OF HOOP STRESS BY INTERNAL PRESSURE $P_e = 40kg/cm^2$

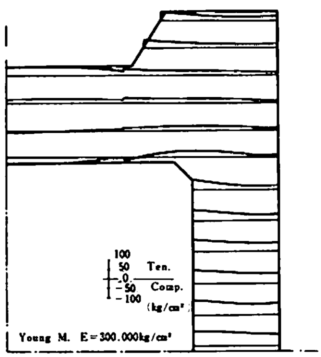


FIG. 5 (d) DISTRIBUTION OF HOOP STRESS BY PRESTRESSING

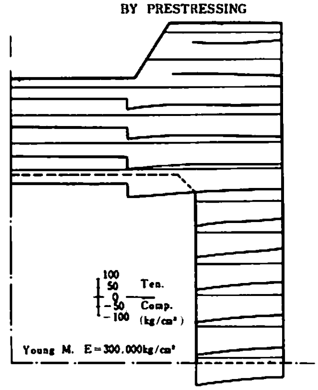


FIG. 5 (c) PRINCIPAL STRESSES AND DEFORMATION BY PRESTRESSING

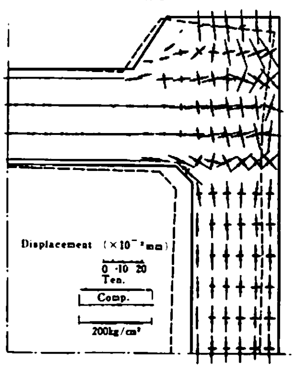


FIG. 5 (e) PRINCIPAL STRESSES AND DEFORMATION BY THERMAL FORCES

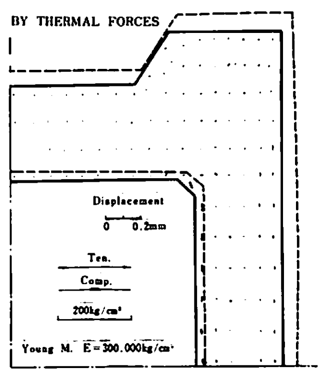


TABLE Ⅰ

	Mix Proportion			Slump
	Gypsum	Light wt Aggregate	Water	cm
No. 1	1	0.70	0.6	21
No. 2	1	0.80	0.6	21
No. 3	1	0.85	0.6	17
No. 4	1	0.90	0.6	9
No. 5	1	0.95	0.65	21
No. 6	1	1.00	0.65	16
No. 7	1	1.05	0.65	7

TABLE Ⅱ

			Age (days)		
		Unit	1	2	3
No. 1	Compressive St.	kg/cm²	58	59	62
	Tensile St.	"	9.5	9.0	9.1
	initial tangent modulus	×10⁴ kg/cm²	8.5	9.6	8.1
	secant modulus	"	5.0	5.2	3.9
No. 2	Compressive St.	kg/cm²	67	63	59
	Tensile St.	"	8.5	9.4	8.2
	initial tangent modulus	×10⁴ kg/cm²	9.2	8.4	8.4
	secant modulus	"	5.0	5.4	4.6
No. 3	Compressive St.	kg/cm²	75	66	66
	Tensile St.	"	10.9	7.5	7.3
	initial tangent modulus	×10⁴ kg/cm²	8.6	7.8	7.7
	secant modulus	"	6.0	4.1	3.8
No. 4	Compressive St.	kg/cm²	63	64	63
	Tensile St.	"	11.0	10.3	9.4
	initial tangent modulus	×10⁴ kg/cm²	10.0	7.8	7.6
	secant modulus	"	7.2	4.6	4.3
No. 5	Compressive St.	kg/cm²	58	57	58
	Tensile St.	"	10.0	8.4	8.9
	initial tangent modulus	×10⁴ kg/cm²	7.9	6.7	7.1
	secant modulus	"	5.3	3.8	3.3
No. 6	Compressive St.	kg/cm²		61	62
	Tensile St.	"		[illegible]	8.0
	initial tangent modulus	×10⁴ kg/cm²		7.9	7.5
	secant modulus	"		4.5	4.3
No. 7	Compressive St.	kg/cm²	62	64	57
	Tensile St.	"	6.6	7.5	7.6
	initial tangent modulus	×10⁴ kg/cm²	8.2	7.8	7.6
	secant modulus	"	5.5	5.0	4.2

TABLE Ⅲ DETAILS OF MICRO CONCRET MIX

	Mix Proportion			Slump
	Cement	Aggregate	Water	
	1	3	0.60	18 21
Aggregate	Maximum Size 5.0mm			
	Grading	2.5mm ~ 5.0mm		20%
		1.2 ~ 2.5		20
		0.6 ~ 1.2		20
		0.3 ~ 1.6		20
		0.15 ~ 0.3		20

TABLE Ⅳ PROPERTIES OF MICRO CONCRETE

		Age (days)	
	Unit	7	10 + 1
Compressive St	kg/cm²	146.6	187.1
Tensile St	kg/cm²	17.3	19.9
initial tangent modulus	×10⁵ kg/cm²	——	——
secant modulus	×10⁵ kg/cm²	——	——
Compressive St	kg/cm²	166 ~ 172	183.0 ~ 235.0
Tensile St	kg/cm²	12.9 ~ 16.0	15.9 ~ 23.0
initial tangent modulus	×10⁵ kg/cm²	——	2.24
secant modulus	×10⁵ kg/cm²	——	2.13 ~ 2.35

FIG. 6 STRESS-STRAIN CURVE OF CONCRETE

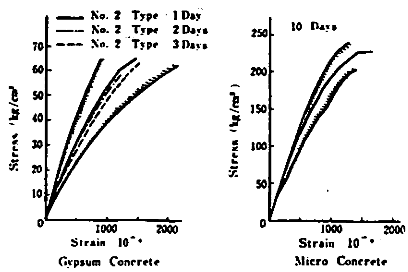


FIG. 7 a CREEP CURVE OF GYPSUM CONCRETE

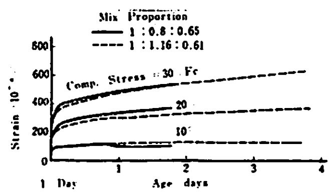
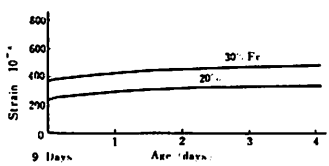


FIG. 7 b CREEP CURVE OF MICRO CONCRETE



In this experiment, to make comparison between gypsum and conventional concrete, the same tests were conducted on micro concrete (strength of which was designed to be about 1/2 of the conventional concreted), the design pressure and the amount of prestressing were decided in proportion to the compressive strength of the respective concrete.

The tests were planned on 3 types of models unreinforced, reinforced in the top slab.

Photo-1 is of the test model before concreting. Sheath for vertical rods can be seen on the outside with core liner in the center. Photo-2 is the completed test model.

(2) Gypsum Concrete and Micro Concrete

The aggregates for gypsum concrete used for the experiment were artificial light weight aggregates of sizes between 0.6 mm and 5 mm.

Some 7 mix proportions were made for gypsum concrete (Table-I) and compressive strength, tensile strength (split test), initial tangent modulus, secant modulus (formed by connecting 90% point of ultimate strength and zero load point) are given in Table-II. Mix proportion for micro concrete is given in Table-III, whereas its properties are given in Table-IV.

Next, the stress-strain curves for gypsum concrete and micro concrete, up to the maximum strength, are given in Fig.-6. Although the curves given for gypsum concrete are for Mix No. 2 only, curves of the other mix proportions all happened to be within the shaded area. The similarity of stress-strain curves of gypsum concrete and micro concrete can be noticed in these figures.

Further, creep curves of gypsum concrete and micro concrete are given in Fig. 7.

From these results, principal difference in properties between the gypsum concrete and micro concrete, besides the compressive strength, can be summarized to two points, namely, (1) tensil to compressive strength ratio of gypsum concrete is 1/6 to 1/8 and (2) creep rate of the gypsum concrete is greater than that of the micro concrete.

The effect of these discrepancy in the property of gypsum concrete was cancelled by adjusting the amount of prestress, i.e. the amount of prestress for the gypsum concrete models was slightly reduced by the value corresponding to the surplus of the tensile strength. On the other hand, prestress was increased, when necessary, for covering the relaxation of prestress caused by creep. According to preliminary investigation, the loss of prestress during 24 hours was about 5%.

(3) Concreting

Owing to the fact that hardening time of gypsum concrete is short (about 40 minutes), concrete was poured in 4 continuous horizontal pours. Slump of both concrete was between 18-20 cm.

Forms of gypsum concrete were stripped the day following concreting and the model was prestressed immediately. Forms for micro concrete were stripped 3 days after concreting and cured, under conditions given in Table-4, for 8 days before being prestressed.

(4) Tendon and Prestressing

a) Vertical Prestressing

Tendons used for micro concrete test model were 16 mm rods whereas those used for gypsum concrete were 9.2 mm in diameters. As shown in Fig-2 16 tendons were used in each of the test models. Wire strain gages attached to the rods were used to measure strain during prestressing.

b) Circumferential Prestressing

The prestressing wire of 2.9 mm in diameter, was used in the circumferential direction. A newly developed device was used to wind the wire around the cylinder and for prestressing. Properties of rods and wires used in the experiment are given in Table-V.

Prestressing device used for winding the wire is shown in Fig. 8, whereas the principle of the device is given in Fig. 9.

The applied tension 2P is registered on load cell and is controled by a lever block. Photo-3 shows the winding device.

(5) Reinforcement

Name of test models and reinforcing methods are given in Table VI.

(6) Pressurizing Method

a) Liner

Two wooden discs were installed on the top and bottom of cylinder made of galvanized sheet metal, which had a inside frame for resisting side pressure during concreting. Cylinder was then covered with urethane rubber. This water tight vessel was covered further with sheets of FRP to resist the inner pressure after cracking of concrete.

b) Pressurization Method

Pressurization method used was to pump water into pressure pipe with manual hydraulic pump.

(7) Instrumentation

Internal pressure was measured with pressure transducer attached to the vent pipe installed in the top slab.

Displacement of test models were measured using dial gauges with sensibility of 1/1000 mm and ring type displacement transducer, (using wire strain gauge), with sensibility of 1.4×10^{-3} cm/microstrain.

Strain on various parts of test models were measured with mould type wire strain gauge (30mm gauge length) for concrete and wire strain gauge (10mm gauge length) for reinforcements and tendons.

Deformation was monitored with X-Y record of internal pressure and displacements at the center of top slab and middle of side wall.

The location and names of displacement gauges and strain gauges are given in Fig.-11.

Photo - 1

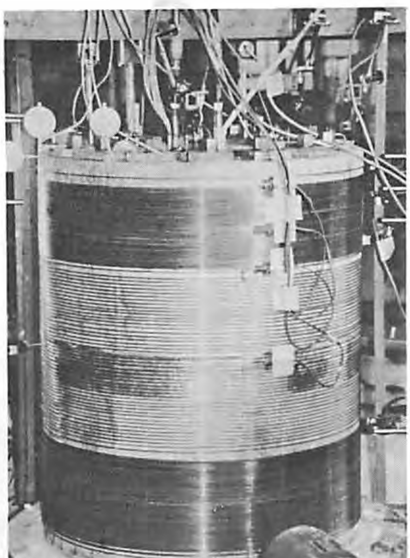
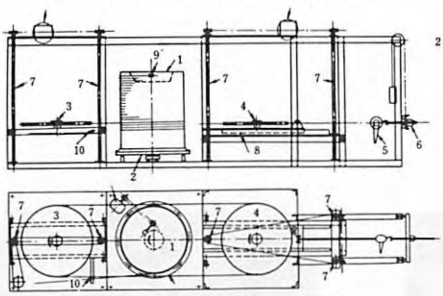


Photo - 2

TABLE-V PROPERTIES OF STEEL

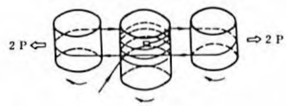
	Dia. (mm)	Section (mm²)	Strength (kg/mm²)	0.2%Strain (kg/mm²)	Young's M. (kg/mm²)	Elongation (%)
Wire 2.9φ	2.91	6.65	209.0	197.1	20 200	6.5
Rod 10φ	9.11	65.2	150.4	126.7	21 800	7.0
Rod 16φ	16.08	203	121.0	110.0	20 300	9.0
Reinforcement	2.60	5.31	68.7	66.0	20 500	—

FIG. 8 PRESTRESSING DEVICE OF STEEL WIRE



1. Testing Model
2. Turning Table
3. Fixed Reel
4. Free Reel
5. Lever Block
6. Load Cell
7. Driving Shaft
8. Truck
9. Anchorage
10. Delivery
11. Electric Motor
12. Shaft Driving Motor

FIG. 9 PRINCIPLE OF DEVICE



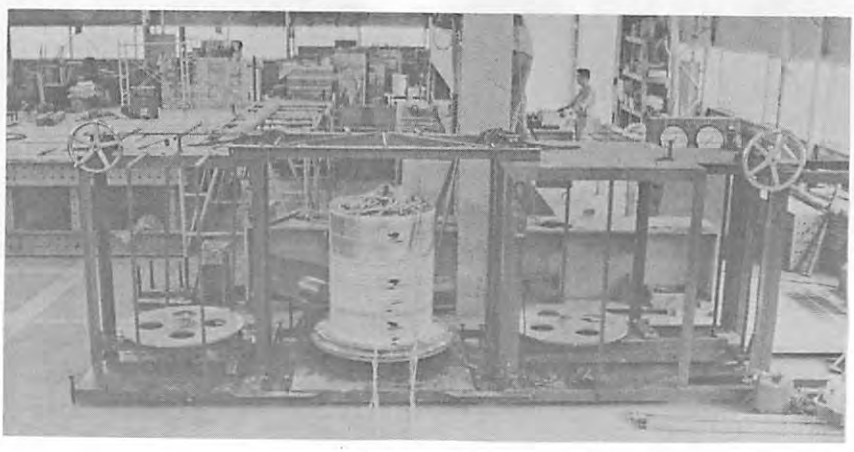


Photo - 3

3. RESULTS OF TESTS

The datas indicating the results of the tests are given by the following graphs and figures.

FIG. 11 MEASURING PLAN

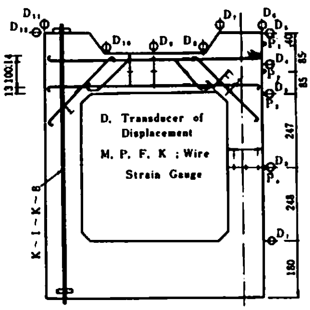


FIG. 13 (a) PRESSURE-STRAIN CURVE
(Top Corner Gauge of Type MC-2)

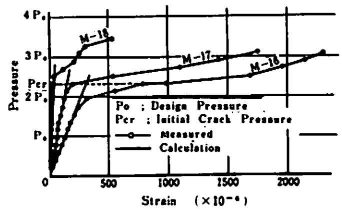


FIG. 12 (a) PRESSURE-DISPLACEMENT CURVE
(Top Slab of Type MC-3)

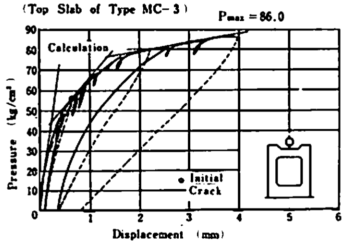


FIG. 13 (b) PRESSURE-STRAIN CURVE

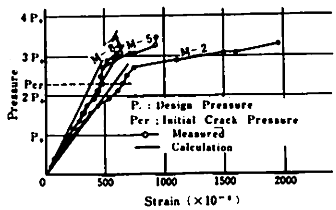


FIG. 12 (b) PRESSURE-DISPLACEMENT CURVE
(Side Wall of Type MC-3)

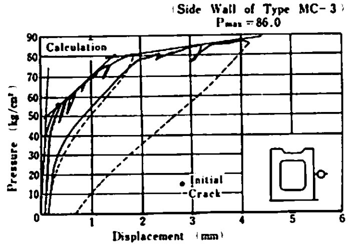


FIG. 14 PRESSURE-STRAIN CURVE
(Steel Rod of Type MC-2)

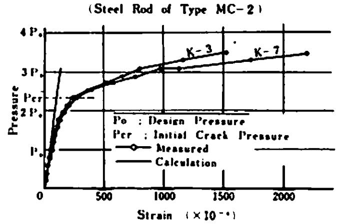


FIG. 16 (b) PRESSURE-DIPLACEMENT CURVE

(Side Wall)

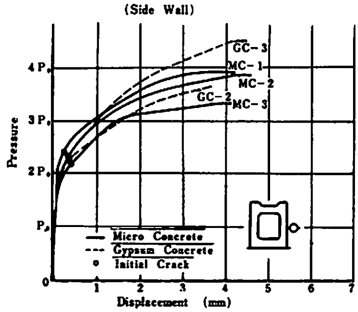


FIG. 17 PROGRESSION OF DEFORMATION (MC-1)

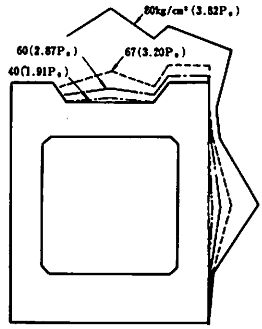


FIG. 16 (a) PRESSURE-DISPLACEMENT CURVE

(Top Slab)

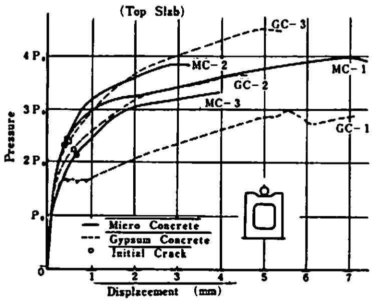


FIG. 15 PROGRESSION OF CRACKS (MC-2)

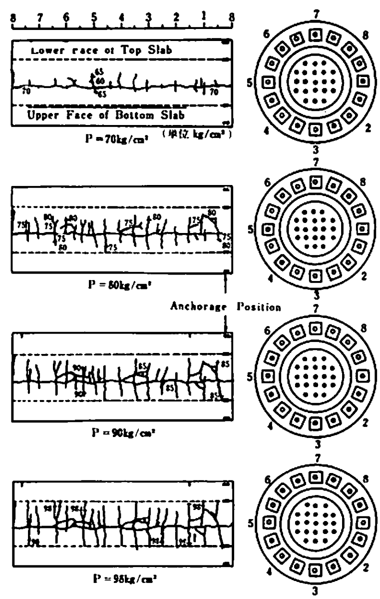
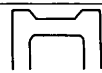
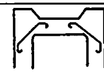
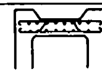
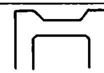
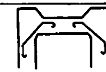
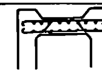
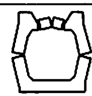
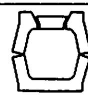
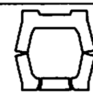
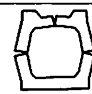
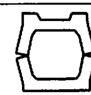
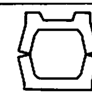


TABLE VI TABLE OF MODELS AND TEST RESULTS

Type of Model		Gypsum Concrete			Micro Concrete		
		GC-1	GC-2	GC-3	MC-1	MC-2	MC-3
Reinforcement			 16-2.6Ω	 16-2.6φ 16-2.6φ 16-2.6φ		 40-2.6φ	 16-3.0φ 16-3.0φ 16-3.0φ
Comp. Strength	Fc kg/cm²	79.1	90.1	91.5	183	227	228
Tens. Strength	Ft 〃	12.4	12.6	11.3	15.9	20.9	23.0
Fc/Ft		6.39	7.15	8.09	11.5	10.9	9.92
Young's Modulus kg/cm²	Eoi	105.000	101.000	110.000	248.000	254.000	224.000
	$E\frac{1}{3}$	97.000	94.000	93.000	230.000	235.000	213.000
Prestress kg/cm²	Pw	7.0(2.9φ @26)	8.5(2.9φ @26)	7.7(2.9φ @26)	20.7(2.9φ @26)	25.2(2.9φ @10)	24.6(2.9φ @10)
	Ps	13.6(2.9φ @11)	17.5(2.9φ @11)	15.8(2.9φ @11)	48.8(2.9φ @4)	58.9(2.6φ @4)	56.4(2.9φ @4)
	Pl	14.2(16-10φ)	17.8(16-10φ)	16.1(16-10φ)	46.4(32-10φ)	56.3(16-16φ)	54.4(16-16φ)
Design Pressure	Po kg/cm²	9.0	10.3	10.5	20.9	26.0	26.1
Ultimate P (calculated)	Pcal 〃	21.5	27.5	25.1	52.9	64.3	62.8
Ultimate P (tested)	Pmax 〃	27.2	37.5	47.5	82.5	98.0	86.0
Pmax/Po		3.02	3.64	4.52	3.95	3.77	3.30
Cracking P	Pcr 〃	14.5	23.3	25.0	59.8	60.0	56.0
Initial Crack Position		Vertical (in Side Wall)	〃	〃	〃	〃	〃
Modes of Failure							
Ultimate Displacement mm	Top slab	9.30	4.46	5.38	7.18	3.11	3.88
	Side wall		3.64	4.22	3.84		4.02

4. CONCLUSION

Gypsum Concrete Model Test

1) The series of tests revealed that the gypsum concrete prestressed models can simulate the characteristics of the elasto-plastic behaviour of PCPV up to the point of collapse.

2) Juding from the comparison with the micro concrete models, the similarity of the gypsum concrete model is acceptable in the sense of qualitative study. But some discrepancy was observed in the absolute values of the ultimate load factor. The improvement of the homogeneity of the gypsum concrete and the reliability of the value of compressive strength is the subject to be further pursued.

3) The gypsum concrete model test is recommendable as an experimental method of design study by the reason of its merits of feasibility and economy.

Mode of Failure of Tested PCPV

1) It was verified that PCPV has a quite progressive mode of failure also in the tested design.

2) It is to be noted that though the ultimate collapse occurs in the form of shearing of the top slab, the parts of the vessel can develop large plastic deformation until the final phase, even in the vessels without any bonded reinforcement.

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