コンクリート工学年次論文報告集 11-1 1989

論 文

[2119] Concrete for Arctic Oil Production Platforms

Mark MAWHINNEY[1], Hiroshi SAEKI[2] and Toshiyuki ONO[2]

1.INTRODUCTION

Offshore oil platforms, as envisaged in Arctic areas where oil exploration is continuing, will need excellent durability and load resistance. Present experience supports the use of both steel and concrete, although the movement of ice and the extreme temperatures will impose severe structural loads and create many restrictions to normal working practices. It seems likely that an offshore production platform will require storage facilities as part of its design,and oil is typically stored at temperatures of between +50^{0}C and +80^{0}C. This will cause elevated temperatures within the structure while outside, in mid-winter, air temperatures may drop to -50^{0}C, with consequent large thermal gradients through the external walls, particularly at the waterline(Fig.1).

By using typical values of stiffness, Poisson's ratio and the thermal expansion coefficient,Mawhinney [1] indicated that theoretical thermal stress can be similar in size to wave and ice loading in fairly rigid members. This hypothesis required experimental support.

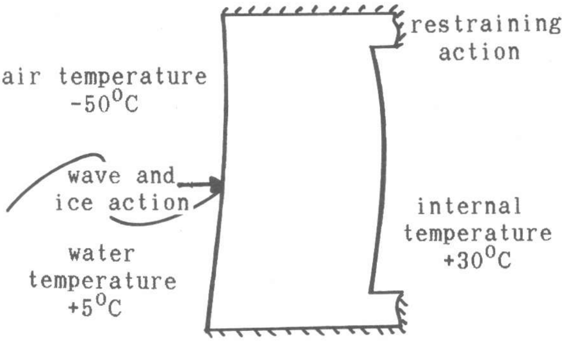

Fig.1 Waterline Temperature Regime

2.EXPERIMENTAL PROGRAMME

The experimental programme was based on earlier work by Clarke and Symmons [2] in the United Kingdom, where the effects of through wall temperature gradients due to sub-sea oil storage were tested. The test temperatures were 5^{0}C on the outside and 70^{0}C on the inside, suitable for North Sea conditions.

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[1] Penta-Ocean Construction Ltd., Bunkyo-ku, Tokyo

[2] Dept. of Civil Engineering, Hokkaido University, Sapporo

In this present case it was assumed that the inside temperature would be elevated, due to the presence of oil storage, to 30^{0}C. The outside temperature was -40^{0}C, simulating winter temperatures for the Arctic. Neither boundary temperature can be considered extreme.

The concrete test mixes are as shown (Tab.1). Each specimen was cast as one block at Nippon Koatsu Concrete Co., Chitose, Hokkaido. Mixing was by electric mixer and the specimens were cast in summer temperatures of 20^{0}C to 25^{0}C. They were then dry cured for 28 days before transfer to Hokkaido University for testing.

Tab.1 Concrete Mix Details (kg/m^3)
steel is % of cross sectional area

Aggregate Type	Large Aggreg	Small Aggreg	Cement	Water	Additives	%Air	W/C Ratio	%Steel
Normal	1235	558	449	184	--	2	0.41	--
Normal	1235	558	449	184	--	2	0.41	0.89
Lightweight	671	639	462	143	4.62	4	0.31	--
Lightweight	671	639	462	143	4.62	4	0.31	0.89

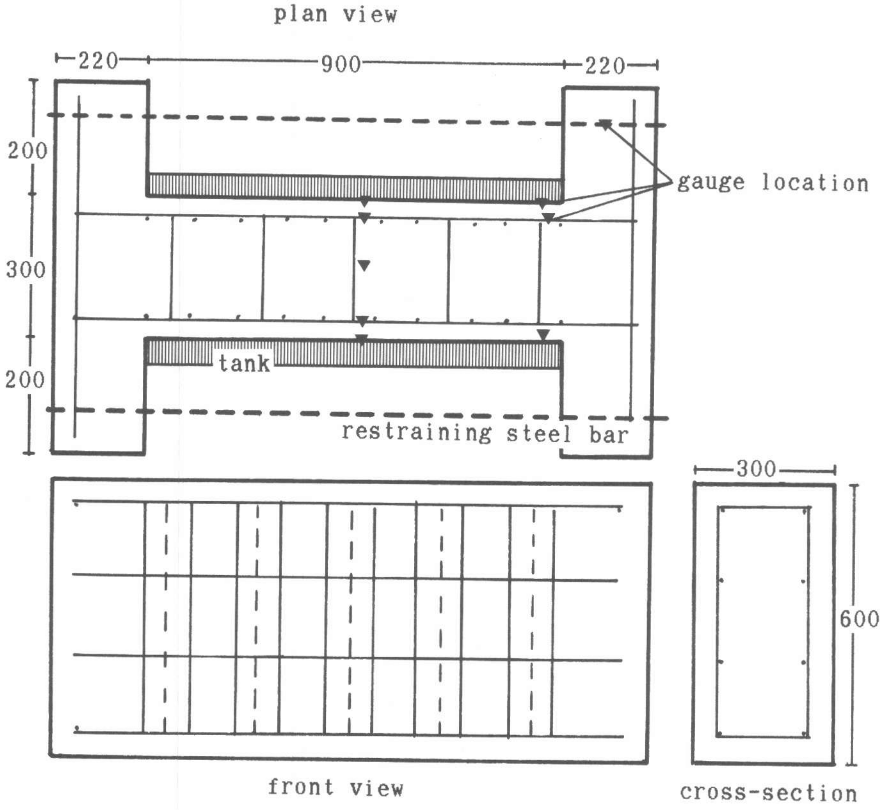

Fig.2 Experimental Arrangement (mm)

The normal density concrete was based on the design mix reported by Clarke and Symmons [2] and the aggregate was of a type typically employed in the Japanese construction industry. The lightweight concrete mix was based on data reported for the Super CIDS exploration platform with a saturated, expanded shale aggregate, 'asanolite'. The experimental arrangement was as shown (Fig.2).

The test involved cooling one side of the beam to -40°C over a period of 12 hours. An antifreeze solution was pumped through a refrigeration unit and into a compartment with one face open to the beam. This was to simulate a cold, saturated environment. At the same time, the temperature of the opposite side of the beam was raised to +30°C. The top and bottom of the beam was insulated.

Full restraint was modelled using a simple stressing system through the arms of the H-block. After 24 hours, the superimposed temperature gradient was reduced, over a period of 12 hours, to normal room temperature (+13°C to +15°C).

After a period of 2-3 days the temperature gradient was again imposed on the beam, but with the beam unrestrained. This was maintained for two days before returning to room temperatures.

3.EXPERIMENTAL RESULTS

Four beams have been tested to date and eight sets of results are available (Tab.2). Strain gauges, mounted on thin steel plates, and thermocouples were employed to assess temperature and strain distribution (Fig.2) and the results were stored in a 40 channel recorder. Testing revealed that both temperatures and strains reached a peak after 24 hours. After the initial 12 hour heating period there was a gradual strain redistribution. In some cases this involved a change in strain direction.

In all four test runs lightweight concrete had large mid-section concrete strains and extremely large steel strains. Normal density concrete showed no significant strains in the initial 24 hour period.

However, both normal and lightweight concretes exhibited large strains during the final period when beams were returned to room temperatures. Clarke and Symmons [2] discovered similar phenomena, and this part of the data will be the subject of a later analysis.

Tab.2 12 Hour Results of Experiment (microstrain)

Gauge Location		Unreinforced				Reinforced			
		Normal Density		Lightweight		Normal Density		Lightweight	
		Free	Restraint	Free	Restraint	Free	Restraint	Free	Restraint
warm	X	-5	-7	-59	79	59	26	127	20
face	Y	25	-21	-49	17	31	-3	69	18
	Z	-21	-9	5	42	-32	22	67	66
rebar	X					3	22	-528	-146
mid-	X	-7	-13	212	-136	8	-6	65	-6
point	Y	-81	-107	88	49	-53	-94	278	194
	Z	-29	-11	50	10	-20	-30	64	-12
rebar	X					-51	-89	2813	3948
cold	X	-56	-110	-24	22	-60	-135	-152	-56
face	Y	66	-92	10	13	-81	-166	-149	-52
	Z	128	74	-93	33	-33	24	-16	-10

The use of an 80% alcohol, 20% water mix allowed reduction of the temperatures to -45°C. Initially the use of this mix appears to have prevented ice formation in the cold surface pores of one specimen. The net result was matrix contraction at that face rather than pore ice expansion. Later experiments used saturated concrete but with a vinyl layer between the surface and the alcohol mix.

Other problems involved the modelling and practical application of restraint. The encasement of the adjoining water tanks to the concrete surface suffered from leakage and the solution was to reduce the flexibility of the joints, which may have provided additional restraint. Strain gauge mountings, through excessive or inadequate restraint, statistical error, scale effects, crack formation in the arms and prestressing bars acting in bending rather than axially may all have caused error, although it is hard to quantify these effects without a much wider database.

4.DISCUSSION AND ANALYSIS

Although strains peaked after 24 hours, the elastic strains were best described after 12 hours. A plane strain model was assumed as a method of checking the cross-sectional strains in the mid-portion of the beam. Restraint, the coefficient of thermal expansion and the temperature boundaries were varied in order to check whether a constant set of these variables could model the results for normal and lightweight concretes. A second model (plane stress) was then employed to check on longitudinal strains and the strains measured in the arms and steel bars of the restraint system.

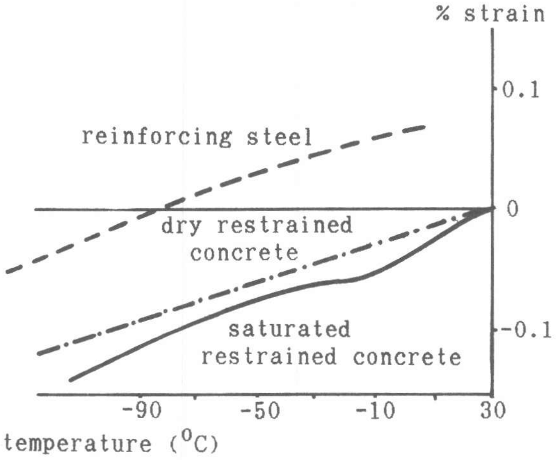

Fig.3 Sub-zero Thermal Expansion [2]

For the unrestrained mass concrete a mesh remotely restrained at one end, with a variable coefficient of thermal expansion produced the best fit for a temperature range 0°C to -70°C. The variation of the thermal expansion coefficient was in agreement with the work of Planas et al.,[3] shown in Fig.3.

Thus, the unrestrained mass concrete expands both at increasing temperature above zero and decreasing temperature between -20°C and -50°C. Between 0°C and -20°C there is a transitional stage.

However, the magnitude of the coefficient of thermal expansion, $2 \times 10^{-6}/^{\circ}C$, was greatly reduced from what is accepted as a typical value for concrete, $10 \times 10^{-6}/^{\circ}C$. This is probably a reflection on the effects of the slow change in temperature and the self-relieving nature of thermal strains and stresses.

Thermal expansion is often treated as a one dimensional longitudinal phenomena. However, experimental results indicate that the expansion (or contraction) is three dimensional such that, in lateral directions, a component of thermal expansion must be added to the Poisson ratio effects.

In the case of unrestrained lightweight mass concrete a mid-sectional expansion is superimposed on the pattern. This may be the result of ice expansion within the porous material although, again, the magnitude of the analytical value, 5 x $10^{-6}/^{0}$C, is greatly reduced from that of pure ice, 50 x $10^{-6}/^{0}$C, reflecting time effects and available pore space.

For the restrained mass concrete a mesh remotely restrained at both ends combined with a constant coefficient of thermal expansion, -1 x $10^{-6}/^{0}$C, provided the best model. This confirms the results of Planas et al.,[3] where restraint produces a more constant variation in concrete thermal expansion below 0^{0}C. The need for a small but negative coefficient of thermal expansion was supported by the results of all the reinforced specimens and points to a small net expansion across the section. Deformation is typically in a direction which would be opposite to external design loads.

Restrained lightweight mass concrete again requires a mid-section expansion superimposed on the otherwise linear behaviour, confirming the trends of the other specimens. Thus, lightweight mass concrete behaves neither linearly nor according to Fig.3. It does, however, confirm the results of freeze-thaw studies where, it has been shown that, in the absence of surface chemical reactions, porous concretes are likely to initially develop internal cracking.

Continuation of the same thermal expansion and restraint modelling confirms the results of the normal density reinforced concrete specimens. However, the temperature boundaries are adjusted to +15^{0}C for the warm face and -55^{0}C for the cold face. This may reflect higher residual temperature strains from the curing period.

The large mid-section expansion of lightweight reinforced concrete in combination with small surface strains follows the general trend of that of the mass concretes, but it was difficult to model such a variation through finite element analysis.

A similar arrangement of restraint and thermal expansion models made it possible to model the distribution of longitudinal strains and stresses in normal density concrete. In the lightweight reinforced cases, concrete strains produced a good match although steel strains, whilst being large, did not match the magnitude of the very large experimental steel strains.

An analysis of the stress resultants allowed comparison with the previous study (Mawhinney [1]), revealing that, through a combination of excessive thermal expansion coefficient and stiffness, the initial study overestimated the effects of thermal gradients. Thermal creep and microcracking greatly reduces strains and stresses in the section, although in this experiment the threshold of plastic behaviour was not reached. Both restraint and a variable stiffness (increasing with decreasing temperature [1]) add further benefits.

Lightweight concrete, however, has large stresses chiefly in the centre section which may be due to ice formation and a reduced thermal inertia effect. This is not readily identifiable through the initial theoretical analysis.

5.CONCLUSION

Within the confines of a limited experimental programme, the results indicate the interesting nature of concrete when subject to sub-zero gradients. With the help of previous work in related fields and use of finite element analysis it is possible to explain the diverse results, particularly the three dimensional nature of the thermal expansion.

Normal density mass concrete follows the behaviour previously explained by Planas et al.[3]. In the context of this study, it is of purely academic interest since such a wall would not be employed in severe Arctic environments.

Normal density reinforced concrete acts as a uniform body with constant thermal expansion coefficient and is the best of the specimens tested. However, the slow change in experimental temperature and consequent reduction in response require further consideration.

The results of the lightweight concrete specimens are of considerable interest since it has already been used for offshore Arctic applications. The mid-section expansion would undoubtedly be a major design problem unforeseen by simple elastic theory, although it confirms the results of freeze-thaw studies. The specimens exhibit properties characteristic of a body where the steel and concrete are straining at different rates and in different directions causing disruption to matrix and bond.

The analysis has concentrated on elastic behaviour although it is quite obvious that creep effects play an important role. In particular, the analysis of the results after the 12 hour stage may provide important clues to freeze-thaw behaviour patterns. The effects of other experimental limitations have already been briefly discussed.

The problem of oil storage facilities for Arctic oil platforms requires further research. The provision of facilities below the waterline or sub-sea pipelines have an increased ice loading risk, while such facilities above the waterline cause large through wall stresses. Outer insulating 'buffer' zones such as used in the Super CIDS design or using new materials or design concepts will involve additional cost. Future research will need to identify suitable alternatives in design and establishing new standards.

ACKNOWLEDGEMENTS

The authors would like to thank Mr.A.L.Marshall of Sunderland Polytechnic,U.K. for support and guidance throughout the project. They would also like to thank the Japanese Monbusho Scholarship and Hokkaido University which provided the research funds.

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