Strain Behaviour Under Uniaxial Compression of Three Concretes During First Heating to 600 °C

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The current gas cooled reactor pre-stressed concrete pressure vessels (PCPV) are designed for concrete operating temperatures up to 65°C, whereas the maximum core coolant gas temperature for an AGR is about 650°C. The concrete is protected from the high temperature by gas streaming, thermal insulation and a cooling water system.

It is by no means certain that this limitation of concrete temperature is by itself necessary. Higher operating temperatures could reduce the cost of insulation and the power consumed by cooling but the limit of this temperature is not well defined. The concrete materials data on which to base an engineering analysis of behaviour is not adequate particularly that related to thermal transient behaviour during periods of initial and/or cyclic heating.

This paper presents initial results from laboratory tests to investigate the transient strain behaviour of three typical pressure vessel concretes when first heated to 600°C. Unsealed cylindrical specimens were exposed to a constant heating rate of 1°C/minute while subject to constant uniaxial compressive loads of 0, 0.1, 0.2 and 0.3 of the initial preheating cylinder strength. The overall axial strain and specimen surface temperature were monitored throughout the tests. The most difficult vessel condition to simulate is the moisture regime during heating. However previous tests had shown that unsealed samples could be more representative than sealed samples for concrete adjacent to the vessel liner and particularly for temperatures above about 150°C.

It is concluded that the magnitudes of the strain values are significantly influenced by the thermal expansion of the aggregate. A gravel concrete had the highest thermal expansion within the temperature range 20°C - 600°C and, therefore, experienced the most expansive strains under load, whereas a basalt concrete having the least thermal coefficient of expansion experienced considerable contraction under the higher loads. The strains were clearly influenced by the chemical and physical changes occurring in the concrete, such as dehydration of the cement paste and deterioration or phase changes of the aggregate.

The differences between the loaded and unloaded total strain curves, taken to represent approximately the 'transient creep' strains, were found to be similar in magnitude for all three concretes up to about 350°C despite the differences in aggregates and cements used. These strains were considerable and typically measured about 0.15% at 400°C at a load of 0.1 of the initial cold strength. The rate of increase in creep strains with temperature increased sharply above about 350-450°C depending on the concrete type. The creep strains were, furthermore, approximately proportional to the applied loads.

1. INTRODUCTION

Work on concrete heated under load/1,2,3/ has shown that greater strain occurs than if the concrete were heated first and then loaded. Also it has been shown that the initial heating produces greater strain than subsequent cycles and that these contain a large irreversible component.

The work by Illston/1/ was conducted with torsional loading of sealed samples to a maximum of 90°C. He termed the additional strain, due to heating under load, as the 'transitional thermal creep' component. Schneider/2/ concluded from uniaxial creep tests to 450°C that the transient creep becomes increasingly important above 80°C. This was confirmed by Anderberg/3/ in uniaxial tests up to 800°C. His work was mainly concerned with the exposure of concrete to fire and the majority of his tests were at heating rates of 5°C/min. or greater. The work of both Schneider and Anderberg was on ordinary portland cement and siliceous aggregate concretes.

This paper examines the behaviour of three pre-stressed concrete reactor vessel (P.C.R.V.) type concretes with limestone, basalt and siliceous aggregate (gravel) heated at a constant rate of 1°C/min to 600°C. The work is relevant to the engineering assessment of P.C.R.V. behaviour should operational temperatures be considered above the present typical limit of 65°C, and to hypothetical fault conditions which could assume an exposure of the concrete to coolant gas temperatures to an upper limit of 600°C.

The behaviour of the aggregate and cement pastes is also examined as an initial step to explaining the observed differences in behaviour between the three concretes tested.

2. DESCRIPTION OF SAMPLES

2.1 Mix Constituents

Although reactor vessel concretes normally use 20mm or 40mm maximum size aggregate it was necessary to restrict the maximum aggregate size to 10mm to be compatible with the sample size. The mix proportions (Table 1) and constituents were however representative of current U.K. pressure vessel concretes and so will provide a qualitative comparison of their behaviour. The chemical compositions of the concrete constituents are shown in Table 2.

2.2 Casting and Curing

The cylindrical samples (62mm diam. x 186mm) were cast in plastic moulds and compacted on a vibrating table. After demoulding at 24 hours the specimens were stored at 20°C and 100% relative humidity until required for testing at an age greater than 230 days. Further cylindrical samples and 100mm cubes were cast as strength controls and were similarly cured. All cylindrical samples had their top surfaces wet ground to be flat and orthogonal to the cylinder axis.

3. APPARATUS

The apparatus consists of a dead weight compression test machine to which is fitted a furnace with three automatically and independently controlled heating zones. This enables a uniform axial temperature distribution to be applied to the specimen despite natural convection effects. The rate of heating was set by an electronic ramp generator. The specimen's total axial deformation was transmitted via two end platens and an invar rod link system to a LVDT transducer placed beneath the furnace and away from the influence of heat, while the specimen's surface temperature was monitored by three Chromel-Alumel thermocouples (Fig. 1). Both displacement and temperature readings were automatically logged by an on-line computer at regular intervals.

4. TEST PROCEDURE

4.1 Main Test Programme

The specimen was removed from the humidity room and placed in position in the furnace between the platens. Three thermocouples were then attached to the surface of the sample with a high temperature ceramic adhesive. To minimize platen bedding-in effects the sample was load cycled within the elastic range. During this setting up period of approximately one hour the sample was losing moisture to the ambient atmosphere. It was then re-loaded to the test stress level immediately before heating at a rate of $1^{o}C$/min to a maximum temperature of $600^{o}C$ while simultaneously monitoring the surface temperature and overall axial displacement. Four constant stress levels were investigated, 0, 0.1, 0.2 and 0.3 of the cylinder strength prior to heating. The combination of specimen size and heating rate ensured average spatial temperature differences throughout the specimen of not more than $10^{o}C$.

4.2 Subsidiary Test Programme

Dilatometer and differential thermal analysis (D.T.A.) tests were conducted on a number of constituents.

The dilatometer tests /4/ were performed on 10 x 10 x 25mm samples under rough vacuum ($\sim$0.1mm Hg) in a Netzsch type 402E quartz tube dilatometer, with constant heating and cooling rates of $2^{o}C$/min.

The D.T.A. tests were performed to detect chemical phase changes or decompositions using a Stanton Redcroft apparatus. These tests were conducted in high purity nitrogen with a heating rate of $10^{o}C$/min.

5. BACKGROUND TO TEST PROGRAMME

Although the precise load, temperature and moisture regime that will be experienced by the concrete in a P.C.P.V. during initial heating cannot be predicted the tests reported here were designed to simulate the exposure of the concrete near the liner taking into account the following factors.

(a) Curing Condition. The P.C.P.V. concrete is considered to hydrate in an as-cast moisture condition at ambient temperature after an initial heat-of-hydration thermal cycle during construction. The latter was not simulated but recent work has claimed that this thermal cycle does not significantly affect subsequent high temperature creep of the mature concrete /5/.

(b) Moisture Condition. This is the most difficult regime to simulate during the thermal transient. The initially moist specimen represents the vessel concrete in its as cast condition at normal operating temperatures /6/. During heating the unsealed condition can be taken to represent the concrete near the liner and in the top cap region as there are numerous paths for moisture vapour to escape /7/. These tests showed that gases introduced at relatively low pressures (<7 bar) behind the liner readily vented to atmosphere via steel/con crete interfaces. The permeability of concrete, furthermore, increases by two orders of magnitude above $100^{o}C$ /8/.

(c) Loading Condition. The vessel concrete is assumed to be loaded before and duringthe thermal transient. The pre-stress system, furthermore, puts the concrete into triaxial compression. However, for this initial work and for ease of testing and analysis of the results, the test regime is simplified to that of uniaxial constant loading. The important point is that the concrete is loaded before the thermal transient. The maximum stress level under normal operating conditions for P.C.P.V. concrete rarely exceeds 0.2 of the uniaxial as-cast strength.

(d) Heating Condition. Calculations based on typical top cap designs have indicated that the mean concrete temperature could reach 300°C about 24 hours after a hypothetical total loss of cooling (i.e. 0.2°C/min). The average rate of increase of temperature clearly decreases with time after the initiation of the transient. A constant heating rate of 1°C/min. was chosen for this series of tests. The maximum temperature of 600°C was chosen to represent the AGR core coolant gas temperature.

6. RESULTS

6.1 Main Programme

The total axial strains induced by the combination of constant (or zero) load and increasing temperature to 600°C at a rate of 1°C/min. are given for the three concretes in figures 2, 3 and 4. Each curve represents results from a single sample and an idea of the reproducibility of the data can be obtained from results of replicate samples shown in figure 3. The initial strain at the beginning of heating of all the curves has been reduced to zero by subtracting the elastic strains on loading from the curves of the stressed specimens.

6.2 Subsidiary Programme

The dilatomater tests on the three cement pastes on first heating indicate that after initial expansion up to about 100°C, the shrinkage due to loss of moisture, both free and chemically combined, predominates up to 600°C. The OPC/PFA paste resulted in the least shrinkage, at 600°C, of 2.3% compared to 3% for OPC and 4.1% for the SRC/Cemsave paste as shown in figure 5.

Aggregate dilatometer tests shown in figure 6 indicated a greater expansion of limestone than basalt material. Also the limestone when heated to 600°C gave a greater irreversible expansion. Established data indicate that the thermal expansion of gravel aggregate is higher than both those of limestone or basalt materials /9/. Another feature of gravel aggregate is the significant increase in the thermal expansion above 350°C due to the break up of the aggregate /10/.

The DTA results on the three cement pastes shown in figure 7 indicate a first broad endothermic peak with a long tail region typical of the dehydration of a porous material of colloidal dimensions. The 2nd sharp peak at about 550°C is due to the decomposition of calcium hydroxide ($Ca(OH)_2$) into water and free lime (CaO).

DTA results on aggregates and sands (diagram not shown) indicated that up to 600°C the only significant effect is the α to β quartz phase change which is accompanied by a significant increase in volume.

7. DISCUSSION

The total strains for the unloaded samples consist of components due to (1) thermal expansion, (2) changing moisture content, (3) chemical transformations and (4) cracking caused by differential thermal expansion and physical deterioration of the concrete constituents. The loaded samples will additionally have components of strain due to (5) temperature dependence of elastic properties, (6) "steady state" temperature creep and (7) "transitional thermal creep" strains induced by first heating under load. The total load induced strain can be determined by subtracting the unloaded strain curves, for each concrete, from those of the loaded samples. The resulting load induced strains are shown in figures 8 and 9 as functions of temperature. Previous work /3/ has indicated that the transitional thermal creep component is by far the largest component of load induced strain. However, the magnitude of this component cannot be accurately determined until the completion of further tests which the authors are at present undertaking.

The shape and magnitude of the total strains for both loaded and unloaded specimens during heating are primarily determined by the physical and chemical properties of the aggregate and the cement paste on heating. These are markedly different as was shown in the results of the subsidiary tests on the concrete constituents. The large differences in the free expansions of the three concretes are clearly related to the aggregate/cement paste type and as the aggregate is the principle volumetric constituent, its expansion dominates the free strain behaviour.

Gravel aggregate, which had the largest expansion, causes the grand concrete to expand by about 0.23% at 300°C even under a compressive stress of 0.2 times the initial unheated strength. Above 350°C the break up of the aggregate resulted in a sharp increase in the thermal expansion of the concrete particularly at low load levels. By comparison, the basalt mix showed the least expansion due to the relatively low thermal expansion of the basalt aggregate combined with the high shrinkage of the SRC/Cemsave cement paste. At 0.2 load level the specimen exhibited a net contraction of about 0.015% at 300°C. All curves, furthermore, indicate a sudden and significant expansion at about 570°C due to the α to β phase change of the quartz present in the aggregates and sands. The tendency for shrinkage to predominate over the thermal expansion for the loaded specimens between 100°C and 200°C as well as between 450°C and 570°C can be related to the DTA endothermic peaks referred to earlier.

The 'load induced strains' given in figures 8 and 9 on the other hand resulted in significantly smaller differences between the mixes with the exception of the gravel concrete which indicated a large strain increase above 350°C. This latter strain is due more to the aggregate behaviour than to a large increase in cement paste strain. Thus the load induced strains are primarily seated in the cement paste except when aggregate damage occurs.

The magnitudes of the load induced strains are considerable. The limestone concrete, for example, registered a load induced strain of about 0.3% at 400°C for a load level of 0.2. Generally, the rate of increase in strain is least below 100°C. It then increases markedly during the period of maximum moisture loss between 100°C and 200°C. The strain rate decreases slightly at higher temperatures but then progressively increases with temperature. It is interesting to note that the effect of the sudden expansion of the concrete at 570°C due to the quartz inversion is absent from the load induced strain curves. This indicates that both loaded and unloaded specimens were similarly affected by the increase in length at that temperature. It is interesting to note the approximate linearity between the load induced strains, and applied load level, shown in figure 10.

8. CONCLUDING REMARKS

This work confirms that the total strain during first heating of concrete to 600°C is dominated by the thermal expansion of the aggregate, the principle volumetric constituent.

The shape of the total strain curves is related to the various physical and chemical properties of the constituents, for example the splitting of the siliceous gravel aggregate at above 350°C and the α to β phase change of quartz at 575°C.

The cement paste contributes noticeable to the strain curves at about 150°C-200°C when free moisture loss occurs, and above 300°C with the continuing loss of chemically combined water.

The load induced strains occur primarily in the cement paste and are approximately proportional to the applied stress. These tests form part of a larger programme and further tests are being undertaken to investigate the effect of variations in the heating rate and initial moisture content on these and other concrete and cement paste samples.

9. ACKNOWLEDGEMENT

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TABLE 1: MIX PROPORTIONS AND PROPERTIES

CONSTITUENT	PROPORTIONS BY DRY WEIGHT		
	LIMESTONE MIX	GRAVEL MIX	BASALT MIX
Cement (OPC)	1.0	1.0	-
Cement (SRPC)	-	-	0.5
Cemsave	-	-	0.5
PFA	0.25	-	-
Sand (Zone 2 B.S.882)	2.30	-	1.8
Sand (<4.8mm)	-	2.3	-
Aggregate (10mm)	3.45	2.39	2.7
Water	0.555	0.6	0.45
Plasticizer	0.005 Plastocrete	-	0.005 Cormix P1
Agg./Cement ratio	4.6	4.59	4.5
Slump (mm)	53.0	63	62 - 75
28 Day strength N/mm^2 (100mm Cube)	51.0	61.0	50.9
Density as cast Kg/m^3	2346	2259	2498
Cement content Kg/m^3	388	365	420
Cylinder strength prior to test (62mm diam) N/mm^2	64.2	30.9	56.5
At age (days)	436	233	296

TABLE 2: CHEMICAL COMPOSITION OF CONSTITUENTS

		CEMENTITION MATERIAL				AGGREGATES			
						BASALT MIX		LIMESTONE MIX	
		OPC	SRC	PFA	CEMSAVE	AGG.	SAND	AGG.	SAND
Lime	(CaO)	63.20	63.90	8.38	43.6	9.35	12.74	52.50	4.13
Silica	(SiO_2)	19.90	20.66	42.51	34.16	51.98	67.83	1.28	78.91
Alumina	(Al_2O_3)	6.73	3.22	33.80	14.10	15.00	3.59	1.52	8.74
Ferric Oxide	(Fe_2O_3)	2.20	4.72	6.10	0.34	12.75	1.99	0.38	1.88
Magnesia	(MgO)	1.30	2.16	1.71	4.68	6.56	0.38	1.54	0.84
Sulphuric Anhydride	(SO_3)	3.00	2.32	0.61	trace	trace	-	0.07	0.07
Potassium Oxide	(K_2O)	0.96	0.55	0.61	0.47	0.60	-	0.01	0.07
Sodium Oxide	(Na_2O)	0.28	0.17	0.18	0.24	2.40	0.92	0.02	0.02
Carbonic	(CO_2)			0.76		0.24		40.20	1.78

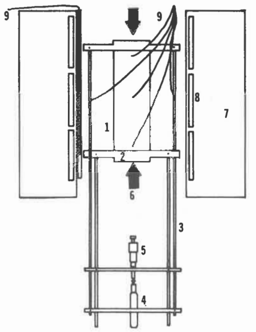

FIG. 1 DIAGRAM SHOWING A SCHEMATIC REPRESENTATION (NOT TO SCALE) OF:

(1) CONCRETE SPECIMEN (2) END PLATENS (3) INVAR RODS (4) TRANSDUCER (5) MICROMETER (6) APPLIED LOAD (7) FURNACE (8) INDEPENDENT HEATING ZONES (9) THERMOCOUPLES

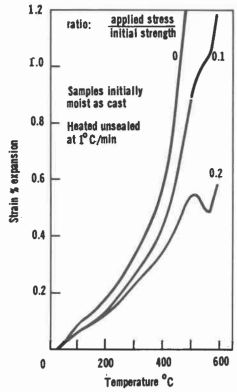

FIG. 2 TOTAL STRAIN OF GRAVEL CONCRETE DURING FIRST HEATING

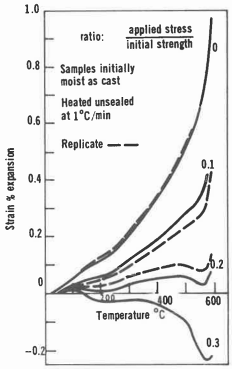

FIG. 3 TOTAL STRAIN OF LIMESTONE CONCRETE DURING FIRST HEATING

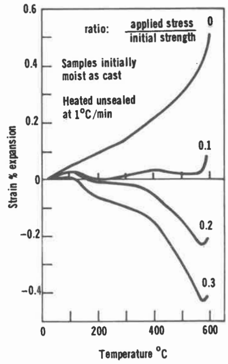

FIG. 4 TOTAL STRAIN OF BASALT CONCRETE DURING FIRST HEATING

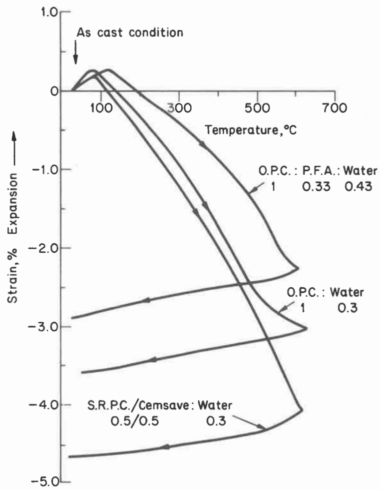

FIG.5 CEMENT PASTE STRAIN ON FIRST HEATING

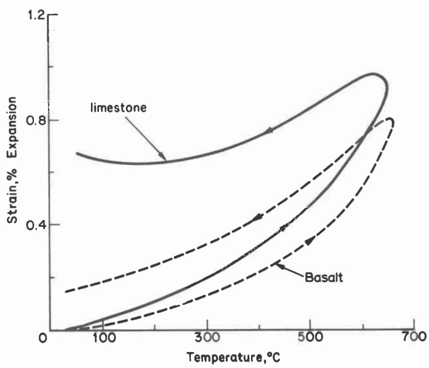

FIG.6 THERMAL EXPANSION OF AGGREGATES ON FIRST HEATING

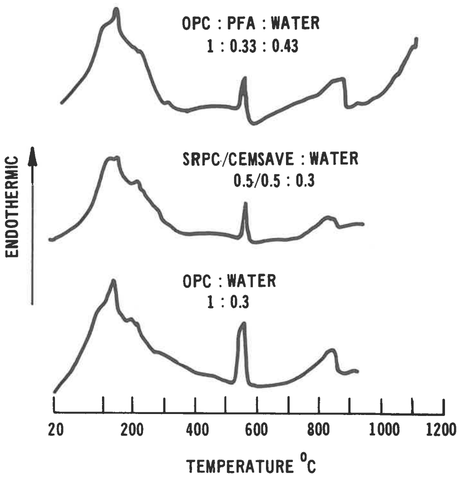

FIG. 7 DIFFERENTIAL THERMAL ANALYSES OF VARIOUS CEMENT PASTES(10°C/min IN NITROGEN)

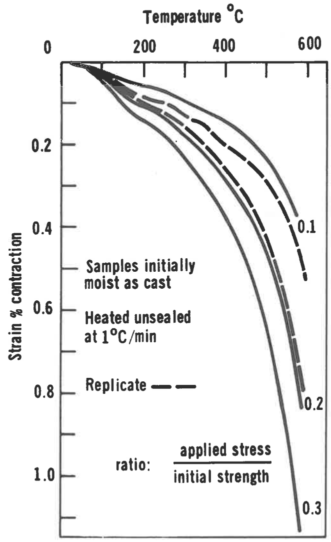

FIG. 8 VARIATION OF LOAD INDUCED STRAIN WITH TEMPERATURE FOR FIRST HEATING OF LIMESTONE CONCRETE

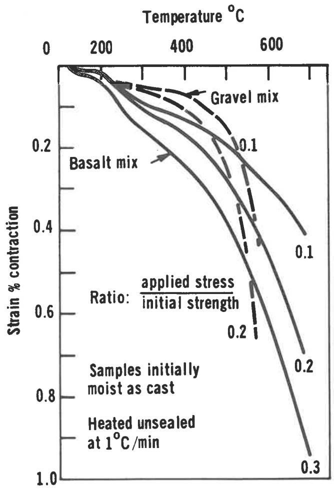

FIG. 9 VARIATION OF LOAD INDUCED STRAIN WITH TEMPERATURE FOR FIRST HEATING OF GRAVEL OR BASALT MIXES

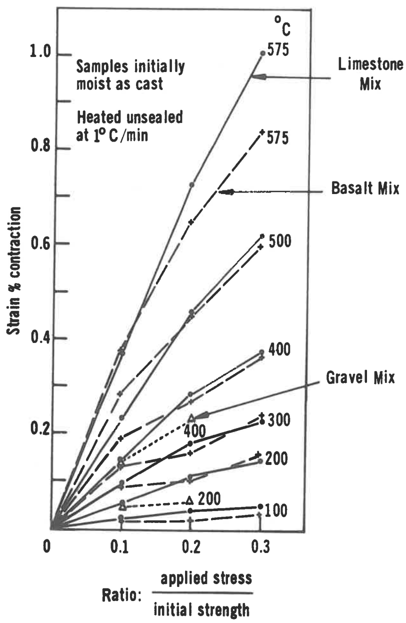

FIG. 10 EFFECT OF LOAD LEVEL ON LOAD INDUCED STRAIN DURING FIRST HEATING