RELAXATION OF RESTRAINT EFFECT CAUSED BY TEMPERATURE DIFFERENCE OR SETTLEMENT OF A SUPPORT IN LONG TERM TESTS

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SYNOPSIS

The creep of concrete has considerable influence on the relaxation of the restraint effects and restraint stresses; particularly if the temperature of concrete is higher than normally. Risk of cracking e.g., caused by the settlement of supports, is also diminished owing to creep; particularly if the rate of restrained displacement (settlement of a support) is slower than the rate of creep. It is difficult to consider the effect of relaxation from a calculational point of view, because the time dependencies of several factors cannot be reliably modelled. In the research, the relaxation of the restraint stresses, due to both sudden and slow settlement of a support, was examined as a function of time; the relaxation of the restraint effect due to a thermal gradient was also investigated. It was observed the relaxation was fairly rapid in a heated beam in particular. Also the relaxation of additional stresses caused by the settlement of supports was considerable.

Keywords: concrete, relaxation, temperature, settlement of support

1 INTRODUCTION

Concrete has characteristic properties such as a tendency to deformations at the changes of temperature or humidity as well as a tendency to creep, which refers to the continued increase with time in deformation of concrete under stress. Creep occurs both in compressed and tensioned concrete. Mechanisms affecting the time-dependent behaviour of concrete are, as well known, fairly complicated and as far as practical calculations are concerned they are not yet under complete control. In most cases, it is also nearly impossible to tell the difference between the mechanical and non-mechanical deformations. Practical calculations are mainly based on the constitutive material models, which do not pay enough attention to the changes of temperature and humidity. Neither can the development of cracking be taken into account by means of these models. So far the problem of the combined effect of cracking, temperature and humidity, let alone the effect of time, has not been solved.

A solution to the problem should take into account both mechanical and other deformations, due to e.g. the conditions of exposure: they include both fast and time-dependent parts, which again can be either reversible or irreversible. Further, deformation processes may be interdependent. The mentioned factors should, in addition, be examined in relation to cracking and the possible dependency on it.

It is known that the effect of temperature is two-way. On the one hand, the rising temperature accelerates the rate of deformation and on the other hand, it accelerates the rate of hydration reactions i.e. the hardening rate of concrete.

If deformations or displacements have been induced or restrained onto a structure, one must instead of creep speak about a relaxation phenomenon which means the continuing reduction of stress with time. An induced or restrained displacement in a structure can, in principle, be of short or long duration. When the time period of formation and effect is short, relaxation cannot take place in concrete and it cracks if the restrained strain is greater than the strain at failure.

Restrained displacements with long-term effects consist of both rapidly and slowly developing displacements. If no cracking occurs in connection with a rapidly forming restrained displacement, the corresponding restraint effect grows in relation to the stiffness of a structure. At the formation phase of cracks, the restraint effect grows clearly more slowly than the restrained displacement since every new crack reduces the stiffness of a structure. The restraint effect cannot be assumed to grow at the rate of the restrained displacement before the crack formation has stabilized. After having reached its greatest value the action effect due to restrained displacement starts to relax owing to creep. Since the rate of creep decreases with time the relaxation of the action effect is the greater the earlier the restrained displacement takes place.

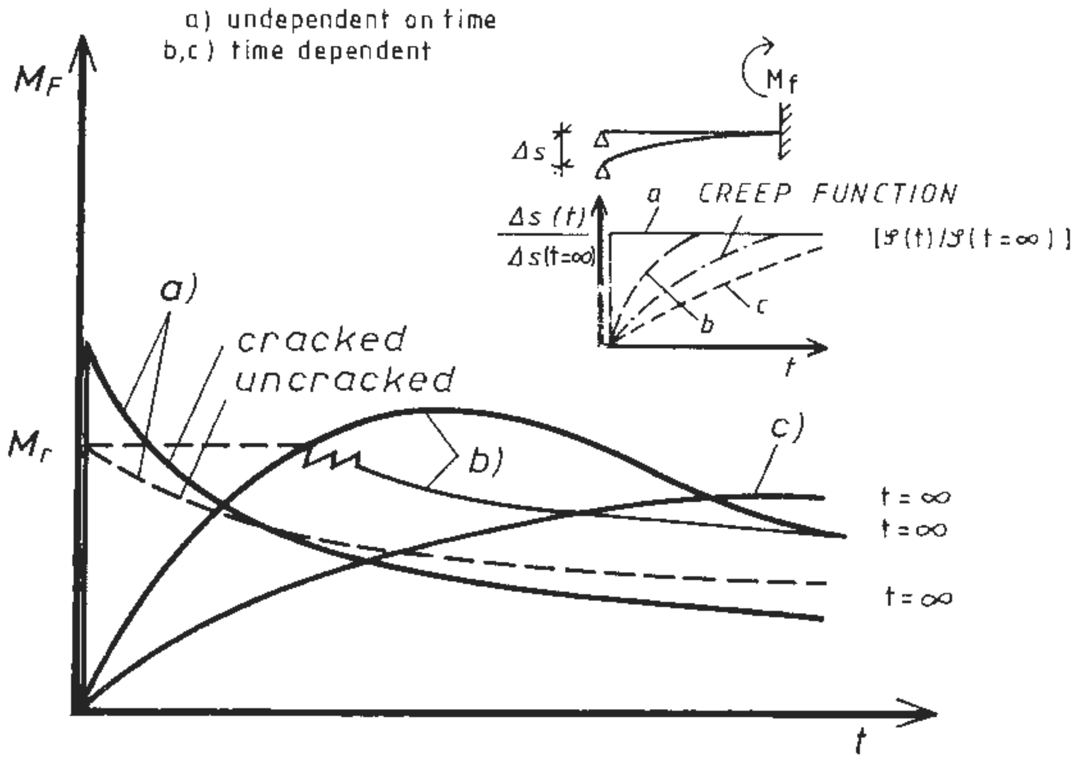

Fig. 1. Influence of the rate of restraint stress development on creep /8/.

As the rate of the displacement formation slows down a partial relaxation of the restraint effect takes place. If the restrained displacement, which only increases at the formation phase of cracks, grows quicker than the deformation induced by creep, the structure will crack, but the restraint effect does not grow greater than the crack action effect. If, on the other hand, the restrained displacement grows more slowly than the creep, the structure will not crack at all (Fig. 1).

In order to estimate relaxation by calculational means the time dependency of restrained displacement and that of creep as well as the changes taking place in the structural properties, above all in stiffness, during the displacement formation must be known. If the temperature deviates from the normal the temperature dependency of creep must also be known. The problem has been examined from the calculational point of view by e.g. in references /1, 3, 8/.

In this article, results from tests with four reinforced concrete beams relating to the relaxation of the restraint effect due to displacement of supports in different situations are presented.

2 EXPERIMENTAL STUDY OF CONCRETE RELAXATION

2.1 Structural model

The statical structural system of the test beams corresponded to a double support beam stiffened at one end, whose free end was subjected to various restrained displacement. A heat gradient of about 50 °C was directed to one beam: a restraint moment was induced at the fixed support.

2.2 Test beams

Two double beams were manufactured for the tests and they were marked with the following symbols: 1a, 1b, 2a and 2b. The amount of tension and compression reinforcement in beams 1a and 1b was 0.43 % and 1.29 % in beams 2a and 2b. The dimensions and structures of the beams set out in Fig. 2 and material properties in Table 1.

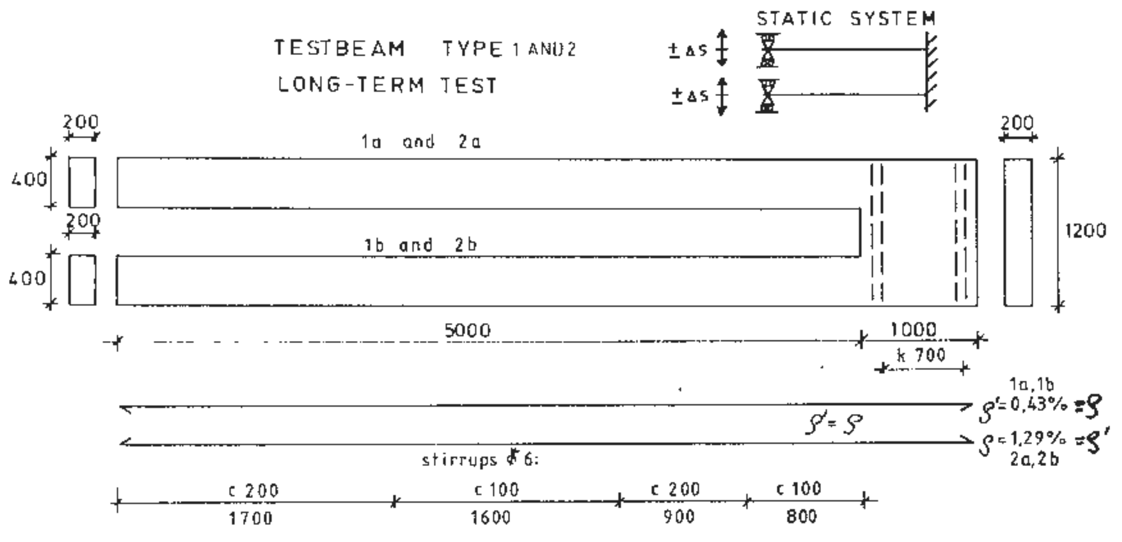

Fig 2. Dimensions and structure of the test beams.

Table 1. Material properties of the test beams based on samples.

Beam	Concrete	Reinforcement (A400H)						
	Compressive strenght MN/m²	Yield stress MN/m²	Ultimate strenght MN/m²	Diameter mm	Rib angles α	Rib angles β	Rip spacing mm	Relative rib area α_{sb}
1a, 1b	52	458	690	10	48	61	6.5	6.7 %
2a, 2b	52	434	630	20	53	69	13.6	8.0 %

2.3 Long-term tests

In long-term tests (total duration 8 months) a thermal gradient of about 0.1 °C/mm (temperature difference of 40 - 50 °C) was directed to beam 1a in such a way that the temperature of the upper surface remained at about 35 - 40 °C and that of the lower surface at about 80 - 85 °C. A thermal gradient was produced by heating the lower surface of a beam using electrical resistance mats. The upper surface was isolated by mineral wool. In order to direct heat flow mainly in one direction and to ensure a maximum thermal gradient, the sides of the beams were provided with approximately 50-mm thick mineral wool insulation. The measuring plugs were installed for deformation measurements along the upper and lower edges of the entire length of the beam. For displacement and rotation measurements inductive displacement transducers were installed. The support reactions of the free end of beams were measured by means of a load cell. The measurement results, along with output, were registered throughout the test using a microcomputer. The loading arrangements of the beam are shown in Fig. 3.

A displacement of about 20 mm, which was kept constant, was instantaneously forced onto the free support of beams 1b (upwards) and 2a (downwards). The temperature of these beams was kept at about 20 °C during the entire test.

Displacement of the support corresponding in size to that of beam 1b and 2a was gradually forced onto the free support of beam 2b over a period of about 2 weeks. Displacement was increased daily in approximately equal amounts; subsequently it was kept constant (Table 2). The temperature of the beam was kept at about 20 °C throughout the test. The final displacement of supports produced a calculational steel stress of about 200 N/mm² at the fixed support, when the stiffness of the beams was chosen as the average value of the uncracked and cracked stiffness.

Table 2. Displacements at the free ends and at the centre of beams in long-term tests.

Beam	Restrained displacements (mm) 1)							
	1a		1b		2a		2b	
Date	end	centre	end	centre	end	centre	end	centre
2) 28.8.-85	-1.55	-0.84	19.10	7.02	-18.50	-7.56	0.05	-0.23
29.8.-85	-1.56	-0.75	19.10	6.99	-18.54	-7.51	3.97	1.07
30.8.-85	-1.86	-3.10	18.92	6.73	-18.54	-7.57	6.09	1.70
3) 10.9.-85	-1.79	-2.68	18.97	6.95	-18.52	-7.37	19.73	6.60
7.1.-86	-1.80	-3.04	18.99	6.69	-18.55	-7.39	19.82	6.50
5.5.-86	-1.78	-3.23	19.00	6.54	-18.59	-7.47	19.84	6.43

1) direction of displacements positive upwards
2) heating of beam 1a starts
3) increase in the settlement of beam 2b was discontinued.

During the tests, measurements were made relating to

- crack widths
- crack spacings
- displacements
  - deflections
  - rotations
- deformations at the upper and lower edges of a beam
  - strains in steel
  - compressive strains and elongations
- support reactions
- temperature of a beam at different heights.

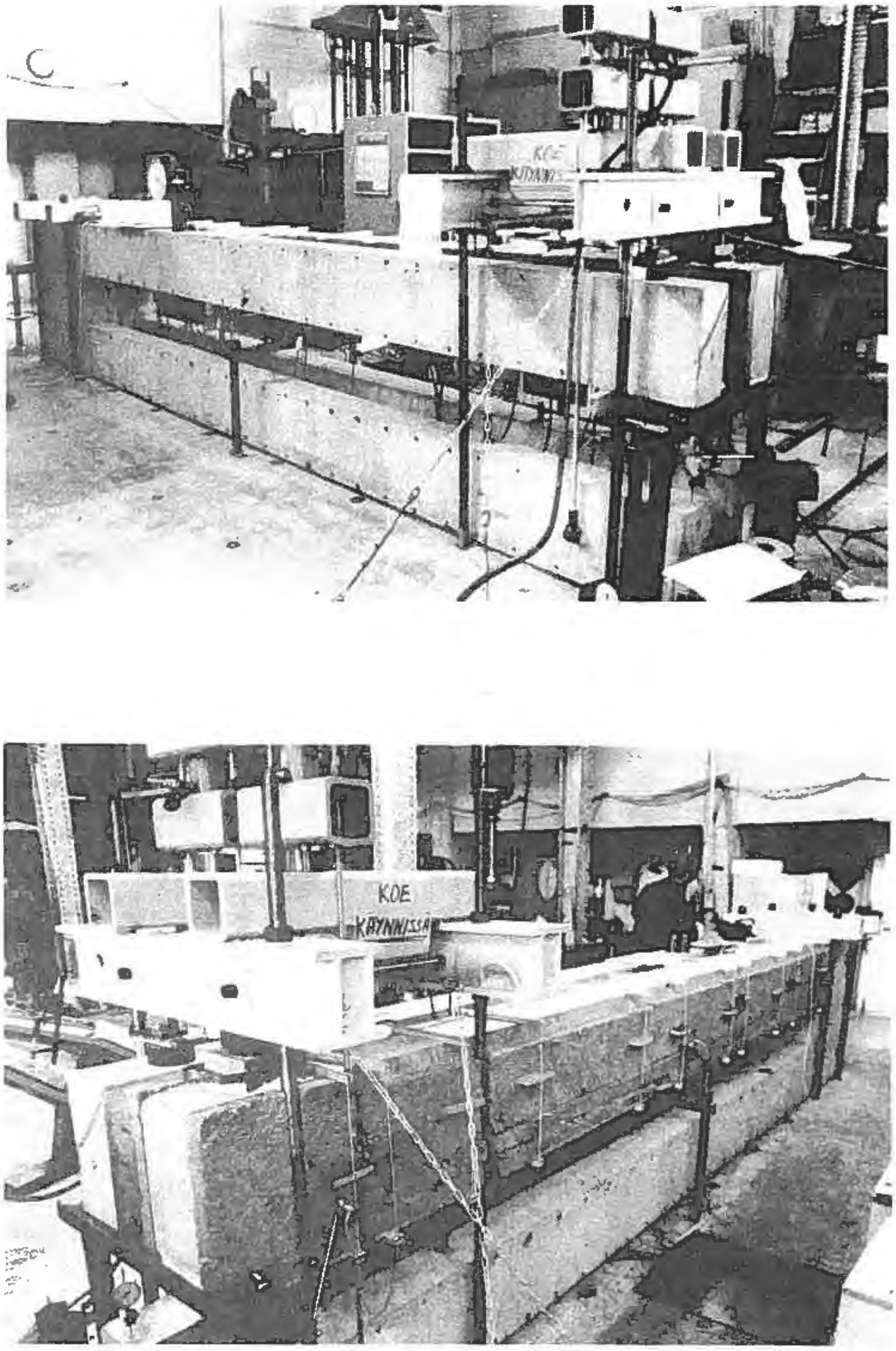

Fig. 3. Test arrangements in long term tests.

2.4 Results

The main results of relaxation tests are presented in the following figures:

- the temperature gradient of the beam 1a measured at different times during the test in Fig. 4.
- the deflection in the mid-span of the beam 1a in Fig. 5
- the support reactions of the free end of the test beams measured during the test in Fig. 6.
- the development of average crack widths measured from the test beams during the test in Fig. 7.

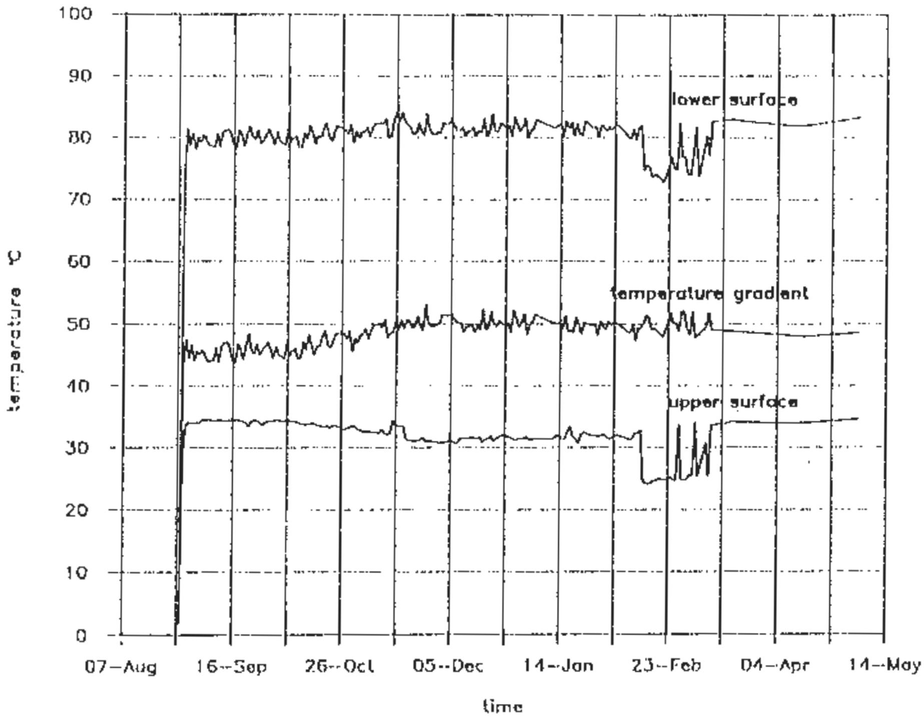

Fig. 4. Temperature of upper and lower surface and temperature gradient of the heated beam during the test.

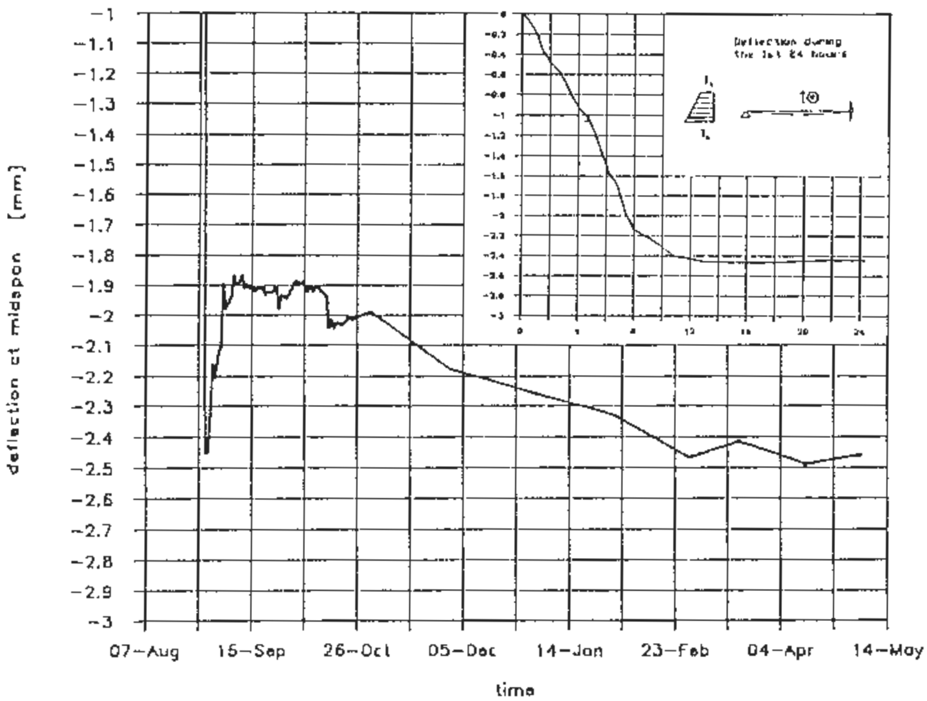

Fig. 5. Deflection at the midspan of the heated beam 1a.

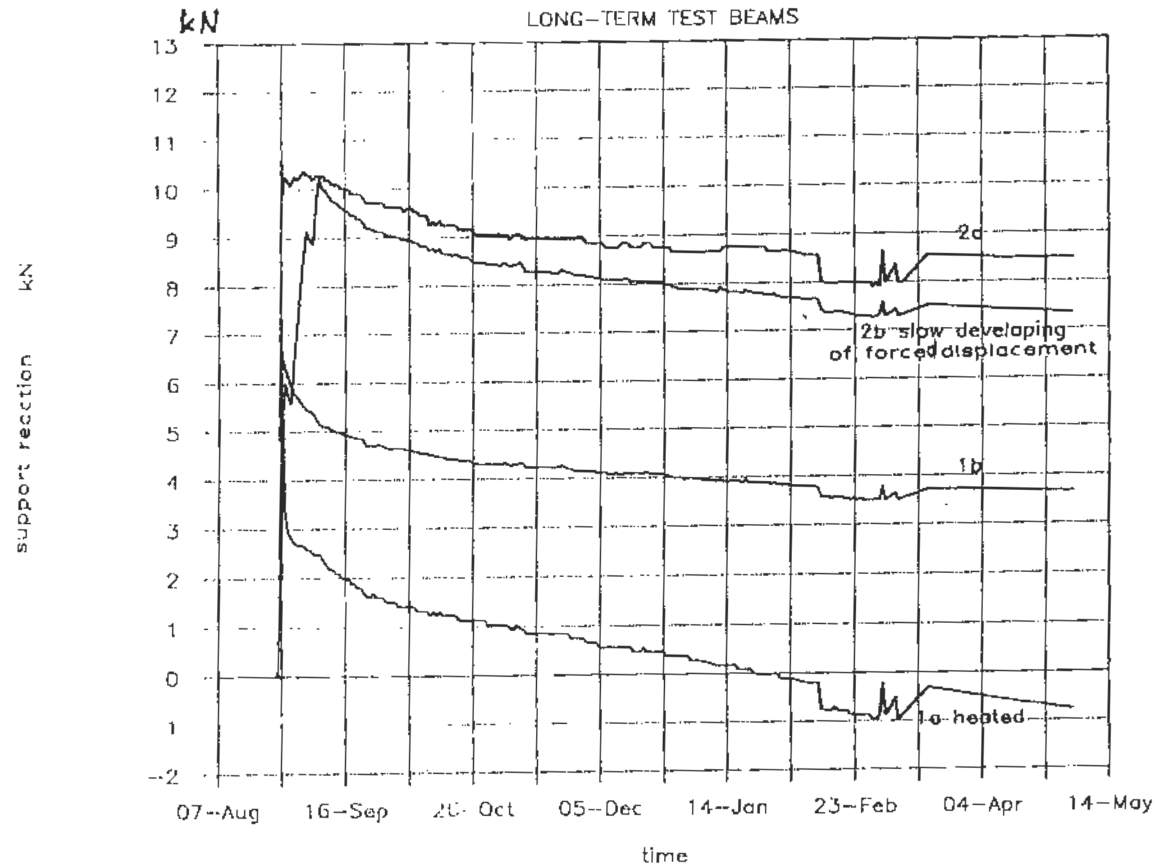

Fig. 6. Support reaction values (including own weight) in the free end of all beam during the first eight months.

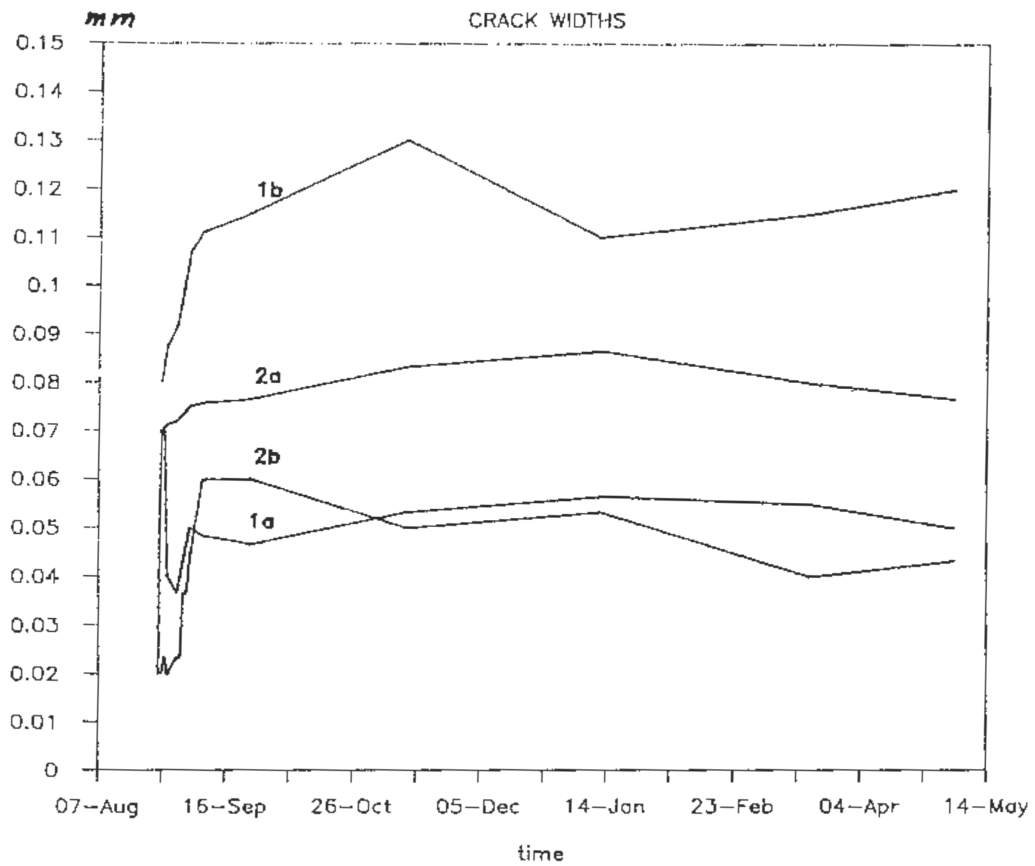

Fig. 7. Development of crack widths during tests.

3 EXAMINATION OF RESULTS

In the heated beam, 1a, a linear thermal gradient of about 0,1 °C/mm was produced about 8 hours from the onset of heating; subsequently it remained nearly the same during the entire test.

The effect of temperature on the creep of concrete and its relaxing influence on the restraint effects is surprisingly powerful. Short-term tests carried out earlier, lasting about 12 h /5/, had yielded similar results.

In the now reported tests, as well as in earlier ones, the temperature of the heated, creeping part of concrete was about 80 °C. The maximum value of the restraint moment in beam 1a, due to thermal gradient, was 27.5 kNm and it was reached about 5 h from the onset of heating. Due to the accelerated rate of creep, over 10 % of the restraint moment had relaxed as soon as 7 h from the onset of heating and about one third (1/3) during the first 24 hours. The relaxation of the restraint moment continued so that after about one month one third of the maximum original value was left and after 6 monts the entire restraint moment due to heating had relaxed. The final measured support reaction of the free end of the beam is greater than the original because the stiffened support had cracked and the weight of the loading equipment had been ignored.

In the beams, the ends of which were subjected to a restrained displacement corresponding to a steel stress of 200 N/mm^2, the relaxation of a support reaction took place quite rapidly even at normal temperature. A decrease in the support reaction with different beams is set out in Table 3, assuming that in all cases the proportion of the beams' own weight is 5 kN of the support reaction.

The proportion of the shrinkage during the tests was not measured. Its influence is estimated approximately from 5 - 10 %, because the tests beams were at the beginning of long-term tests 1,5 years old and stored in test hall conditions.

Table 3. Decrease in restraint effect owing to creep.

Beam	Proportion of the relative value of the restraint effect to its greatest value during different testing periods, %						
	14 days	1 month	2 months	3 months	4 months	6 months	8 months
1a [1]	42	31	22	18	10	0	-3 [3]
1b	71	67	61	58	55	53	52
2a	97	94	88	85	84	84	82
2b [2]	90	84	78	76	74	71	68

1) heated
2) displacement of a support carried out step by step during the course of 2 weeks.
3) due to cracking of the support and the measuring equipment's own weight.

Relative relaxation of the support reaction due to the creep and shrinkage of more heavily reinforced beams 2 (ρ = 1.29 %) was distinctly slower than in the case of more lightly reinforced beams (ρ = 0.43 %).

The relative relaxation of the restraint moment in beam 2b, the restrained displacement of which took place in 2 weeks, was faster than in beam 2a, the restrained displacement of which took place momentarilly. Also the degree of relaxation of beam 2b, corresponding to the end of the test, was greater. The difference in the degree of relaxation was considerable already at the beginning of the test.

The deflection downwards of the mid-span of the heated beam increased nearly linearly in relation to the thermal gradient; subsequently its value remained constant at 2.45 mm for about 12 hours. As the heated and compressed lower surface of the beam started to creep, the deflection decreased rapidly i.e. about 25 % in a few days. As it has been stated, the restraint effect also relaxed down to half of its maximum value in the equivalent course of time. Subsequently, the value of the deflection remained nearly unchanged for about 2 months, after which the deflection started to grow again. This is due to the fact that after 2 months about 20 % of the maximum value of the restraint effect remained and owing to the moment caused by its own weight, the upper surface of the beam gradually became compressed and thus creep could begin. Since also the temperature of the upper surface was above the normal (about 35 ^{o}C) the rate of creep, even in this phase, was greater than normally. The increase in the deflection was slowed down about 6 months after the start of the test when the value of the deflection was approximately the same (about 2.5 mm) as the maximum deflection due to a short-term thermal load (about 0.1 ^{o}C/mm).

The average crack widths did not change essentially during the long-term test.

4 CONCLUSIONS

1. The effect of temperature (+80 ^{o}C in the test) on the rate of the creep in concrete and thus on relaxation is considerable. With the thermal gradient used in the test, the restraint effect was reduced to 30 % of its original value during one month when the corresponding reduction without heating was only to 65 % of the original value. After six months the restraint effect was totally reduced in the heated beam.
2. The relaxation of the restraint effect in a stiff, heavily reinforced beam is relatively slower than in a lightly reinforced beam, and the degree of relaxation is not as great.
3. The slower development of the restraint effect cauces a faster relaxation and a greater degree of relaxation.
4. If a structure is subjected to a thermal gradient and some other mechanical load (e.g. own weight) the statical system of a structure and the relaxation of the restraint effects must be taken into account when estimating structural long-term deformations in order to find out the direction of curvature that is caused by creep. The direction of change of the deflection may vary according to which side of a structure is compressed or heated and according to the degree of relaxation of the restraint effects and the redistribution of the external load effects due to cracking.
5. The average width of cracks is not essentially changed at the relaxation of the restraint effects, but instead keep approximately the same width they had at formation.

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