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Elastic strain, Young's modulus variation during uniform heating of concrete

H. Sabeur*, H. Colina† and M. Bejjani†

University of Marne La Vallée; Navier Institut

In this work, the variations in elastic strain and Young's modulus of high-performance concrete under constant load and increasing temperatures up to 400°C in accidental conditions are studied experimentally. The same study is carried out under service conditions for high-performance and ordinary concrete subjected to temperatures up to 220°C. The corresponding heating rates are applied until successive constant temperature levels are achieved, and are maintained for several hours to ensure the stabilisation of internal temperature and physico-chemical thermo-dependent processes. The analysis centres on the elastic strain and Young's modulus variations as a function of temperature. The current paper also focusses on the influence of the heating rate. The elastic strain and Young's modulus values are estimated at different temperature levels: 150°C, 200°C, 300°C and 400°C for the high-performance concrete under accidental conditions and 140°C, 190°C and 220°C for both high-performance and ordinary concrete under service conditions.

Introduction

Several investigations into the effects of high temperature on the thermal and mechanical properties of concrete have been reported in the last half century.[1–11] Nevertheless, these variations in concrete properties continue to be the subject of research. Many questions remain unanswered because the test parameters vary between investigations. Among the investigations, some of the research is directed at the variation of elastic strain and Young's modulus during uniform heating of concrete.[2–6,9–11]

When concrete is subjected to high temperature, the breaking of bonds in the microstructure of the cement paste, caused by temperature increase, results in a reduction of Young's modulus. Simultaneously, the increase in temperature produces an acceleration of the creep process, which reduces the value of Young's modulus.[4–5] The evolution of the Young's modulus is influenced by the initial value, water content, type of aggregate and the heating rate (i.e. the faster the heating, the lower the elastic modulus).[3,5]

Furthermore, it should be noted that drying, which results from temperature increase, induces a decrease in the Young's modulus value. Moreover, during fast drying the Young's modulus drops more rapidly than it does during slow drying shrinkage.[2,9] This is attributed to the higher stresses, caused on the one hand by the thermal incompatibility between the cement paste and aggregate and on the other hand by the developed pore pressure that leads to greater damage of the microstructure.[2,9]

The experimental studies show a gradual reduction of the Young's modulus with temperature. The current paper evokes tests carried out on three high-performance concretes (HPCs)—M100C, M75C and M75SC—and an ordinary concrete (OC), (M30C), by Hager[10] in the Centre Scientifique et Technique du Bâtiment (CSTB) laboratory in France, tests carried out by Xiao and Konig[11] on HPC and normal-strength concrete (NSC), and the results given by Schneider[5] from literature on the variations of the elasticity modulus of concrete at high temperatures. Schneider noted that the original strength of concrete, the water–cement ratio, the stress level within a range of 0·1 to 0·3 of compressive strength and the type of cement had little effect on the elasticity–temperature relationship.

The elastic strain, and particularly Young's modulus variation during uniform heating, are of great importance when determining (a) the thermal damage of con-

* Laboratory of Mechanics (LAM), University of Marne La Vallée, UMLV Joint Laboratory, Navier Institut, Champs Sur Marne 77454, France.
† Laboratory of Material Analysis and Identification (LAMI), ENPC–LCPC Joint Laboratory, Navier Institut, Champs sur Marne 77455 Marne-la-Vallée, France.

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crete in any kind of condition (service and especially accidental) and (b) the performance of concrete structures. Despite this importance, only a few investigations have been reported, especially in the case of HPC in accidental conditions (heating rates higher than 0·5°C/min and temperatures in the range 20°C to 800°C or above).

In the current paper, the variation of elastic strain and Young's modulus of OC and HPC in service and accidental conditions is studied experimentally. The influence of the heating rate owing to the type of conditions for the HPC in the temperature range of 20°C to 400°C and the difference in the behaviour of the elastic strain for the two types of concrete at service conditions in the temperature range of 20°C to 220°C are of great interest.

Materials and test methods

Materials and test device

The materials and test device have been introduced in previous papers[12–14] and are briefly described here. The tests were performed on hollow cylinders in order to obtain a uniform distribution of temperature inside the specimens. The specimens were heated from the external top and bottom surfaces and internally. The specimen dimensions were 160 mm for the external diameter, 30 mm for the internal diameter and 640 mm for the length. The temperature change inside the material was monitored by means of five thermocouples, distributed as indicated in the Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages (RILEM) recommendations.[15]

The constant load, 20% of the reference 'cold' compressive strength of the concretes, was applied by means of the two plates of a heating power press. Two average heating rates were applied: the first one equal to 0·1°C/min corresponding to service conditions and the second one applied at 1·5°C/min corresponding to accidental conditions. Length variations during the test were measured with a compressometer rig that was designed especially for this experiment, with three linear variable differential transducers (LVDTs) lodged in Invar supports disposed vertically at 120°.

Two concrete mixes were tested: an OC and a HPC. In the case of accidental conditions, three specimens of HPC per mix were cast for the principal test. For the service conditions test, three specimens of OC and two specimens of HPC per mix were cast. For the two conditions, five normalised cylinders for the compressive strength and Young's modulus tests were also cast. The mix design properties of the OC and HPC are given in Table 1. More details on the materials and test device can be found in references 12–14.

Test development

The specimens were prepared in a suitable way[13] and put into the press. The constant load of the tests was 20% of the reference 'cold' compressive strength of the concretes; 7 MPa and 20 MPa were therefore applied to OC and HPC specimens, respectively. For service conditions, the specimens, were heated at a constant rate of 0·1°C/min until successive temperature levels of about 140°C, 190°C and 220°C were constantly maintained for several hours to ensure the stabilisation of internal temperatures and then of mass loss in each case. For accidental conditions, the heating rate was equal to 1·5°C/min until successive temperature levels of 155°C, 200°C, 310°C and 400°C were reached.

In all the tests, the elastic strain at ambient temperature was recorded when loading the specimen. Subsequently, this strain component was measured at the end of all the constant temperature stages by means of a quasi-instantaneous unloading–loading cycle (with a

Table 1. Details of the tested concrete mixes

Constituents	Quantity: kg/m^3	Aggregate/cement ratio	Water/cement ratio	Compressive strength: MPa
OC : ordinary concrete		4·8	0·5	35
CEM II/A-LL 32·5 cement	350			
0/4 Seine's sand*	672			
5/20 mm silico-calcareous gravel	1008			
Water	175			
HPC: high-performance concrete		5·1	0·3	100
CEM I 52·5 cement	377			
0/4 Seine's sand	432			
0/5 Boulonnais's sand*	439			
5/12·5 Boulonnais's gravel*	488			
12·5/20 Boulonnais's gravel*	561			
Silica fume	37·8			
Plasticiser	12·5			
Setting delayer	2·6			
Water	124			

*Seine's sand is a silico-calcareous sand, while Boulonnais's sand and gravel are calcareous aggregates.

duration of less than 2 min). The determination of the elastic strains during the tests permits the evaluation of the Young's modulus change with temperature for both conditions.

The schedule of tests performed on the unsealed concrete specimens under accidental and service conditions is given in Table 2.

Results and discussion

Test results presented here include the change in elastic strain and Young's modulus in both service and accidental conditions for HPC and only in service conditions for OC.

The temperature is referred to as the 'mean reference temperature', T_{ref}, which represents the weighted average value of specimen temperatures. It is expressed by equation (1)

$$T_{ref} = T_s - 2/3(T_s - T_a) = (T_s + 2T_a)/3 \quad (1)$$

where T_a is the mean axial temperature

$$T_a = (T_2 + T_4)/2 \quad (2)$$

and T_s is the mean surface temperature

$$T_s = (T_1 + 2T_3 + T_5)/4 \quad (3)$$

where T_j, $j = [1 \ldots 5]$ refers to the number of thermocouples placed within specimens.

The elastic strain is given by the average value measured by the three LVDTs. For all the cases only the heating part of the heating–cooling cycles is considered.

Elastic strain variation during uniform heating

The test results for HPC under accidental and service conditions are presented first. Fig. 1 shows the change in elastic strain for the three HPC specimens (HPC 3–5) as a function of the temperature under accidental

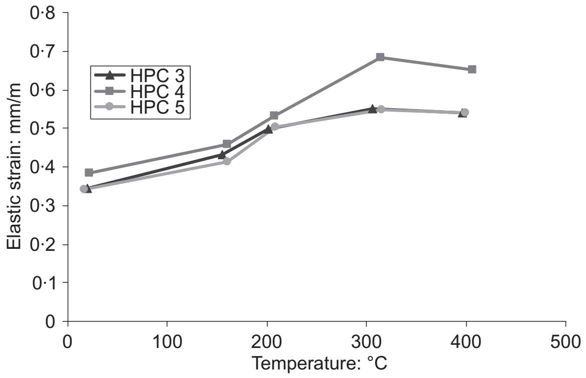

Fig. 1. Elastic strain as a function of temperature for three HPC specimens (HPC 3–5) under accidental conditions

Table 2. Details of heating tests made on 160 mm×640 mm OC and HPC concrete specimens in service and accidental conditions

Specimen	Mix	Type of conditions	Age at test: days	Weight loss before test: %	Mean compressive strength: MPa	Mean T_{ref} (°C) of the stage
OC1	OC	Service	91	1·60	35	185 203
OC2	OC	Service	93	1·49	35	139 190 220
OC3	OC	Service	71	1·78	39	140 198 220
HPC1	HPC	Service	103	0·62	100	140 194 219
HPC2	HPC	Service	126	0·64	100	142 196 219
HPC3	HPC	Accidental	253	0·22	95	158 203 311 407
HPC4	HPC	Accidental	231	0·22	107	159 207 318 417
HPC5	HPC	Accidental	334	0·20	100	160 208 315 400

conditions. It is important to note that the temperature is nearly uniform inside the specimens. The elastic strains were measured at different moments of the process: at the beginning of the test and at the end of each temperature stage.

In terms of the variation of the elastic strain with temperature, it should be noted that the three specimens behave the same: in the temperature range 20–300°C, the elastic strain increases in a nonlinear way with an asymptotic tendency in the temperature range 300–400°C. This asymptotic tendency may be explained by the fact that the temperature of 400°C corresponds to the end of the dehydration process. This means that the specimens have lost nearly all of the chemically bound water. The release of this water induces a consolidation of the solid skeleton, which becomes stiffer.

As shown in Fig. 1, the repeatability of the method and the reproducibility of the phenomenon are evident. For the same per cent of load and identical temperature stages, a similar behaviour of the three specimens with comparable values of elastic strain is obtained, with the exception of specimen 3 which presents higher values in the temperature range 300–400°C.

The same figure shows that the elastic strain changes with temperature, which is not in complete agreement with the observations made by Khoury:[16,17] the elastic strains of limestone and basalt concretes measured at constant temperature (110–600°C) after heating under 20% load indicated little change with temperature level, particularly when compared with the magnitude of free thermal strain. Nevertheless, a comparison between these results and those of Khoury shows a similar behaviour of the elastic strain as a function of temperature: increasing values until 300°C with an asymptotic tendency in the temperature range 300–400°C.

The method used to measure the elastic strain must be taken into account: the 'hot' elastic strain is measured directly during the principal test at the end of the temperature stages. In other tests,[5,6,10,11] the stress–deformation curves are used to estimate the elastic strain indirectly.

The change in the elastic strain for the specimens HPC 1 and HPC 2 under service conditions is shown in Fig. 2. Here, the values in the temperature range 20–220°C are very close, with a nonlinear increase in temperature.

To investigate the effect of heating rate (and then type of conditions) on elastic strain, the average values of the three HPC (3–5) specimens are compared with those of the two specimens HPC 1 and 2 under the same load in the temperature range of 20° to 220°C—see Fig. 3. The values of the elastic strain are very close, so it appears that the type of condition does not have a great influence on the change in the elastic strain in this temperature range. This conclusion is not in agreement with the observations made by Harada *et al.*[3]

Figure 4 shows the changes in elastic strain for the three OC specimens as a function of the temperature under service conditions. It should be noted that all three, particularly specimens OC2 and OC3, show the same behaviour, with comparable values. This figure allows the variation of the elastic strain with temperature to be estimated in the case of OC under service conditions: for example, in the case of OC 3 the elastic strain value was equal to 0·21 mm/m at 20°C and increases to 0·37 mm/m at 220°C, which represents an increase of about 76%.

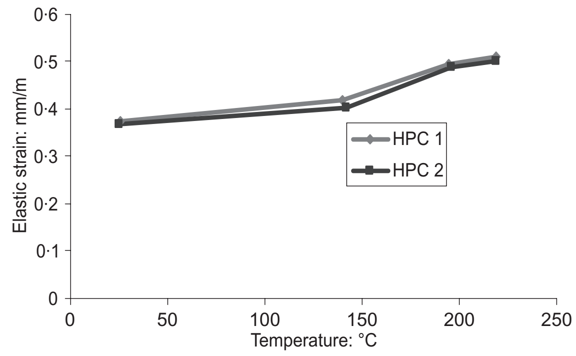

Fig. 2. Elastic strain as a function of temperature for two specimens, HPC1 and HPC 2, under service conditions

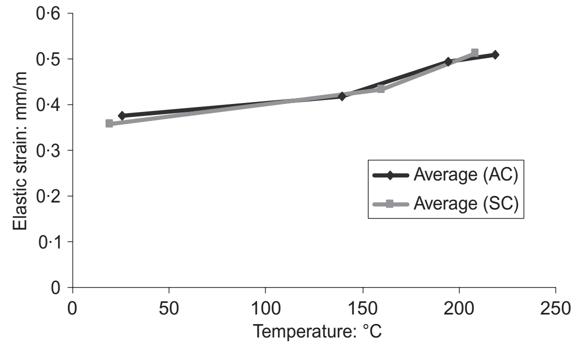

Fig.3. Average elastic strain changes of the HPC under accidental (AC) and service (SC) conditions as a function of temperature

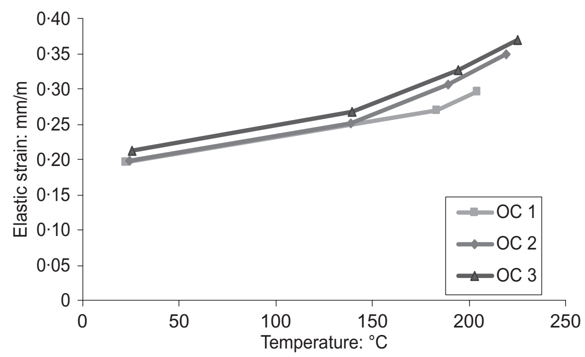

Fig. 4. Elastic strain as a function of temperature for three OC specimens (OC 1–3) under service conditions

This similar behaviour for OC and HPC under service conditions permits the comparison of the average values of the elastic strain as a function of temperature, which are plotted in Fig. 5. This figure shows that the elastic strain values of HPC are greater than those of OC under the same conditions. It can also be observed that this difference remains nearly constant as the temperature increases. At the beginning of the test (20°C) there is a difference of about 0·15 mm/m and this becomes 0·17mm/m at 220°C. This implies that this difference is essentially caused by the initial elastic strain and also by the differences of the tested concrete mixes: in the case of HPC there is less water and more solid constituents (cement + gravel + sand).

Young's modulus variation during uniform heating

The determination of the elastic strains $\varepsilon^e(T)$ during the tests enables the estimation of the change in the Young's modulus with temperature. With the constant load of the tests, σ, being 20% of the reference 'cold' compressive strength of the concretes, the Young's modulus $E(T)$ can be estimated as

$$E(T) = \frac{\sigma}{\varepsilon^e(T)} \tag{4}$$

Figs 6 and 7 show the change with temperature of the Young's modulus and of the relative Young's modulus (ratio between the 'hot' and 'cold' value), respectively, for the three HPC specimens under accidental conditions.

As expected, the Young's modulus for the three specimens decreases with increasing temperature in the range 20–300°C, with a nearly constant value at 300–400°C. From these figures, it is clear that the change is similar, with close values showing the repeatability of the experiment. However, this pattern seems to be different when compared with other works[5,6,10,11] where a gradual reduction in the Young's modulus with the temperature is reported. As already stated, the method employed here is different: the elastic strain is determined directly, at its 'hot' value, and then the values of Young's modulus are estimated using equation (4).

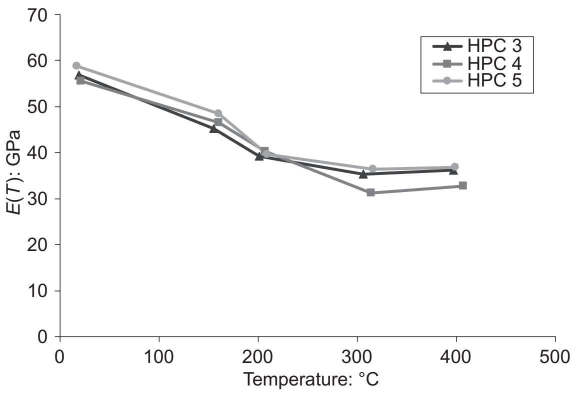

Fig. 6. Young modulus as a function of temperature for the three HPC specimens (HPC 3–5) under accidental conditions

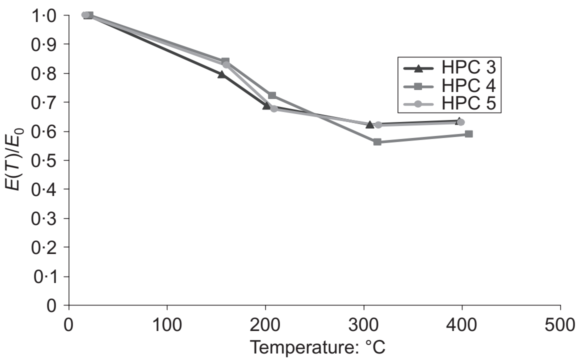

Fig. 7. Relative Young modulus as a function of temperature for the three HPC specimens (HPC 3–5) under accidental conditions

The results for HPC under service conditions are given in Fig. 8, where the Young's moduli of HPC 1 and 2 are represented. The results for the elastic strain imply a very close value for Young's modulus in the temperature range 20–220°C.

The representation of the two average values of Young's modulus variation as a function of temperature for HPC under accidental and service conditions in Fig. 9 confirms the fact that the heating rate does not have a great influence on the Young's modulus variation in

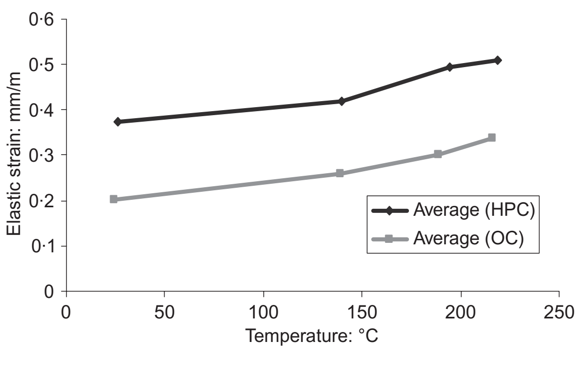

Fig. 5. Changes in average value of elastic strain for HPC and OC specimens as a function of temperature under service conditions

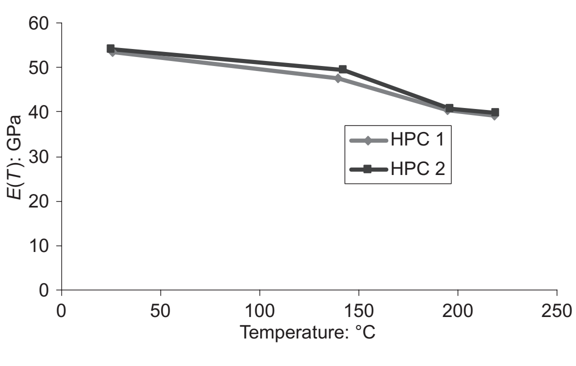

Fig. 8. Young modulus as a function of temperature for the HPC 1 and 2 specimens under service conditions

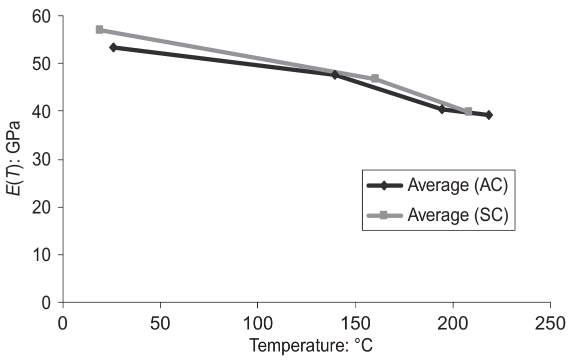

Fig. 9. Change in average Young's modulus for the HPC under accidental (AC) and service (SC) conditions as a function of temperature

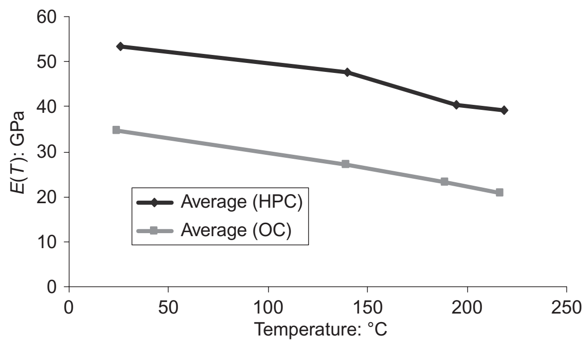

Fig. 11. Change in average value of Young's modulus for HPC and OC specimens as a function of temperature under service conditions

this temperature range. This is not in agreement with the results given by Harada et *al.*[3]

Figure 10 shows the change in the Young's modulus with temperature of the three OC specimens (OC 1–3) using equation (4) under service conditions. The figure shows very close values with a tendency that seems to be linear in the temperature range 20–220°C, confirming the repeatability of the experiment in such conditions for OC.

The values of the elastic strain, Young's modulus, relative Young's modulus and the average values for the HPC and OC are summarised in Table 3.

Figures 10 and 11 show the changes in the average values of the Young's modulus and relative Young's modulus for the two HPC and the three OC under service conditions, respectively. From Fig. 10, it can be seen that the values of the Young's modulus of HPC are higher than those of OC, which seems to have a linear variation in function of the temperature.

In Figs 11 and 12 a linear variation of the relative Young's modulus of OC can be seen with an average value of 0·6 corresponding to 40% of degradation of the initial Young's modulus, compared with the 27% in the case of HPC at 220°C.

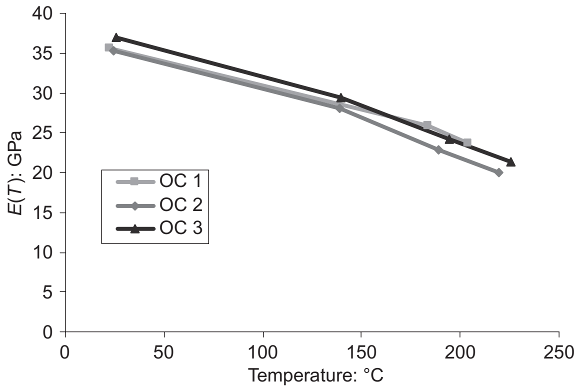

Fig. 10. Young's modulus as a function of temperature for three OC specimens (OC 1–3) under service conditions

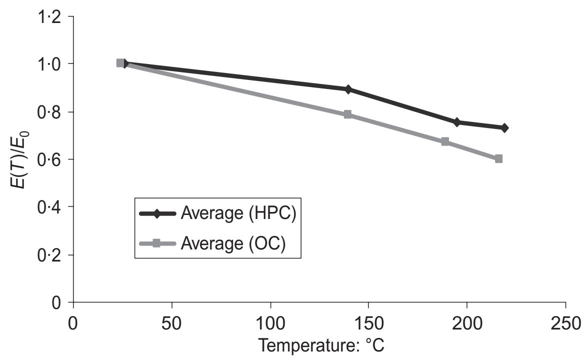

Fig. 12. Change in average value of relative Young's modulus for HPC and OC specimens as a function of temperature under service conditions

Conclusion

The test method presented follows the variation with temperature of the elastic strain of HPC and OC specimens during uniform heating in both accidental and service conditions, with a quasi-uniform temperature field inside the material. The determination of the elastic strain also permits the estimation of the Young's modulus. The following conclusions can be drawn from the test results.

(*a*) The estimated values for elastic strain for HPC under accidental conditions show that it increases with rising temperatures with an asymptotic behaviour in the temperature range 300–400°C. This implies a decrease in the Young's modulus, with an asymptotic behaviour in the same range of temperature. According to the current authors, this behaviour is attributable to the release of nearly all the chemically bound water at about 400°C, implying a consolidation of the solid skeleton, which becomes stiffer.

(*b*) The comparison of the variation in both elastic strain and Young's modulus for HPC under accidental and service conditions shows close

Table 3. Elastic strain, Young's modulus and relative Young's modulus values at different temperature levels for HPC and OC under accidental and service conditions

Specimen	Type of conditions	Mean T_{ref} (°C) of the stage	Elastic strain: mm/m	Young's modulus: GPa	Relative Young's modulus
OC1	Service	22	0·1967	35·6	1·00
		185	0·2701	25·9	0·72
		203	0·2962	23·6	0·66
OC2	Service	24	0·1980	35·3	1·00
		139	0·2501	27·9	0·79
		190	0·3065	22·8	0·64
		220	0·3489	20·0	0·56
OC3	Service	25	0·2130	36·9	1·00
		139	0·2671	29·4	0·79
		194	0·3262	24·1	0·65
		225	0·33692	21·3	0·57
Average OC(1–3)	Service	24	0·2025	34·5	1·00
		139	0·2586	27·0	0·78
		189	0·3009	23·2	0·67
		216	0·3381	20·7	0·60
HPC1	Service	26	0·3749	53·3	1·00
		140	0·4196	47·6	0·89
		194	0·495	40·4	0·75
		219	0·5102	39·2	0·73
HPC2	Service	25	0·3689	54·2	1·00
		142	0·4039	49·5	0·91
		196	0·4901	40·8	0·75
		219	0·5023	39·8	0·73
Average HPC (1–2)	Service	25	0·3719	53·7	1·00
		140	0·4118	48·6	0·90
		195	0·4925	40·6	0·75
		218	0·5063	39·5	0·73
HPC3	Accidental	19	0·3437	56·7	1·00
		158	0·4313	45·2	0·79
		203	0·4985	39·1	0·68
		311	0·5512	35·3	0·62
		407	0·5398	36·1	0·63
HPC4	Accidental	21	0·3846	55·6	1·00
		159	0·4589	46·6	0·83
		207	0·5322	40·2	0·72
		318	0·6835	31·3	0·56
		417	0·6526	32·7	0·57
HPC5	Accidental	16	0·3407	58·7	1·00
		160	0·4123	48·5	0·82
		208	0·5040	39·6	0·67
		315	0·5479	36·5	0·62
		400	0·5414	36·9	0·62
Average HPC (3–5)	Accidental	19	0·3562	57·0	1·00
		160	0·4342	46·7	0·82
		208	0·5116	39·6	0·69
		314	0·5942	34·4	0·60
		401	0·5779	35·2	0·61

values. The heating rate, up to 1·5°C/min, does not have an important influence on those variations for temperatures less than 220°C for the specimens tested in the current work.

(*c*) The elastic strain and Young's modulus variations for OC under service conditions show a linear behaviour for temperatures up to 220°C.

(*d*) Under service conditions, HPC under constant load shows higher values of Young's modulus than OC. The difference between them seems to be invariant in the temperature range 20–220°C. According to the present authors, this invariant difference is attributable to the difference in the initial composition of each type of concrete, which implies higher values of the initial elastic strain for the HPC.

(*e*) The repeatability of the experimental technique, which is the same as that used for the study of the behaviour of HPC in service and accidental conditions and ordinary concrete under service conditions, is validated.

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Discussion contributions on this paper should reach the editor by 1 April 2008