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Durability of Concrete in Nuclear Power Plants under Temperature Extremes

Tibor Jávor

Technical University Košice, Slovakia

ABSTRACT

The paper inform about the results of the experimental analysis of the durability of concrete in laboratory of 3 nuclear power plants for various levels of heating at temperature up to 800°C and determination of heat transfer properties and of chemical behaviour. We observed also 3 other type of gravels for the high strength concrete at elevated temperatures. The analysis of the temperature influences up to 800°C degrees into the decreasing of strength, Young modulus as well as strains included creep and shrinkage of various concrete will be shown in various diagrams. The kinetics concept of durability of hard bodys explain heterogeneous behaviour of concrete during heating under compression after heating.

INTRODUCTION

The nuclear safety and diagnosis of concrete structures in nuclear power plants as well as the structural aging program was generally prepared in the CONT - PECO program. The objectives of this study are to analyse the safety - related concrete components of nuclear power plants and predict the effects of aging on the performance of concrete - based materials and components.

A change in temperature of concrete during its creep under load causes a significant transient of creep. This effect, which has been sometimes referred to as the thermal creep occurs for both heating and cooling. It has been regarded as a special peculiar property of concrete, which added further complexity to the multitude of various effects exhibited by this common yet intriguing material.

THE EXPERIMENTAL PROGRAM

The experimental study of the durability of concrete was made for 6 type of concrete for various level of temperature until 800°C at the Technical University Košice. The investigations were focused some physical and mechanical properties of concrete under testing: volume densities, dynamic modulus of elasticity, static modulus of elasticity, compressive strength and splitting strengths. Temperature effects were studied with regard to free shrinkages and to combined shrinkage with mechanical long term compressive stress of 5 MPa. The durability of concrete was analysed by various temperature levels from 20°C until 800°C without compression and in compression as well as in tension. The determination of thermal conductivity used the „Hot - wire method" following the ISO 8894-1 Standard. This method was applied until 1250°C temperature. The thermal conductivity is the density of heat flow rate divided by temperature gradient. The unit of thermal conductivity is the watt per metre kelvin.

The samples 10/10/40 cm were tested for creep stressed by 5 MPa after 28 days by 60°C after 24 hours, by 200°C after 48 hours, by 400°C after 48 hours, by 600°C after 48 hours and by 800° C after 48 hours. The increasing of temperature as well as the decreasing was 20°C per hour. The samples of 10/10/40 cm without compression as well as the samples 15/15/15 cm for control of the Young modulus abd strength after heating were observed with the similar program like the stressed samples, where the springs of special steel were used for compression. The second group of samples 10/10/40 cm were tested in the INSTRON furnace using hydraulic compressing. This equipment is automatised.

The samples 4/4/16 cm were observed with tension under stress of 30 % of strength by 60, 100, 200 and 400°C without interruption of the stress, where the sample is measured by dial gauges outside of the heating box. The samples are anchered by steel bars of high quality and well known low temperature gradient. Similar samples were heated also with the samples 10/10/40 cm for the quality compression strength and tensile tests as well as for testing of the Young modulus after each heating level. The quality was tested also by ultrasound and Schmidt hammers. The Fig. 1 and 2 show us the cycles of heating and the decreasing curves of strength, Young modulus, shrinkage with thermal expansion for various temperature levels and for various tested concrete samples are analysed in the next chapter.

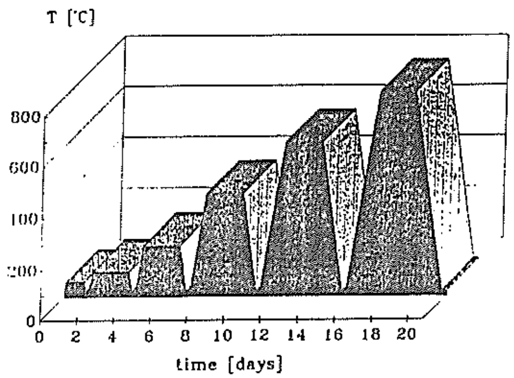

Fig. 1 The heating program for concrete samples until 800°C

THE DECREASING OF THE MATERIAL CONSTANTS AFTER VARIOUS LEVELS OF HEATING

Decreasing of strength of cubes in compression measured by destructive tests after various temperatures level are in Fig. 3 and 4, and in Tab. 1.

The statical Young modulus of the 3 type concrete with various gravel compaired with concrete of the 3 various NPPs is shown in Fig. 5, Tab. 2.

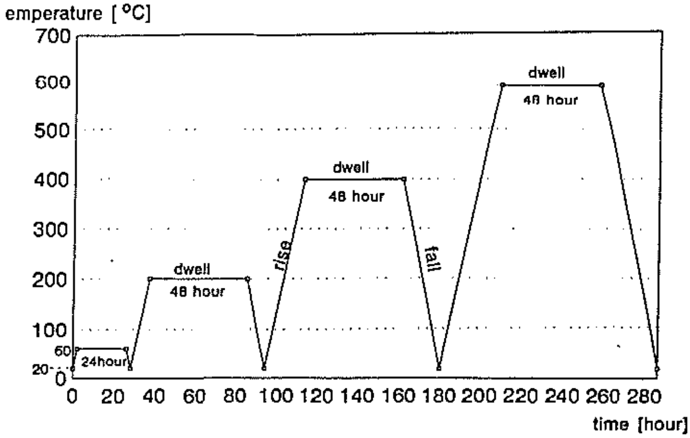

Fig. 2 Heating and cooling program by INSTRON furnace

Table 1 Concrete strength after various temperatures level (MPa)

Temperature (°C)	20	60	200	400	600	800
Temelín	53.85	45.44	61.83	54.08	28.95	4.49
Mochovce	36.69	36.63	41.22	31.92	19.78	-
Penly	68.61	68.18	78.57	53.68	20.78	13.01
Dolomite	57.10	46.20	59.20	51.00	53.20	6.10
River aggregate	39.56	39.85	46.89	37.41	32.67	3.00
Andesite	45.90	41.85	52.44	46.89	29.21	11.79

Table 2 Young modulus of elasticity of 6 concrete after various temperatures level (MPa)

Temperature (°C)	20	60	200	400	600	800
Temelín	35487	36098	22088	10774	3688	1228
Mochovce	27789	25303	19506	7180	1822	392
Penly	48383	44137	35115	11162	1402	808
Dolomite	56300	51000	37200	25308	12650	1570
River aggregate	24490	25980	21570	10843	3873	418
Andesite	32180	32595	19811	7857	5711	-

THE SHRINKAGE AND CREEP ANALYSIS OF VARIOUS CONCRETE

Following the heating and cooling program the so called elastic strains are measured on the surface of the prism during the Young modulus tests after their heating into the 20°C. The shrinkage with the thermal expansion of various concrete after heating in various temperature levels wad measured after the cooling to +20°C (Fig. 6, 7 and Tab. 3). The creep coefficient is calculated: total strain - strain of temperature with shrinkage divided by elastic strain before heating. The elastic strain before heating is the compression stress divided by the Young modulus of prisms after 28 days before beating.

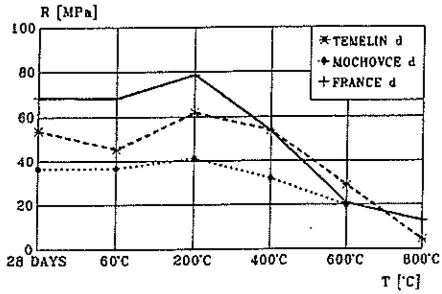

Fig. 3 Decreasing of concrete strength after various temperatures level of 3 NPPs

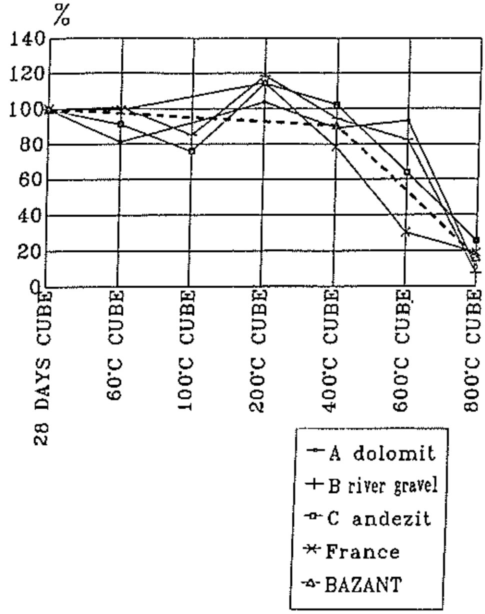

Fig. 4 Decreasing of concrete strength after various temperatures level with 3 type of gravel

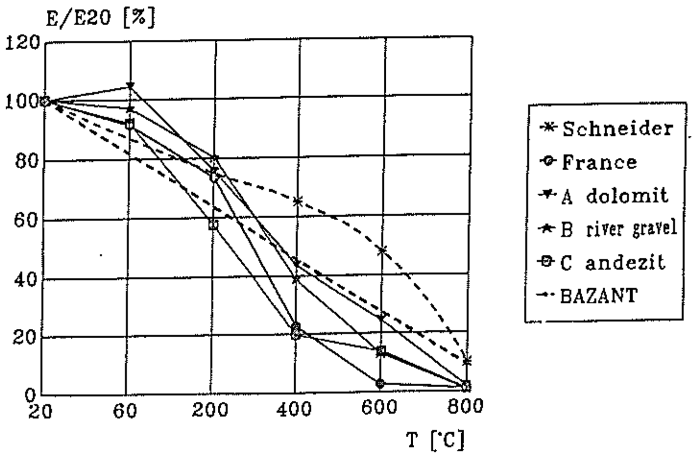

Fig. 5 The Young modulus of various concrete compaired with the theoretical analysis by Bažant and the results by Schneider

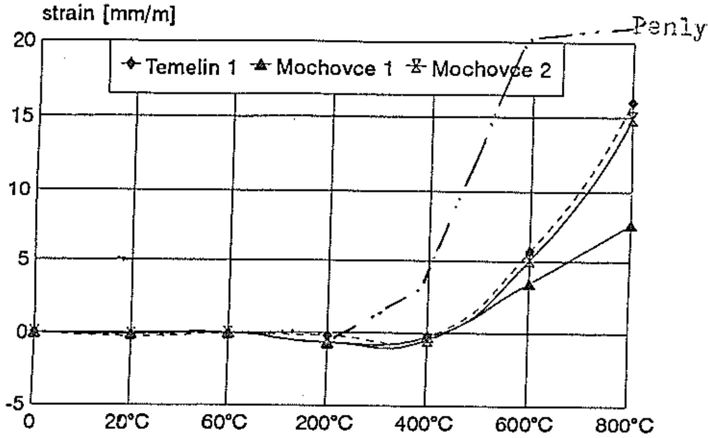

Fig. 6 The shrinkage with the thermal expansion of 3 concrete made by various NPPs during heating

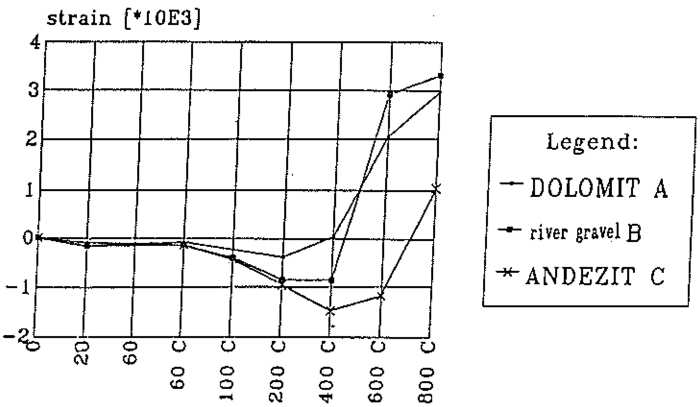

Fig. 7 The shrinkage with the thermal expansion of 3 concrete made with 3 type of gravels during heating

Table 3 The strain from temperature influence incl. shrinkage [‰]

Temperature (°C)	60	200	400	600	800
TEMELIN	0.4207	0.1550	0.2374	6.7480	-
MOCHOVCE	0.0735	-0.5631	-0.2907	4.3660	11.4232
PENLY	0.0418	-0.2302	2.9563	20.9092	21.6860
DOLOMITE	0.0830	-0.2270	0.2240	2.2060	3.4290
RIVER AGGREGATE	0.0330	-0.7050	-0.7810	3.0990	3.5020
ANDESITE	-0.0540	-0.8760	-1.3760	-1.0810	1.1320

Using this calculation we received the creep coefficients for various concrete after various heat level in Tab. 4.

Table 4 Creep coefficient after heating of various temperature for 6 type of concrete

$\varphi = [(\varepsilon_{tot} - \varepsilon_{comp}) / \sigma_{(5\,MPa)}] . E_{(28\,day)}$

Temperature (°C)	60	200	400	600	800
DOLOMITE	1.13	3.72	14.04	39.37	43.37
RIVER AGGREGATE	1.00	3.43	8.46	24.50	18.89
ANDESITE	0.91	5.98	12.89	17.10	30.45
TEMELIN	2.93	6.82	13.76	62.35	-
MOCHOVCE	1.67	3.68	12.74	36.12	48.52
PENLY	0.17	2.84	24.96	129.95	154.51

Very similar results we received also by the testing of prisms in the INSTRON equipment. Much higher creep coefficient we can receive, if we will use for the calculation the elastic strains after heating. Generally we can say, that until temperature of 200°C the smaller creep coefficient is by the Penly concrete, but later by high temperatures this concrete has the highest creep coefficients. If we compaire the concrete samples for various gravels, the concrete made from andesite is the best one with the lowest creep coefficient.

Judgement of the aggregate behaviour in tested concretes in temperature range between 20°C - 800°C is in Tab. 5, where the explanation of abbrevations related to individual minerals: Q - quartz $(SiO)_2$, F - group of feldspars (K, Na - Ca) $AlSiO_3O_8$, Cc - calcite $(CaCO)_3$, D - dolomite ($MgCO_3$. $CaCO_3$), MH - magnesium oxide (MgO).

Table 5 Judgement of the aggregate bebaviour in tested concretes for various temeprature levels

Type of concrete	Temperature of heat (°C)		Main minerals in verified aggregates major	minor	Characteristic feature of aggregate exposed to elevated temperatures
TEMELIN	20 -	200	Q, F	Cc	thermally stabil
		800	Q, F	decomp.	
MOCHOVCE	20 -	200	Q	F, Cc, D	thermally stabil
		800	Q	F, decomp.	
PENLY	20 -	200	Q, Cc	F	thermally not fully stabil
		800	Q, decomp.	F	
DOLOMITE AGGREGATE	20 -	200	Cc, D	Q, F	thermally unstabil
		800	MH	Cc[1], QF	
RIVER AGGREGATE	20 -	200	Q, F, Cc, D	-	thermally not fully stabil
		800	Q, F decom	-	
ANDESITE AGGREGATE	20 -	200	F	Q	thermally stabil
		800	F	Q	

[1] at 800°C calcite is partially decomposed to CaO and CO_2

The thermal expansion for various temperatures is shown in Fig. 8.

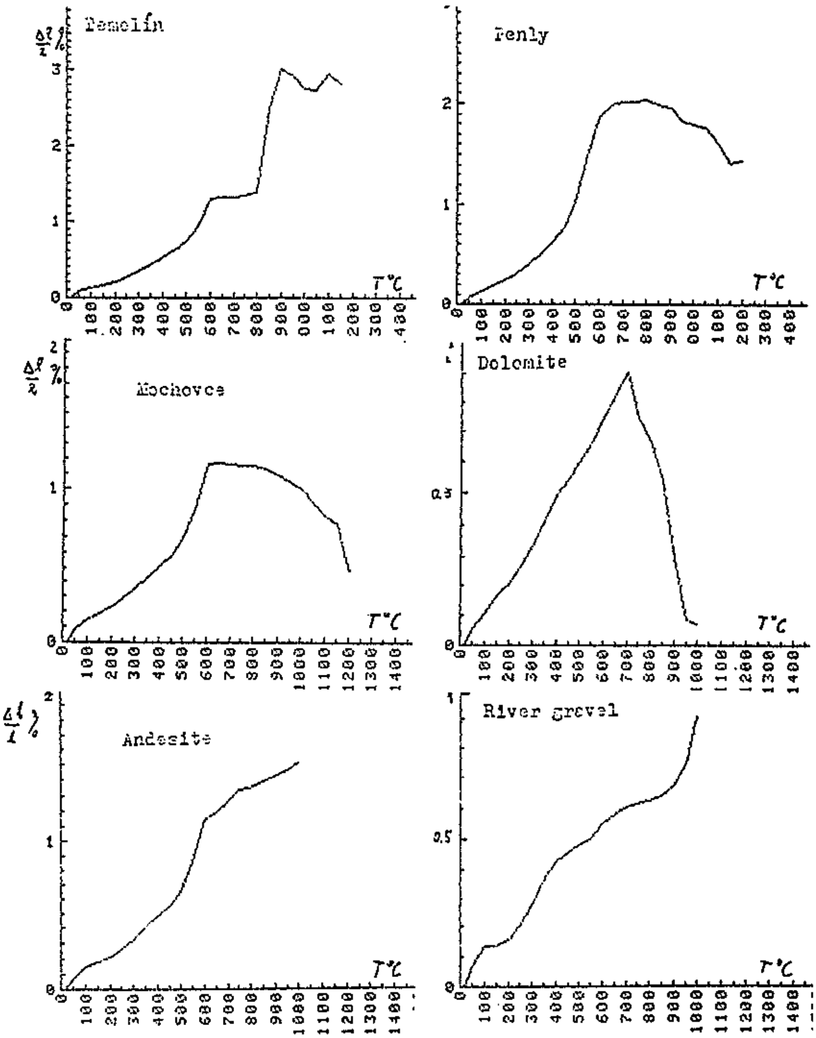

Fig. 8 The thermal expansion of various concrete during the heating

CONCLUSIONS

The experimental analysis of creep and shrinkage of 6 various concrete (3 from NPPs and 3 with various gravel) was made on prisms and cubes until 200°C. The highest quality was obtained for the Penly concrete. The shrinkage strain for the Penly concrete was also smoller than by concrete from Mochovce or others, but after heating of 200°C was this concrete from Penly not the best one. We received strains by 200°C twice so high as for Temelin or Mochovce.

The second group of the experiments was over 200°C, where we cannot speak about creep more, because it is only the question of durability and the temperature influence into the durability with the measuring of the thermal expenasion without or with compression of samples. Various electrical heating systems were used incl. tensile creep furnace. The best heating system was the INSTRON furnace with hydraulic constant pressions jack.

The best concrete after 800°C temperature was obtained by the concrete with andesit gravel. Until 200° C the nest was the Penly concrete. The analysis of the Young modulus is similar like by the decreasing of strength. The theory after Bažant is very similar to our experimental results.

The mineral composition of the dolomite concrete consists predominantly the decomposed dolomitic aggregates MgO, CaO and the best amounts of $CaCO_3$ and $CaCO_3$. $MgCO_3$. Up to 600°C dolomite is stabil. At the temperature of 800°C the decomposition of calcit to CaO and CO_2 takes places. Quartz and feldspars are stabil until 800°C. This was typical for the river gravel.

The Penly concretes chemical composition of aggregate and powder admixtures may influence to a large extent thermal resistivity of concrete against the effect of elevated temperatures. From this viewpoint thermal unstabil calcareous aggregate is not recommended for concrete application at elevated temperatures. At elevated temperatures the properties of Penly concrete specimens would be markedly improved when calcareous aggregate would be substituted by thermally stabil aggregate based on quartz.

Very interesting are the creep coefficients received from the measured datas. Over 200°C the creep coefficient is changed first of all by the Penly concrete by 800°C is after the desintegration

following the previous physico - chemical analysis this coefficient was 154. If we compaire the 3 concretes with various gravel, the highest creep coefficient was by the dolomite gravel. The Penly concrete has also the highest thermal coefficient. It was by 200°C 0.0000161 and by 800°C it was 0.0000384. By dolomite gravel for 200° C it was 0.0000117 and for 800° C it was 0.0000081. The main minerals by the Penly concrete was quartz and calcit, by dolomite concrete dolomite, calcit and magnesium oxide.

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