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REDUCTION FUNCTIONS FOR MECHANICAL/FRACTURE PARAMETERS OF CONCRETE AT ELEVATED TEMPERATURES

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Abstract

Based on the compiled data this work proposes new temperature-dependent relationships/functions for concrete strength (compressive and tensile), modulus of elasticity, fracture energy, bulk density and Poisson ratio. The curves are designed on the basis of literature survey published in [7]. Comparison of the designed function with their counterparts found in existing codes, authoritative design guides and literature is presented. Surprisingly enough, functions for selected parameters (namely fracture energy, Poisson ratio and bulk density) were not found in any code although they are necessary for realistic numerical simulations of structural response. For the practical reasons, relationships proposed in this work are designed as continuous functions whilst data found in codes are presented as discrete points in tables. We believe that an analytical formulation is more friendly for implementation to computational models, e.g. sort of transient coupled thermal and structural analysis and others. The temperature depence of parameters is an important ingredient of the safe design and assessment of structures undergoing high temperature loading (fire, etc.).

1 DESIGN OF FUNCTIONS

The functions were designed based on the compiled data presented in [7]. The averages of the data for each temperature were used for regression analysis. It followed from the data that we should distinguish between compressive strength of normal strength concrete (NSC) and high strength concrete (HSC) and bulk density according to aggregate type (siliceous and calcareous). No special distinction seems to be necessary for the other parameters - tensile strength, modulus of elasticity, fracture energy and Poisson ratio. The functions are formulated as a dependence of reduction coefficients k for particular parameters at elevated temperatures. In all cases the functions $k(t)$ are designed such that the reduction parameter k equals 1 at temperature t=20ºC.

For reduction coefficient of compressive strength the exponential functions are suggested here, see eqs. 1 and 2 for NSC and HSC, respectively.

$$k_{fc,NSC}(t) = \exp\left[-\left(\frac{t-20}{\alpha}\right)^3\right] \tag{1}$$

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$$k_{fc,HSC}(t) = \exp\left[-\left(\frac{t-20}{\alpha}\right)^2\right] \tag{2}$$

k is the reduction coefficient, t is the maximum temperature of concrete reached during its temperature loading history in ºC, α is the only unknown constant to be determined based on the experimental data. Solution of the unknown parameter α leads generally to nonlinear regression and use of e.g. Levenberg-Marquart algorithm would be necessary. Fortunately, by taking the natural logarithm we can rewrite eq. 1 (further procedure will be shown only for NSC) to:

$$\ln\left[k_{fc,NSC}(t)\right] = \left[-\frac{t-20}{\alpha}\right]^3 \tag{3}$$

Further on, by substituting

$$\ln\left[k_{fc,NSC}(t)\right] = Y(t), \quad \frac{-1}{\alpha^3} = A, \quad (t-20)^3 = X(t), \tag{4}$$

we can simplify eq. 3 into:

$$Y(t;A) = AX(t) \tag{5}$$

which is a linear equation with one unknown parameter A. The best fit is done by solving the linear eq. 5 for A and transforming the linear relation back into the original space by exponentiating. Resulting unknown parameters are α= 689.57 ºC and α= 679.94 ºC for eq. 1 and 2, respectively. Plots of these equations are given in figs. 1 and 2 together with averages of compiled experimental data.

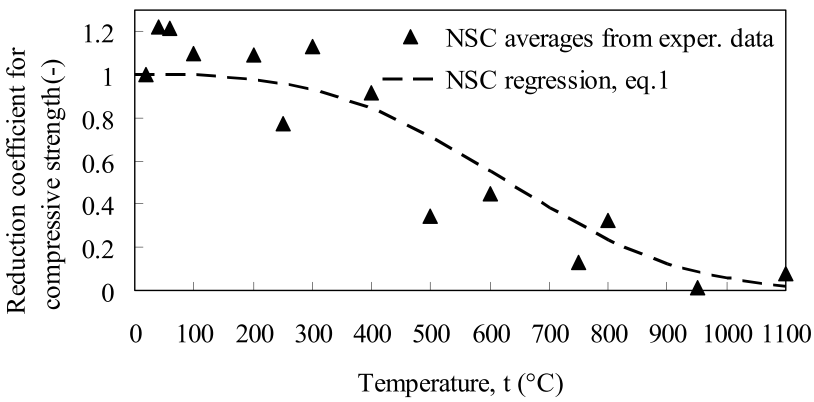

Fig. 1. Reduction coefficient for compressive strength of NSC at elevated temperatures: averages of compiled experimental data and the suggested functions.

The other parameters were approximated by polynomial functions of the second or third order. The following eq. 6 gives a relationship for the reduction coefficient k for tensile strength, modulus of elasticity, fracture energy, bulk density (distinguished for siliceous and calcareous aggregate) and Poisson ratio. Parameters A, B and C as a solution of linear regression on polynomial eq. 6 are given in table 1.

$$k(t) = A(t-20)^3 + B(t-20)^2 + C(t-20) + 1 \tag{6}$$

The plots of particular equations together with compiled data averages are in figs. 3 - 7. The proposed functions are valid in the temperature intervals given in table 2. The reason for such a limited range is the lack of data for higher temperatures (lower temperatures are not in the scope of this work). The extrapolation by the proposed function could be accepted in some cases on the basis of reasonable considerations for each particular case (such as whether the right asymptote for $t \to \infty$ becomes negative or not). However, for most practical situations the temperature ranges in table 2 are sufficient.

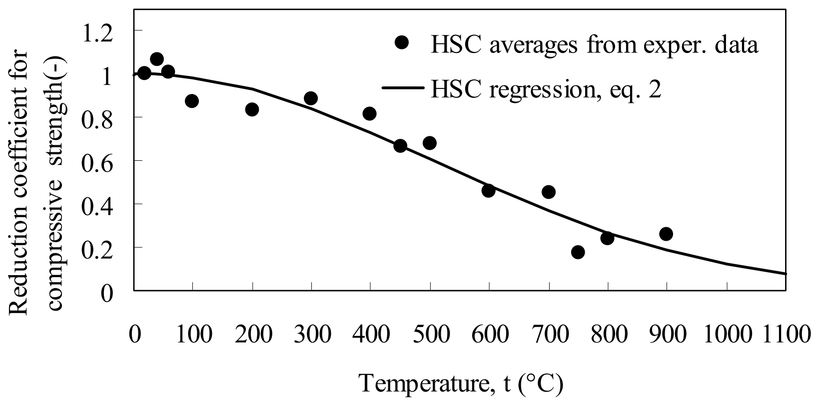

Fig. 2. Reduction coefficient for compressive strength of HSC at elevated temperatures: averages of compiled experimental data and the suggested functions.

Concrete parameter	**A**	**B**	**C**
Tensile strength	0	1.80E-07	-1.21E-03
Modulus of elasticity	0	1.04E-06	-1.95E-03
Fracture energy	2.37E-09	-5.97E-06	2.74E-03
Bulk density -- silic. agg.	-1.93E-10	4.66E-07	-3.76E-04
Bulk density -- calcar. agg.	-5.85E-10	3.72E-07	-2.66E-04
Poisson ratio	0	3.92E-07	-9.14E-04

Tab. 1. Parameters of eq. 6 for particular concrete characteristics

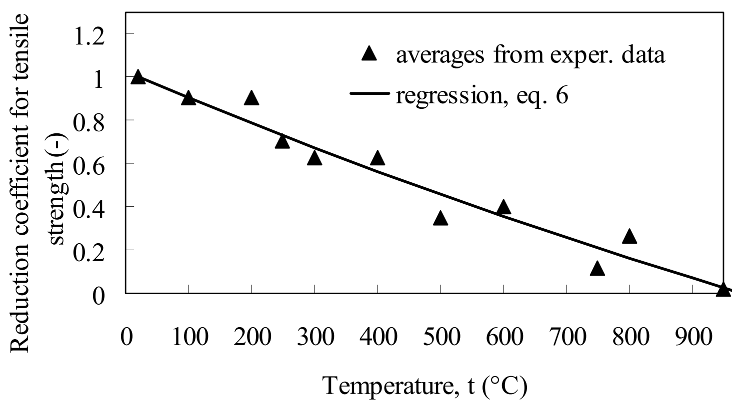

Fig. 3. Reduction coefficient for tensile strength at elevated temperatures: averages of compiled experimental data and the suggested function.

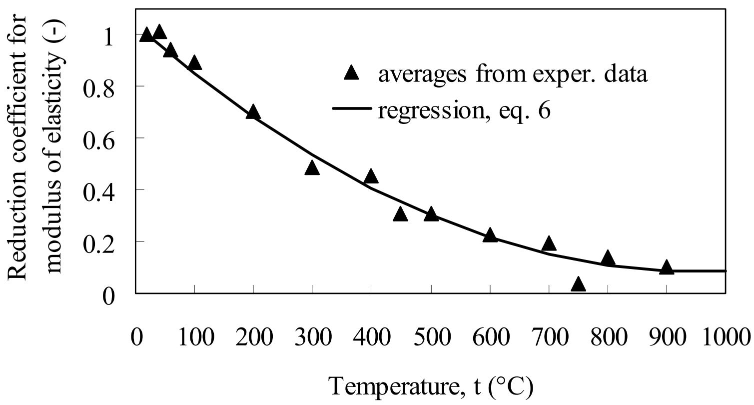

Fig. 4. Reduction coefficient for modulus of elasticity at elevated temperatures: averages of compiled experimental data and the suggested function.

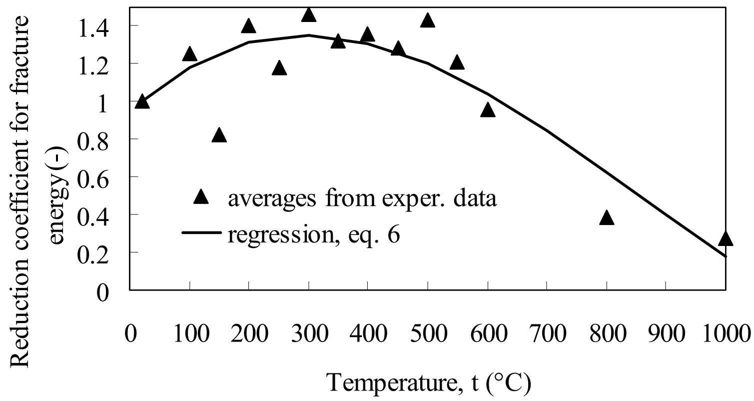

Fig. 5. Reduction coefficient for fracture energy at elevated temperatures: averages of compiled experimental data and the suggested function.

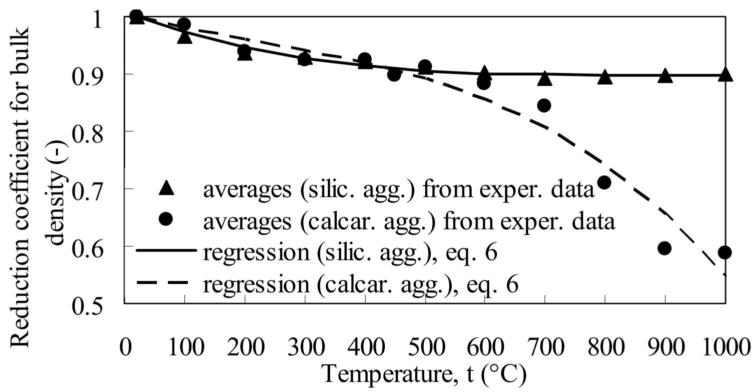

Fig. 6. Reduction coefficient for bulk density at elevated temperatures: averages of compiled experimental data and the suggested functions.

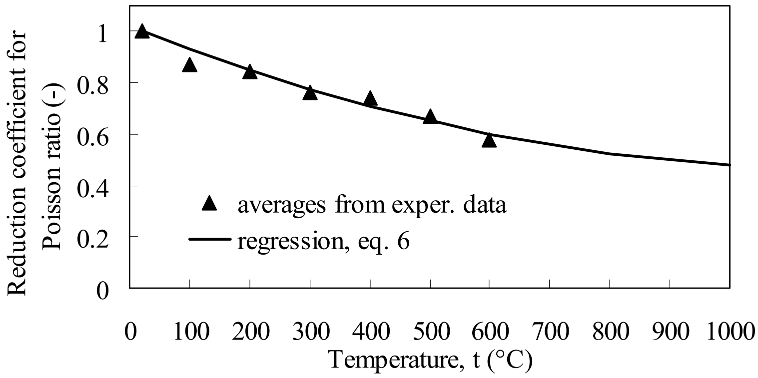

Fig. 7. Reduction coefficient for Poisson ratio at elevated temperatures: averages of compiled experimental data and the suggested function.

Parameter	**Interval of validity**
Compressive strength NSC, HSC	⟨20; 1100⟩
Tensile strength	⟨20; 950⟩
Modulus of elasticity	⟨20; 900⟩
Fracture energy	⟨20; 1000⟩
Bulk density - silic., calcar.	⟨20; 1000⟩
Poisson ratio	⟨20; 600⟩

Table 2 Intervals of validity of proposed temperature dependant functions $k(t)$.

2 VARIABILITY OF DESIGNED FUNCTIONS

The knowledge of variability of the parameters is necessary especially for stochastic analysis. Some publications exist on variability of the concrete parameters at room temperature however, no one has been found for temperature loaded concrete or mortar. There is no such information in the publications collected for data compilation in [7]. Moreover usually only three specimens are tested under the same conditions that does not suffice for statistical purposes. To have at least a rough idea about parameters' variability at different temperatures, data in [8] were analyzed and coefficients of variation of selected characteristics are presented in figs. 8 and 9.

No significant trend of the coefficient of variation (COV) with increasing temperature can be observed and therefore we suggest to use the functions $k(t)$ as reduction factor of the mean value of parameters for elevated temperatures (with respect to t=20ºC). To account for variability, we suggest to keep COV obtained at t=20ºC for the whole temperature range. As an extensive source of information on variability of various parameters at t=20ºC we recommend e.g. publication by Wittman et al. [10] where more than 20 specimens (unheated) were tested under the wedge splitting test conditions. The coefficients of variation were found 20% and 27% for fracture energy and 9 and 9.3% for tensile strength.

3 COMPARISON WITH EXISTING PROVISIONS

The suggested functions are compared with the provisions for computing concrete strength at elevated temperature prescribed by existing codes and authoritative design guides. Among the codes and design guides which specify design rules for computing concrete parameters at elevated temperature belong the Comité Europeen de Normalisation, CEN ENV (Eurocode 2 - Part 1-2: Structural Fire Design [5] and Eurocode 4 – Part

1-2: General Rules for Structural Fire Design [6], the Comites Euro-International du Beton (CEB model code), Fire Design of Concrete Structures [3] and the National Building Code of Finnland's RakMK B4 [4]. ACI 216 R Guide for Determining the Fire Endurance of Concrete Elements [2] provides strength test data obtained by Abrams [1] but did not prescribe a strength-temperature relationship for concrete. Abrams test results are also referenced in the CEB model code. The CEN ENV [5, 6] makes distinction between NSC concrete with siliceous and calcareous aggregate and also proposes two rules for HSC according to strength - C>55/67 to C≤80/95 and C>80/95 to C≤90/105. It also proposes a prescription for tensile strength without any distinction for different types of concrete. The Concrete Association of Finland's RakMK B4 [4] prescribes different design rules for HSC and NSC. HSC is concrete with designated strength grades of K70 to K100 (concretes with 70 MPa to 100 MPa compressive strength if 150 mm cubes are used, or 62 to 90 MPa if 150 x 300 mm cylinders are used). NSC is concrete with designated strength grades of K10 to K70 (concretes with 10 MPa to 70 MPa compressive strength if 150 mm cubes are used, or 7 MPa to 62 MPa if 150 x 300 mm cylinders are used). The RakMK B4 also prescribes different design rules for concrete in service (stressed, 30% preload) and for concrete which is not (unstressed). Phan and Carino [9] proposed a rule for HSC. By comparison of residual, hot stressed (in service) and hot unstressed (not in service) data they suggested only one rule for all the cases as the data did not show considerable differences. Comparison of designed functions for compressive and tensile strength with codes and provisions is given in figs. 10 and 11, respectively.

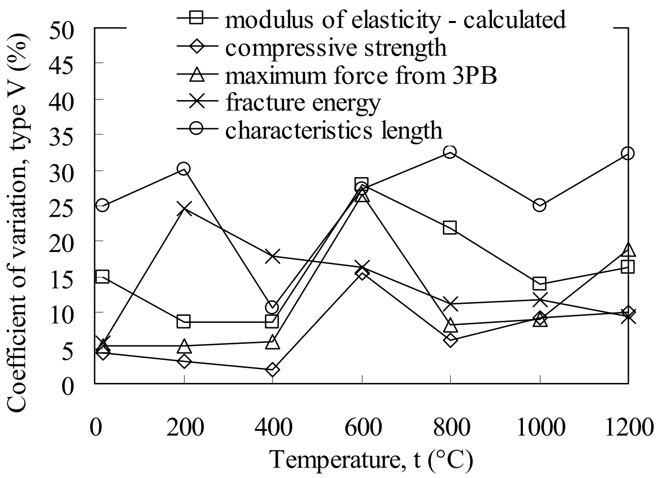

Fig. 8. Coefficient of variation of alumo silicate mortar (air curing) for chosen parameters vs. temperature.

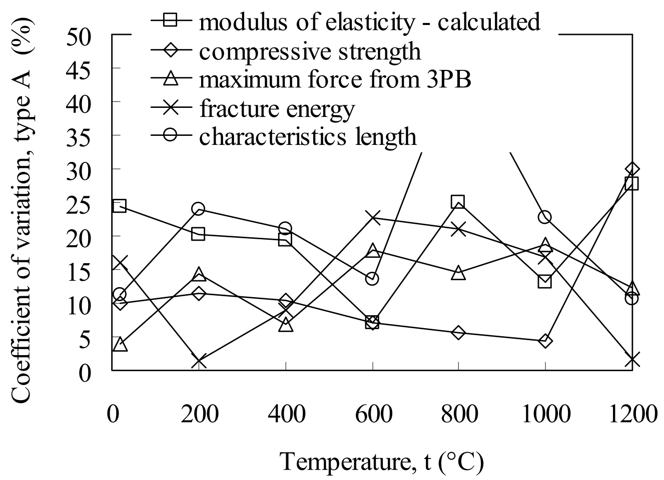

Fig. 9. Coefficient of variation of alumo silicate mortar (water curing) for chosen parameters vs. temperature.

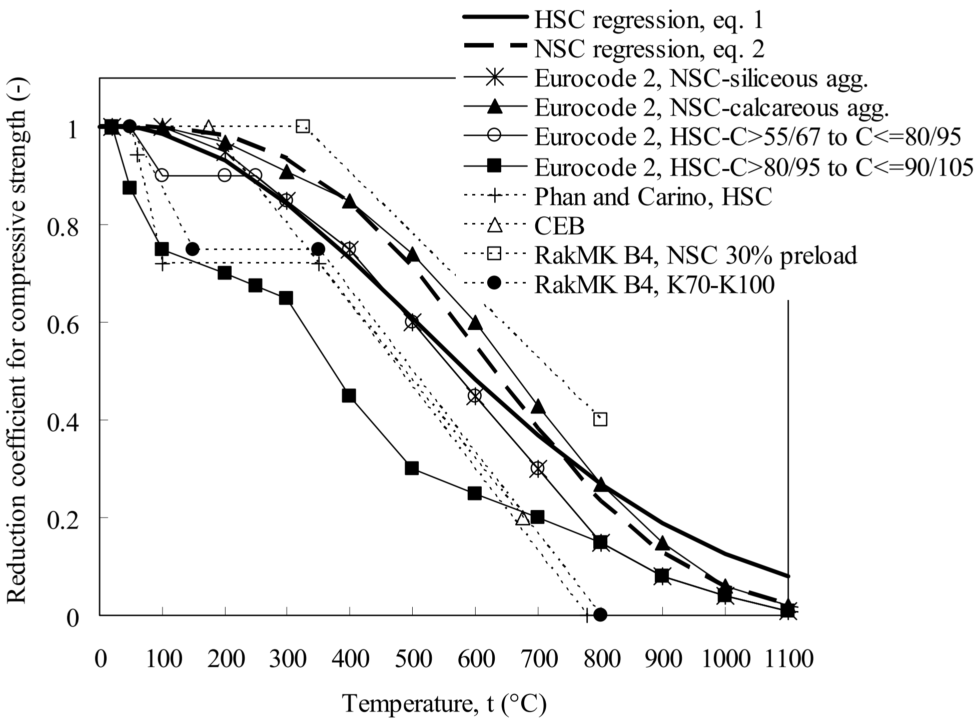

Fig. 10. Reduction coefficient for compressive strength: comparison of proposed functions with existing codes and provisions.

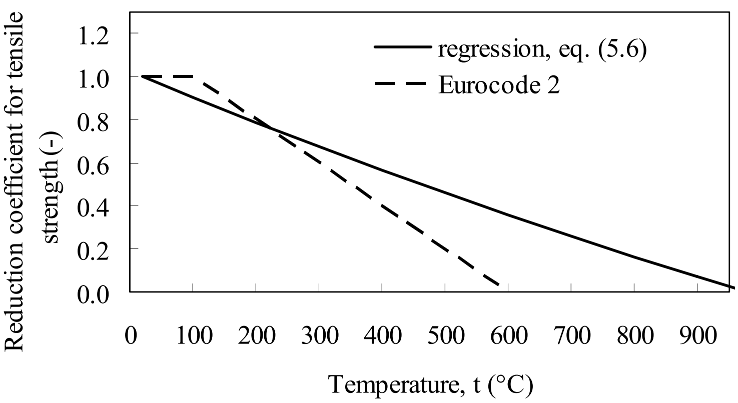

Fig. 11. Reduction coefficient for tensile strength: comparison of proposed function with existing codes and provisions.

4 DISCUSSION AND CONCLUSIONS

On the basis of compiled data, functions for reduction of concrete characteristics at high temperatures necessary for numerical modeling of temperature loaded structures are proposed. A survey of existing provisions and codes for fire design shows that only data on compressive and tensile strength are available. These data are in the form of tabulated discrete points. Temperature functions for modulus of elasticity, fracture energy, bulk density and Poisson ratio designed in this work were not found in any available document. Comparison of the functions for compressive and tensile strength suggested herein with the existing ones reveal that most of the values provided by provisions and codes are more conservative. Distinction between NSC and HSC for compressive strength is necessary and is established in most of the refereed provisions. On the other hand, based on the compiled data no special distinction was found necessary for modulus of elasticity, tensile strength, fracture energy and Poisson ratio. Bulk density was found to be sensitive on the type of aggregate: siliceous or calcareous. Still, more experimental data is necessary mainly for fracture energy of concrete at high temperatures and the dependence of coefficient of variation on temperature. The distinction of HSC compressive strength on residual, hot stressed and hot unstressed is not necessary according to Phan and Carino [9].

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