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RESEARCH ARTICLE

Compressive strength of normal and high strength concretes under combined influence of loading rate and service temperature

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Abstract

The combined influence of service temperature and loading rate on the compressive strength of concrete has been studied over a wide range of compressive strength. New simplified prediction formulae are proposed to take the influence of temperature and loading rate into account. It is demonstrated that the new formulae are suitable to effectively predict the compressive strength of concrete under the combined influence of temperature and loading rate. It is also demonstrated that the Dynamic Increase Factor, DIF is not a practical tool in the representation of the combined influence of service temperature and loading rate on the compressive strength of concrete.

Keywords

concrete · high strength concrete · compressive strength · loading rate · temperature

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1 Introduction

Structural concrete in service condition is usually exposed to a combined influence of climatic temperature changes and mechanical loads of different intensity and loading rate. Technical literature indicates that both actions have influences on the performance of hardened concrete, especially on the compressive strength that is the material property of most importance during design. Technical literature and design codes suggest models that can follow the response of compressive strength of concrete to thermal influences in the service range as well as to influences of loading rate within and outside the service range. Combined effects of the two actions are, however, not analysed in details in the technical literature. The present paper gives a summary of laboratory test results that targeted the experimental study of concrete compressive strength over a wide range under the combined influence of service temperature and loading rate.

1.1 Influence of temperature on the strength of concrete

Seasonal or daily variation of air temperature under non-extreme, continental weather conditions may result service temperature of concrete as low as −40 °C or as high as +60 °C (in the case of direct sunlight exposure). As an example, the highest and lowest monthly air temperature recordings in the Carpathian Basin during the last 100 years [1] are indicated in Fig. 1.

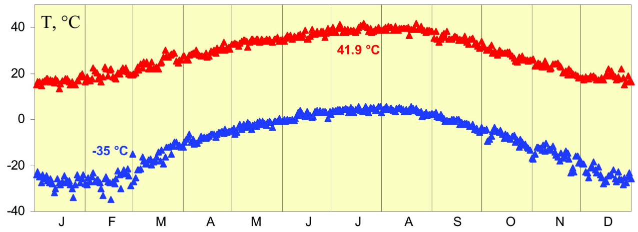


Fig. 1. The highest and lowest monthly air temperature recordings in the Carpathian Basin during the last 100 years [1]

Static compressive strength of concrete specimens in the service temperature range is found to slightly increase with decreasing temperature or, vice versa, slightly decrease with increasing temperature [2]. Technical literature indicates that the chemical structure of the hardened cement paste is not changed below 80 °C, therefore, the change in strength may be attributed to changes in the van der Waals cohesive forces, porosity, surface energy or microcracking due to thermal incompatibility between aggregate particles and hardened cement paste [3]. Microstructural changes of the hardened cement paste due to temperature change below 80 °C have not been studied in details in the technical literature and models have not been established due to the excessive complexity of the phenomena. General explanation can not be found in the technical literature for the reasons of change in compressive strength of concrete due to temperature change below 80 °C.

The ***fib*** Model Code 2010 (similarly to its predecessor CEB-FIP Model Code 1990) suggests a simplified, linear prediction model for the effect of temperature in the range of 0 °C to 80 °C on the compressive strength of concrete [4], Eq. (1):

$$f_{cm}(T) = f_{cm,20°C} \cdot (1.06 - 0.003T) \qquad (1)$$

where

$f_{cm,20°C}$ static mean compressive strength at 20 °C
T temperature, 0 °C < T < 80 °C

Graphical representation of Eq. (1) in the range of $f_{cm,20°C} = 20\,\mathrm{N/mm^2}$ to $80\,\mathrm{N/mm^2}$ is indicated in Fig. 2. It can be realised that the absolute decrease in strength is more pronounced with increasing the strength of concrete.

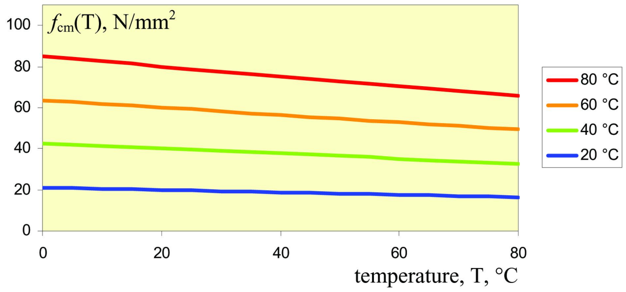


Fig. 2. Graphical representation of the linear prediction model of the ***fib*** Model Code 2010 for the effect of temperature on the compressive strength of concrete [4]

1.1 Influence of loading rate on the strength of concrete

Numerous experiments were carried out and large number of scientific papers and reports were published on the investigation of compressive strength of concrete exposed to high rate or impact loading since Abrams [5] reported his observations on the rate sensitivity of compressive strength of concrete for the first time in his paper in 1917. The most comprehensive review reference was published by Bischoff and Perry [6] in 1991. It was demonstrated that both the strength class of concrete and the type of aggregate has considerable influence on the material response under higher rates of loading.

The ***fib*** Model Code 2010 suggests a simplified, bilinear prediction model for the effect of strain rate on the characteristic compressive strength of concrete for monotonically increasing compressive strains at a constant range of 30×10^{-6} 1/s $< \dot{\varepsilon}_c < 3 \times 10^2$ 1/s [4], Eqs. (2)(a) and (2)(b):

$$\begin{aligned} f_{c,imp,k}/f_{cm} &= (\dot{\varepsilon}_c/\dot{\varepsilon}_{c0})^{0.014} && for\ \dot{\varepsilon}_c \le 30\,1/s \quad (a) \\ f_{c,imp,k}/f_{cm} &= 0.012 \cdot (\dot{\varepsilon}_c/\dot{\varepsilon}_{c0})^{1/3} && for\ \dot{\varepsilon}_c > 30\,1/s \quad (b) \end{aligned} \qquad (2)$$

with $\dot{\varepsilon}_{c0} = 30 \times 10^{-6}$ 1/s

Graphical representation of Eqs. (2)(a) and (2)(b) in comparison with the results of Bischoff and Perry [6] is indicated in Fig. 3. It can be realised that the MC2010 formula – that is developed for the characteristic compressive strength of concrete – is not suitable to describe experimental results on their mean level, but provide a reasonable lower boundary to experimental data.

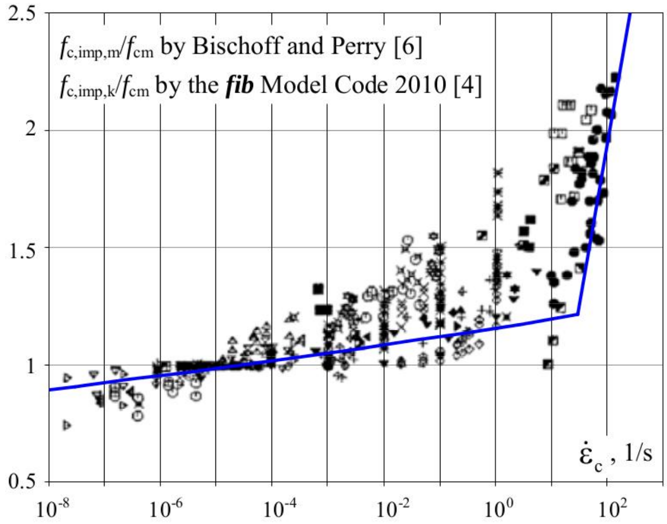


Fig. 3. Graphical representation of the bilinear prediction model of the ***fib*** Model Code 2010 for the effect of loading rate on the compressive strength of concrete [4] in comparison with the results of Bischoff and Perry [6]

2 Selection of test parameters and methods

Based on the findings of the literature review, parameters of the laboratory tests were limited to three items: the strength class of concrete, the testing temperature and the rate of loading were considered as parameters and the type of cement and the type of aggregate was chosen to be constant. Quartz sand and gravel was used as aggregate and CEM II/A-S 42.5 N cement was selected for the concrete mixes. Three different strength classes were targeted: one lower strength (*L*), one middle range strength (*M*) and one high strength (*H*) concrete mix was designed. Targeted mean cube strengths were 30, 50 and $70\,\mathrm{N/mm^2}$, respectively. Consistence of the fresh mixes was set by water reducing admixture to provide constant 500 ± 20 mm flow for all mixes. Specimens were compacted by laboratory vibration table and were stored under water for 7 days and under laboratory condition up to the age of 28 days. Strength tests were performed on specimens of 28 days of age.

The loading rates were selected to be in the possible range of service loads of concrete structures under normal service or accidental conditions, and the study of hard impact or missile impact was not considered in the present study. Typical strain rates for different types of loading are summarised in Table 1 based on [7] together with the applied strain rates during the present experimental investigations.

Temperature of the test specimens was selected as the lower and upper temperature range of concrete structures (−25 °C and 65 °C, respectively), additionally to the laboratory temperature of 20 °C. Targeted temperatures were reached by a drying oven (with nominal inner temperature of 70 °C) and by a refrigerator (with nominal inner temperature of −30 °C). Actual temperature of the specimens was measured by non-contact laser thermometer before and after the strength tests. Cold and hot specimens were covered by expanded polystyrene plates of 40 mm thickness during handling and during testing. The effectiveness of the heat insulation covering was found to be acceptable; difference between initial and final temperatures never exceeded 5 °C even for the lowest strain rate tests. The initial temperature for the cold specimens was in the range between −29 °C and −27 °C and the final temperature was in the range between −25 °C and −22 °C. The initial temperature for the hot specimens was in the range between 70 °C and 67 °C and the final temperature was in the range between 65 °C and 63 °C.

3 Test results and evaluation

Laboratory tests were performed at the Budapest University of Technology and Economics (BME), Department of Construction Materials and Engineering Geology. In the following sections the results are first introduced separately by the main influences (temperature and loading rate) and then the combined influence of the two parameters are shown on the compressive strength performance of concretes.

3.1 Influence of temperature on static compressive strength

Static load was represented with a monotonically increasing load at strain rate of 4.63×10^{-5} 1/s. Fig. 4 indicates the compressive strength (mean value) results of specimens tested under static load at different temperatures. A clear decreasing tendency is observed for all the three concrete mixes. It can be seen that the model of the ***fib*** Model Code 2010, see earlier Eq. (1), follows the experimental results rather well (Fig. 4(a)), however, it indicates an apparent tendency of different slopes corresponding to different strength classes that is actually not visible in the measured results. Technical literature data [2, 8] also do not fully confirm the model of the ***fib*** Model Code 2010 and illustrate parallel decreasing tendencies for different strength classes rather than slightly converging slopes. The best fit model for the present experimental results is given by Eq. (3). Graphical representation can be seen in Fig. 4(b).

$$f_{cm}(T) = f_{cm,20°C} \cdot \left[1 + 4 \cdot \frac{1 - 0.05 \cdot T}{f_{cm,20°C}}\right] \tag{3}$$

where

$f_{cm,20°C}$ static mean compressive strength at 20 °C

T temperature, -25 °C $< \mathrm{T} <$ 65 °C

3.2 Influence of loading rate on compressive strength at room temperature

Loading rates were selected in a range that makes possible to study the strength behaviour under the increase of strain rate by 10^3 (see Table 1). Fig. 5 indicates the compressive strength (mean value) results of specimens tested under different loading rates at room temperature. The semi-logarithm type diagrams indicate the strain rate in logarithm scale for the better visualisation. A clear increasing tendency is observed for all the three concrete mixes. It can be seen that the in the studied range of the loading rate the model of the ***fib*** Model Code 2010, see earlier Eq. (2)(a), does not follow the experimental results (Fig. 5(a)), since the formulation is given for characteristic compressive strength and the test results are mean values. The best fit model for the present experimental results is given by Eq. (4). Graphical representation can be seen in Fig. 5(b).

$$f_{c,imp,m} / f_{c,stat,m} = (\dot{\varepsilon}_c / \dot{\varepsilon}_{c0})^n \tag{4}$$

in which $n = \frac{1}{225}\left(7 + \frac{f_{c,stat,m}}{f_{c0}}\right)$

where:

$f_{c,imp,m}$ mean compressive strength under impact loading

$f_{c,stat,m}$ mean compressive strength under static loading, $\dot{\varepsilon}_c = \dot{\varepsilon}_{c0}$

f_{c0} $= 10\ \mathrm{N/mm^2}$

$\dot{\varepsilon}_{c0}$ $= 30 \times 10^{-6}$ 1/s

3.3 Combined influence of temperature and loading rate on compressive strength

Laboratory tests were carried out over the complete range of loading rates at low temperature (−25 °C) and elevated temperature (65 °C) as well. Fig. 6 indicates the compressive strength (mean value) results of the specimens. Influences of both effects are clearly visible. For comparison, calculated results using Eq. (3) and Eq. (4) is also given. In the calculations, the compressive strength obtained at room temperature under static loading ($\dot{\varepsilon}_{c0} = 30 \times 10^{-6}$ 1/s) is considered as the basic input data, from which Eq. (3) provides the $f_{c,stat,m}(T)$ values and Eq. (4) provides the $f_{c,imp,m}(T)$ values for the studied temperature range of -25 °C $< \mathrm{T} <$ 65 °C and rate of loading range of $4.63 \times 10^{-5}\ \mathrm{1/s} < \dot{\varepsilon}_c < 4.63 \times 10^{-2}$ 1/s. It can be seen, that the proposed formulae of Eq. (3) and Eq. (4) are suitable to describe the compressive strength performance of concretes over a wide range of strength under the combined influence of loading rate and service temperature. General formulation is given by Eq. (5).

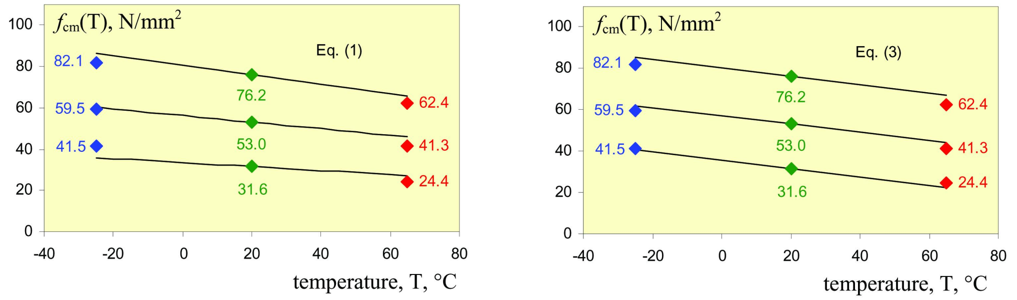
$$f_{c,imp,m}(T) / f_{c,stat,m}(T) = (\dot{\varepsilon}_c / \dot{\varepsilon}_{c0})^n \tag{5}$$

in which $n = \frac{1}{225}\left(7 + \frac{f_{c,stat,m}(T)}{f_{c0}}\right)$ where:

$f_{c,imp,m}(T)$ mean compressive strength under impact loading at -25 °C $< \mathrm{T} <$ 65 °C temperature

Tab. 1. Typical strain rates for different types of loading [7] together with the applied strain rates during the present experimental investigations

Based on [7]		Applied strain rates during the present tests, 1/s
Type of loading	Strain rate, 1/s	
Traffic load	10^{-6} to 10^{-4}	4.63×10^{-5}
Gas explosion	5×10^{-5} to 5×10^{-4}	1.16×10^{-4}
		2.31×10^{-4}
		4.63×10^{-4}
Airplane impact	5×10^{-3} to 5×10^{-2}	1.16×10^{-3}
		2.31×10^{-3}
		4.63×10^{-3}
Earthquake	10^{-2} to 10^{0}	2.31×10^{-2}
Pile driving	10^{-2} to 10^{0}	4.63×10^{-2}



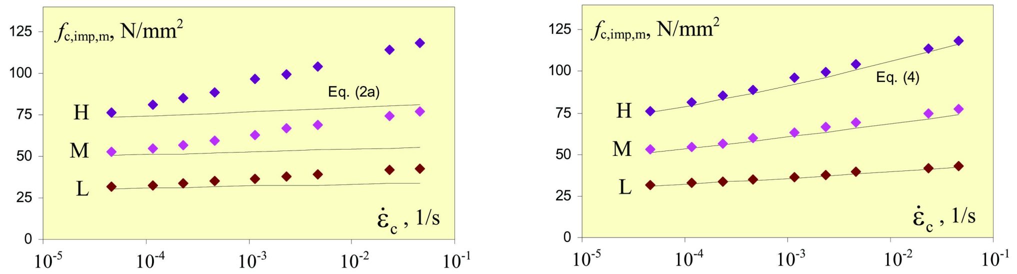
(a)

Compressive strength (mean values) of specimens tested under static load at different temperatures, together with Eq. (1) prediction

(b)

Compressive strength (mean values) of specimens tested under static load at different temperatures, together with Eq. (3) prediction

Fig. 4.



(a)

Compressive strength (mean values) of specimens tested under impact load at room temperatures, together with Eq. (2)(a) prediction

(b)

Compressive strength (mean values) of specimens tested under impact load at room temperatures, together with Eq. (4) prediction

Fig. 5.

$f_{c,stat,m}(T)$ mean compressive strength under static loading, $\dot{\varepsilon}_c = \dot{\varepsilon}_{c0}$ at -25 °C < T < 65 °C temperature, calculated as $f_{c,stat,m}(T) = f_{c,stat,m,20°C} \cdot \left[1 + 4 \cdot \frac{1-0.05 \cdot T}{f_{c,stat,m,20°C}}\right]$

$f_{c0} = 10\ \mathrm{N/mm^2}$

$\dot{\varepsilon}_{c0} = 30 \times 10^{-6}\ 1/\mathrm{s}$

4 Discussion

The technical literature defines the Dynamic Increase Factor, DIF for the ratio of dynamic (impact) strength to static strength of materials. DIF is a practical tool if one would like to compare different strength parameters (compressive, splitting-tensile, flexural-tensile etc.) or different type of concretes (normalweight vs. lightweight, normal strength vs. high strength etc.). To see the results of the present experimental studies in comparison to literature data, Fig. 7 is prepared indicating DIF for the obtained test results together with DIFs available in the technical literature [6, 9–14] and with the response given by Eq. (2)(a). Present test results are showing in the range of literature data.

Fig. 8 is prepared to demonstrate the Dynamic Increase Factor, DIF for the present test results separated by testing temperature to see the combined influence of concrete strength, loading rate and temperature on the DIF. It can be realised that the DIF apparently hides the influence of the temperature in the studied range and the data points corresponding to the same concrete mix are located around the same trend line independently of the service temperature applied. Fig. 9 is prepared for the better visualisation with the indication of the DIF for the present test results separated by concrete strength classes. It can be confirmed that the influence of service temperature is not visible in this type of representation. The effect of the loading rate governs the concrete compressive strength performance.

It can be concluded from a practical point of view that the Dynamic Increase Factor, DIF is not a suitable measure for the influence of the service temperature since the influence of the strain rate is more pronounced. Present results have confirmed, however, that it is possible to model the combination of both actions with rather good accuracy (see R^2 values in Fig. 6). Findings may be successfully used when accurate modelling of e.g. large concrete bridges is needed where both dynamic loading and service temperature changes are present combined.

5 Conclusions

Technical literature and design codes suggest models that can follow the response of compressive strength of concrete to thermal influences in the service range as well as to influences of loading rate within and outside the service range. Combined effects of the two actions are, however, not analysed in details in the technical literature. The present paper introduces laboratory test results that targeted the experimental study of concrete compressive strength over a wide range under the combined influence of service temperature and loading rate. The following conclusions can be drawn by the laboratory observations.

1. Simple testing conditions with the application of expanded polystyrene heat insulation plates of 40 mm thickness are suitable to study the influence of service temperature and loading rate on the compressive strength of concrete in the range of T = −25 °C to 65 °C and $\dot{\varepsilon}_c = 4.63 \times 10^{-5}$ 1/s to 4.63×10^{-2} 1/s.
2. The simplified, linear prediction model of the ***fib*** Model Code 2010 can be improved and a new formulation can be suggested as of Eq. (3) for the influence of service temperature on the compressive strength of concrete in the range of T = −25 °C to 65 °C.
3. The simplified, bilinear prediction model of the ***fib*** Model Code 2010 for the influence of loading rate indicates values exclusively for the characteristic compressive strength of concrete, therefore, a new prediction model is suggested for mean values as of Eq. (4) for the influence of loading rate on the compressive strength of concrete in the range of $\dot{\varepsilon}_c = 4.63 \times 10^{-5}$ 1/s to 4.63×10^{-2} 1/s.
4. It is demonstrated that the combined influence of service temperature and loading rate can be effectively predicted by the combined use of Eq. (3) and Eq. (4) in the range of T = −25 °C to 65 °C and $\dot{\varepsilon}_c = 4.63 \times 10^{-5}$ 1/s to 4.63×10^{-2} 1/s.
5. It is demonstrated that the Dynamic Increase Factor, DIF is not a practical tool in the representation of the combined influence of service temperature and loading rate on the compressive strength of concrete.

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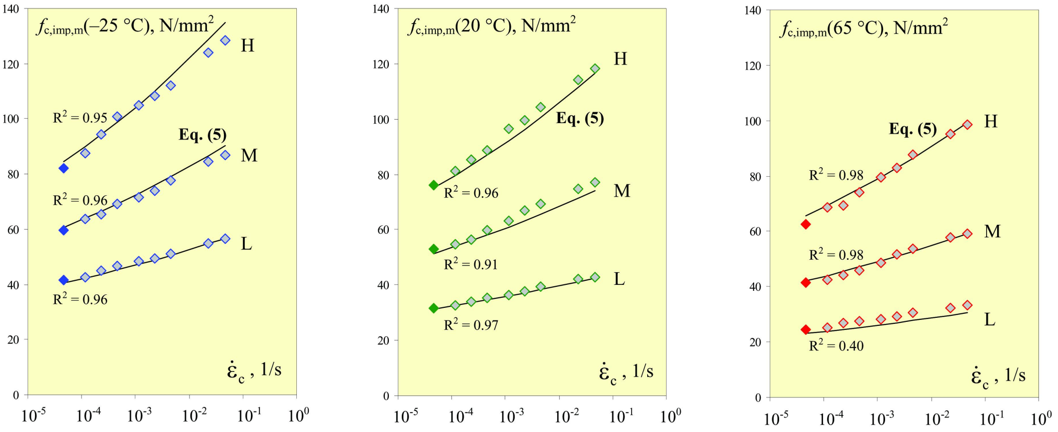


(a)
(T = −25 °C)

(b)
(T = 20 °C)

(c)
(T = 65 °C)

Fig. 6. Compressive strengths under impact loading

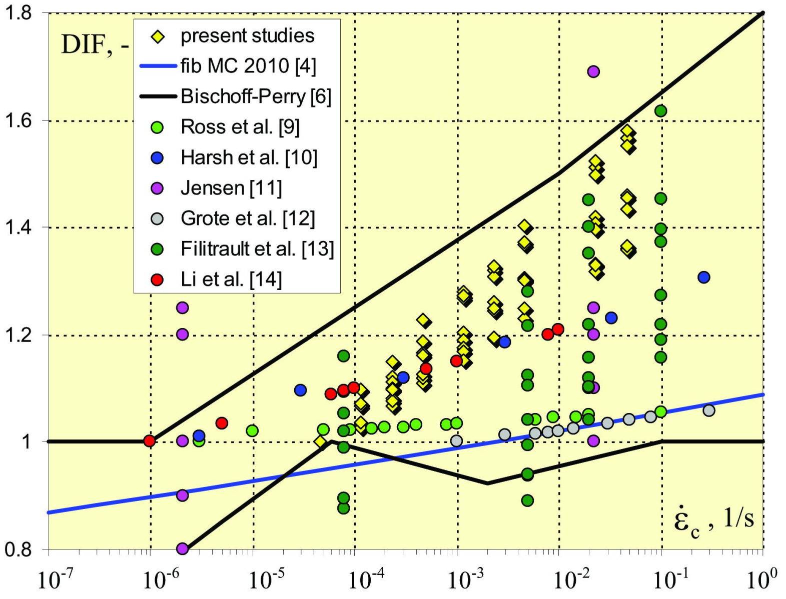
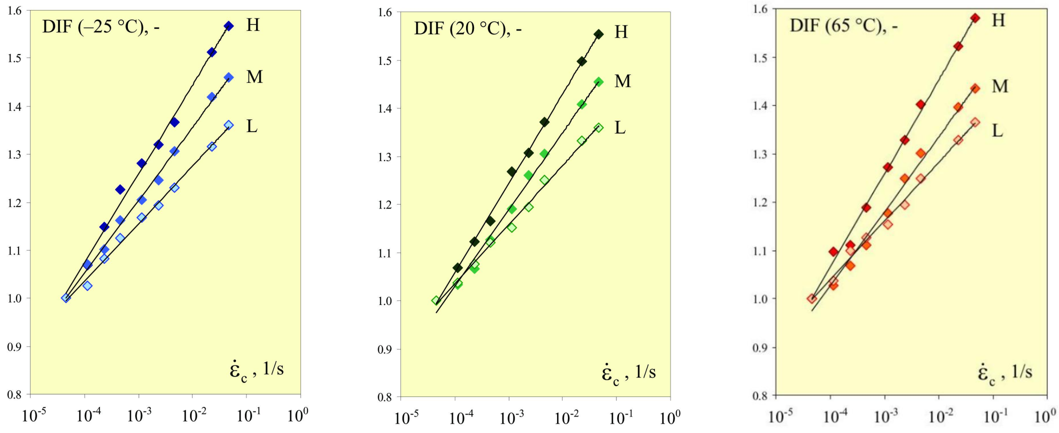


Fig. 7. Dynamic Increase Factor, DIF for the present test results together with literature data

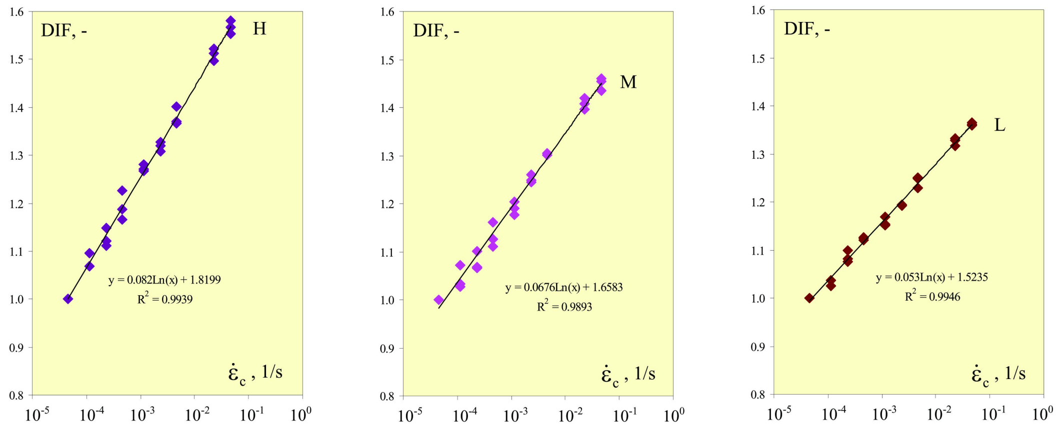


(a)
(T = −25 °C)

(b)
(T = 20 °C)

(c)
(T = 65 °C)

Fig. 8. Dynamic Increase Factor



(a)
(high strength concrete)

(b)
(medium strength concrete)

(c)
(lower strength concrete)

Fig. 9. Dynamic Increase Factor

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