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Research paper

Accuracy of models for mechanical properties of concrete subjected to the elevated temperature

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Abstract

For the fire safety design of concrete structures and repairing damaged members as a result of fire exposure, accurate equations for the residual mechanical properties of concrete usually required. Equations given by the international codes or proposed by the researchers may not be accurate and should be assessed carefully when applied on the locally produced concretes. In this research study, available data on the residual compressive strength, elastic modulus and tensile strength of concrete mostly from Iraqi sources were collected, analyzed, and equations were proposed for calculating the three mechanical properties. Different response of past proposed models for the mechanical properties against the collected test data is observed. Using regression analysis equations were proposed for calculating the residual compressive strength, splitting tensile strength and elastic modulus of heated concrete. Simple statistical tests indicate that the proposed equations are accurate and safe. There is a chance to use some equations proposed by the researchers and codes but the equation given by the ENV 1992 Code for the residual elastic modulus was found not accurate.

Keywords: *Compressive Strength; Elastic Modulus; Elevated Temperature; Regression Analysis; Tensile Strength*

1. Introduction

It is experimentally evidence that mechanical properties of concrete are adversely affected by thermal exposure [1-3]. The losses take place is not compatible with the temperature increase. For normal strength concrete the compressive strength reduction is between 10 to 20% for a concrete heated to 300oC. For high strength concrete the compressive strength loss was larger and found to be about 40% of the original strength at temperature below 450oC [2]. However, the ranges of losses take place for a given exposure temperature are wide, and usually depend on concrete material properties and testing condition, in addition to the duration of exposure. In laboratory, mechanical properties of concrete subjected to high temperature usually determined from testing specimens using one of three types of steady-state temperature tests, namely stressed tests, unstressed tests and unstressed residual property tests. Abrams [4] studied behavior of normal strength concrete under these test conditions.

Structural concrete design for fire safety and repairing of damaged members by high temperature usually is based on the residual concrete and steel materials properties after exposure to the elevated temperatures. Mechanical properties of concrete subjected to high temperature may be calculated using design curves given by codes [1], [5], [6] or equations proposed by the researchers [7-14]. Applying equations given by some international codes and researchers may not be safely done for the residual properties and these equations should be checked based on local test data. For each country or region the materials sources for producing concrete may be different from others and as consequence the properties of concrete produced from such materials may be different. It is followed that any equation proposed for mechanical properties of concrete for a given country may not be accurate when applied on concrete from other sources. Therefore, there is a need for researches in this context to check the accuracy of the models proposed for the residual properties of concrete subjected to high temperature. If necessary, other equations based on the test data on the locally produced concretes can be proposed. The aim of this research is to check the accuracy of equations proposed for the mechanical properties of compressive strength, elastic modulus and splitting tensile strength of concrete subjected to elevated temperatures tested mostly by the Iraqi researchers. New equations from regression analysis on these test data were proposed for the mentioned properties. This work can be utilized for the fire safety design of concrete structures and repairing concrete members damaged by high temperature.

2. Decryption of test data

Test data on compressive strength of concrete subjected to the elevated temperature were taken from eleven past research studies and those on splitting tensile strength from eight studies while those on elastic modulus were taken from seven studies. The majority of test data collected (about 84%) are those taken from experimental tests carried out by the Iraqi researchers. Details of the collected test data are shown in Table 1. Compressive strength values given in the table are cylinder compressive strengths. For those tests carried out on cube specimens the cube strength was multiplied by 0.8. Accordingly, a total of 129 data points were collected for compressive strength, 95 data points for splitting tensile strength and 92 data points for elastic modulus. It should be noted that all tests were determined according to the unstressed residual property tests. The aggregates used in the concrete mixes were rounded river siliceous aggregate. Maximum aggregate size varied between 9.5mm and 20mm. Exposure temperature varied between 105oC and 1100oC and exposure time between 1hr to [9] hrs.

Table 1: Description of Test Data

Property studied	fc' (MPa)	MS (mm)	T (oC)	t (hours)	N (fc' , fsp, Ec)	Reference
fc' , fsp and Ec	24.08 and 28.64	20	200, 400 and 600	1	8,8,8	Al-Hayali [3]
fc' , fsp and Ec	28.08	10	250,350,450,550 and 750	1	6,6,6	Khaleel [15]
fc' , fsp and Ec	30.34 and 25.37	14	200, 400 and 600	1	8,8,8	Abdurrahman[16]
fc' and fsp	29.36	20	200, 400 and 600	1	4,4,-	Ahmad and Al-Zubady [17]
fc'	28.49	12.5	300, 500 and 700	1, 3, 6 and 9	13,-,-	Toumi et al[18]
fc' and fsp	23.25	20	100,200,300, 400, 500 and 600	5	7,7,-	Kulkarni and Patil [19]
fc' , fsp and Ec	38.29	10	200, 400 and 600	1	4,4,4	Ahmad and Shaker [20]
fc', fsp and Ec	18.06,23.88,28.53,30.13,32.88,36.43, 40.83,42.76,46.11, 34.51,33.6,32.84 and 31.91	20	200, 400 and 600	1	52,52,52	Al-Barznge [21]
fc' and fsp	37.36	20	100,200,400, 600 and 800	2	6,6,-	Morsy et al [22]
fc'	22.14	20	150,250,400, 600 and 900	1	6,-,-	Hachemi et al [23]
Ec	37.36 and 30.64	20	400,500 and 600	1	-,-,8	Essa et al [24]
Ec	31.2 and 42.4	20	105,200,300,400, 600,800,1000 and 1100	1	-,-,6	Lau [25]
fc'	33.04,46.24,61.28	9.5	150,350,500 and 700	-	15,-,-	Al-Owaisy [26]

* including control concrete.

The effects of these variables on the behavior of concrete subjected to heating are discussed later. Specimens tested by Al-Barznge [21] were fully dried in an oven. [12] test series out of 52 were immersed in water for different periods to study the effect of moisture contents of 1.4%, 2.4% and 3.2% in concrete subjected to high temperature. Most of the specimens tested by the other researches were left in the laboratory to dry slowly after curing then subjected to the elevated temperature. Test results indicate that the effect of moisture content on the residual compressive strength of concrete subjected to the elevated temperature is not important. Fig.1 shows variation of test compressive strength and Fig.2 shows variation of compressive strength ratio (heated/control) (i.e. $f_{c\ T}^{'} / f_c^{'}$) with the elevated temperature variation. One can observe the continuous loss in compressive strength of normal strength concretes tested by the researchers. Fig.3 shows variation of splitting tensile strength values and Fig.4 shows variation of splitting tensile strength ratio (heated/control) (i.e. f_{spT} / f_{sp}) with the elevated temperature variation. Figs 5 and 6 show variation of elastic modulus and elastic modulus ratio of concrete with exposure temperature. It is observed that there is a continuous and relatively steady reduction of splitting tensile strength and elastic modulus with the temperature increase and the scatter of data for these cases is lower compared with that of compressive strength. This behavior will affect the correlation between dependent and independent variables in the regression analysis.

3. Regression analysis

First, there is a need to know the role of each independent variable on the property in question. In this study, the proposed equations are restricted to the case of unstressed residual compressive and tensile strengths and elastic modulus properties of concrete, made from ordinary Portland cement and siliceous aggregates. For the residual compressive strength ($f_{c\ T}^{'}$) the independent variables (x) are exposure temperature (T), exposure time (t) and aggregate maximum size (MS). For the splitting tensile strength and elastic modulus the residual compressive strength is added to the mentioned independent variables.
Table 2 shows correlation coefficient between each dependent variable and the three independent variables. It is observed that the strongest independent variable affects $f_{cT}^{'}$ is the exposure temperature (T). The correlation between the compressive strength ratio (fc'T / fc') with temperature seems to be better. Therefore, the compressive strength ratio (heated/ control) is considered instead of the residual compressive strength for regression analysis. The correlation coefficient between $f_{c\ T}^{'} / f_c^{'}$ and both independent variables of MS and t is low, accordingly there is a good chance to correlated the residual compressive strength ratio with the exposure time. For the residual splitting tensile strength and elastic modulus ratios the strongest independent variable yet remains the exposure temperature (T). One can find that the strongest correlation among all cases is that between the splitting tensile strength ratio and the exposure temperature which is 0.948 (see Fig. 4). There is no correlation between E_{cT} and the exposure time because the latter was found constant based on the test data collected. Results also indicate that there is a good correlation between elastic modulus and compressive strength ratio but not better than that based on exposure temperature. The same observation can be made with regard the splitting tensile strength, based on the calculated correlation coefficients shown in Table 2. Using regression analysis the following equation is obtained for the residual compressive strength ratio

Table 2: Correlation Coefficient between Dependent and Independent Variables

Parameter	fc'T	fc'T / fc'	T	MS	t
fc'T	-	-	- 0.624	0.019	- 0.350
fc'T / fc'	-	-	- 0.817	0.334	- 0.312
fspT	0.807	-	-0.908	0.150	0.072
fspT / fsp	0.673	0.824	-0.948	0.152	0.136
EcT	0.739	-	- 0.899	0.002	-
EcT / Ec	0.644	0.752	- 0.935	0.003	-

fc'T / fc'=0.978 – 3.4x10-6 T – 1.19 x10-6 T2 (1)

Applicable for temperature ranges $20^oC \leq T \leq 900^oC$. The coefficient of variation (R^2) for the above equation is 0.698 and the mean (test/calculated) value is 1.122.
The following equation is obtained for the residual splitting tensile strength ratio based on regression analysis

fspT / fsp = 1.0254 – 0.0006 T – 7 x 10-7 T2 (2)

Applicable for temperature ranges $20^oC \leq T \leq 800^oC$.

The coefficient of variation (R^2) for the above equation is 0.932 and the mean (test/calculated) value is 0.975.

Based on regression analysis the following equation for the residual elastic modulus is obtained

EcT /Ec =1.0688–0.001575T +7.875x10-8T 2+5.25x10-10T 3 (3)

Applicable for temperature ranges $20^oC \leq T \leq 1100^oC$. The coefficient of determination (R^2) for the above equation is 0.894 and the mean (test / calculated) value is 0.99.

4. Validity of the proposed equations

It is important to check the accuracy of the proposed equations for the three residual properties via the statistical parameters of regression analysis. It is also important to check the accuracy of the equations given by some codes and researchers, applied on the data collected in this investigation. Table 3 shows the parameters of regression analysis. With regard the equations proposed by the author one can observe that the R^2 value for Eq.2 is the highest (except that for the ENV 1992 Code [1] model) and the mean square error (S_E) is the lowest among all predictions, indicating that the quality of equation for the splitting tensile strength is better, followed by that for elastic modulus. Comparison of mean test/calculated value indicates that there is higher safety related using Eq. 1 for the residual compressive strength compared with the other cases. Now, it is useful to compare the results of the proposed equations with those given by some codes and researchers, and compare the validity of these equations when applied on the collected test data.

Variations of calculated residual compressive strength, elastic modulus and splitting tensile strength using different models are shown in Figs. 7, 8 and 9 respectively. From Fig.7a and Fig.7b. one can observe that, in general, all relationships are close to each other except those given by the BS code [6], Lie et al [7], Kodur et al [8] and Lie and Irwin [9]. From Fig. 7a one can observe that the predictions based on the proposed equation and that given by the BS code are nearly identical for exposure temperatures larger than 600^oC. However, better comparison can be obtained via the simple statistical test. For this purpose the coefficient of determination (R^2), mean (test/calculated) value (μ) and mean square error (S_E) were calculated for all predictions and the results are given in Table 3. Accordingly, the equation given by the author is the best one among all proposed models for the residual compressive strength, because of the lowest S_E followed by those of ENV 1992 Code [1] and Bastami et al [14]. The model proposed by Lie and Irwin [9] is not accurate because of low R^2 and high S_E values and not safe because the mean value is considerably smaller than unity. The model given by Hertz [11] is considerably under estimates test data and there is a high safety related to this model (i.e. 32.5%) followed by that proposed by Lie et al [7] and Kodur et al [8]. Equations proposed by ENV 1992 Code [1], Bastami et al [14] in addition to that proposed in this investigation (i.e. Eq.1) can be accurately and safely applied for the residual compressive strength. Figs.8a and Fig.8b show the calculated elastic modulus variation with the exposure temperature. According to the results shown in Table 3 the model given by the ENV 1992 Code [1] is somewhat different because of lower values of R^2 and μ in addition to higher S_E. Based on the comparison with the collected test data there is no safety related to using the equation given by ENV 1992 Code for calculating the residual elastic modulus. The predictions of other models are close to each other, but that given by Li and Purkiss [10] is somewhat unsafe because of low mean value. There is a large safety accompanied with the equation proposed by Chang et al [12] reached 86.1% followed by that proposed by Bastami et al [14], but the standard error for the former model is high. The model proposed in this study is both accurate and safe and can be used for the residual elastic modulus and there is chance to use those models proposed by Khennane and Baker [13], Li, and Purkiss [10]. Fig. 9 shows variation of calculated tensile strength ratio with the temperature variation. Results shown in the figure and Table 3 indicate that the proposed model by the author is accurate because of lower standard error. Although there is a safety related to the model by ENV 1992 Code [1] because of high mean value, this model is not accurate for calculating the residual tensile strength because of high standard error. The predictions of Chang et al [12], Bazant, and Chern [27] are accurate because of high R^2 and low S_E, but that given by Bastami et al [14] is not accurate because of the low R^2 value and high S_E compared with the other models.

Table 3: Regression Analysis Parameters for Different Proposed Models

Models	Compressive strength			Tensile strength			Elastic modulus		
	R^2	μ	S_E	R^2	μ	S_E	R^2	μ	S_E
ENV 1992-1-2 [1]	0.696	1.024	0.137	0.938	1.303*	0.224	0.853	0.847	0.161
BS [6]	0.665	0.997	0.154						
Lie et al [7]	0.584	1.282	0.215						
Lie and Irwin [9]	0.568	0.880	0.187						
Kodur et al [8]	0.658	1.175	0.161						
Li and Purkiss [10]	0.686	1.098	0.147				0.893	0.954	0.103
Hertz [11]	0.692	1.325	0.175						
Chang et al [12]	0.684	1.150	0.157	0.915	1.062	0.086	0.902	1.861	0.152
Khennane and Baker [13]							0.892	0.992	0.103
Bastami et al [14]	0.703	1.068	0.138	0.699	1.017	0.148	0.892	1.633	0.111
Bazant and Chern [27]				0.898	0.994	0.093			
Proposed	0.698	1.122	0.133	0.932	0.975	0.078	0.894	0.99	0.103

* Excluding data of tensile strength at 600oC, because at this temperature the strength is equal to zero.

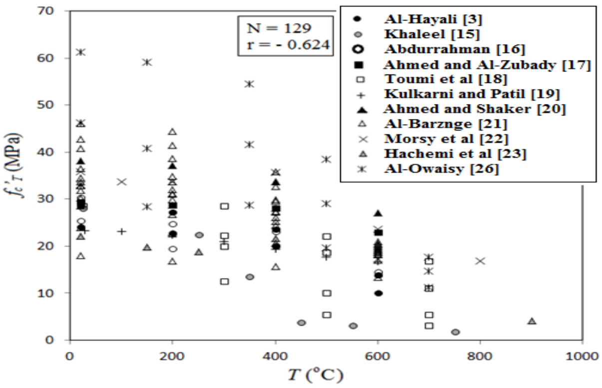

Fig. 1: Variation of FC'T with Exposure Temperature.

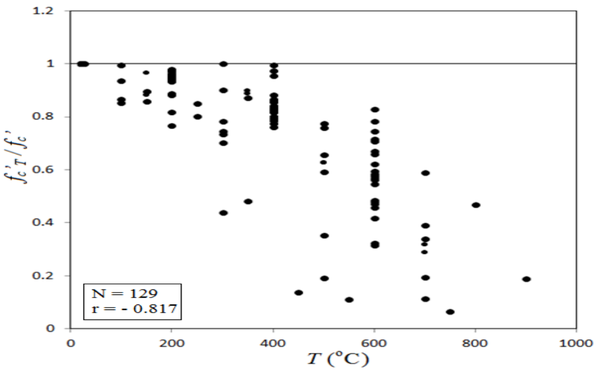

Fig. 2: Variation of FC'T / Fc' with Exposure Temperature.

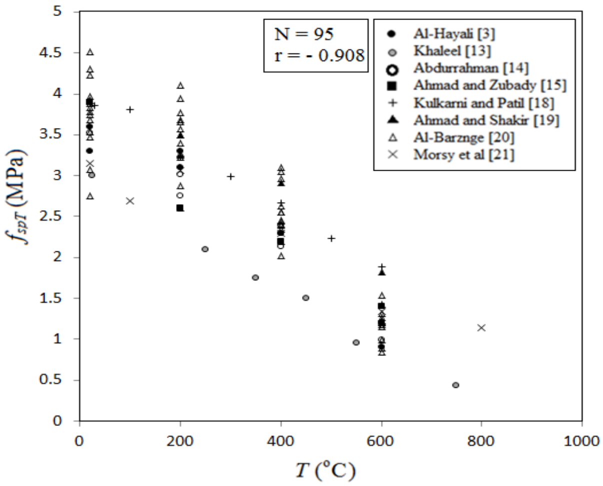

Fig. 3: Variation of Fspt with Exposure Temperature.

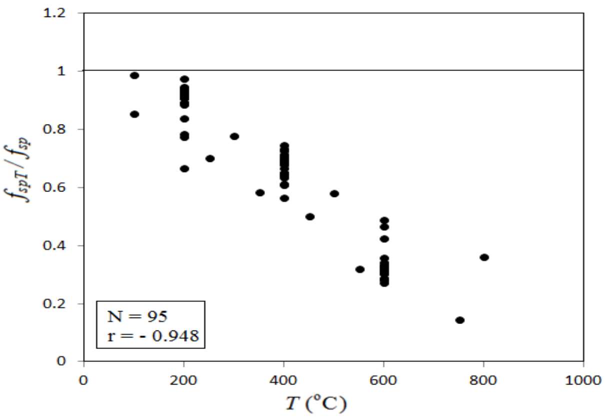

Fig. 4: Variation of F_{spt} / F_{sp} with Exposure Temperature.

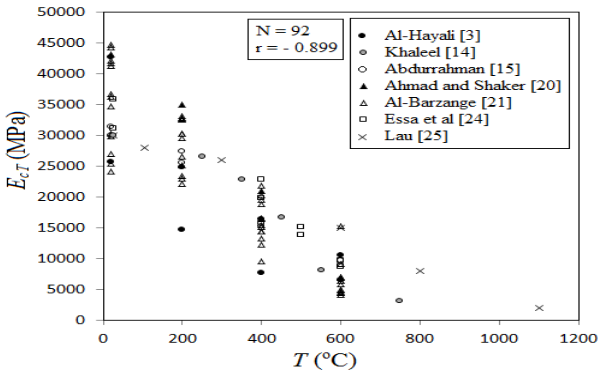

Fig. 5: Variation of ECT with Exposure Temperature.

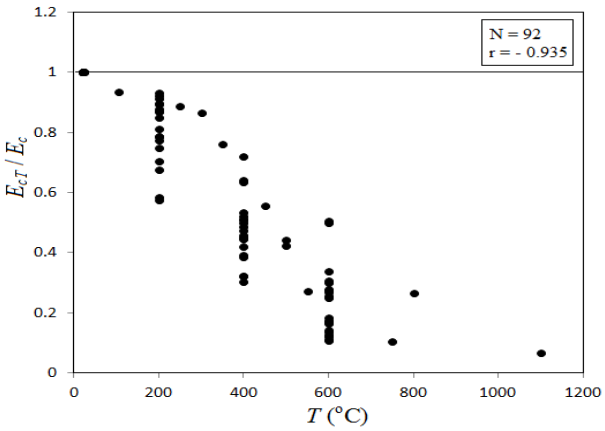

Fig. 6: Variation of E_{CT} / E_C with Exposure Temperature.

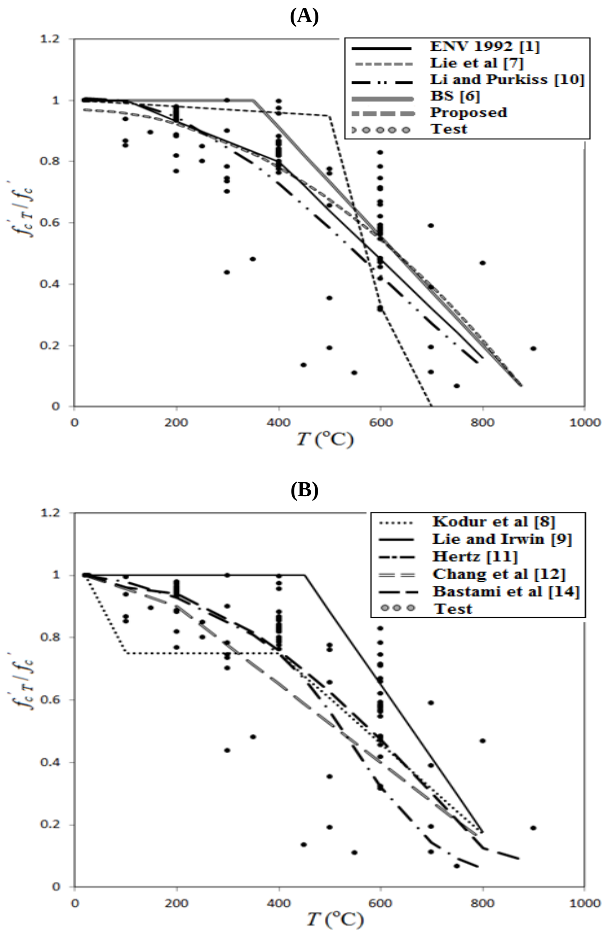

Fig. 7: Test and Calculated FC'T / FC' Variation with Exposure Temperature.

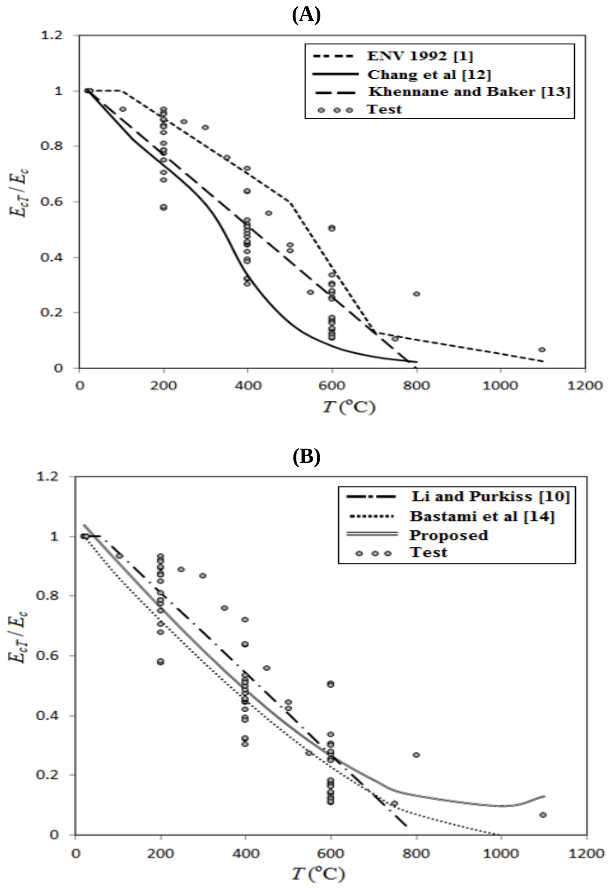

Fig. 8: Test and Calculated Ect /Ec Variation with Temperature.

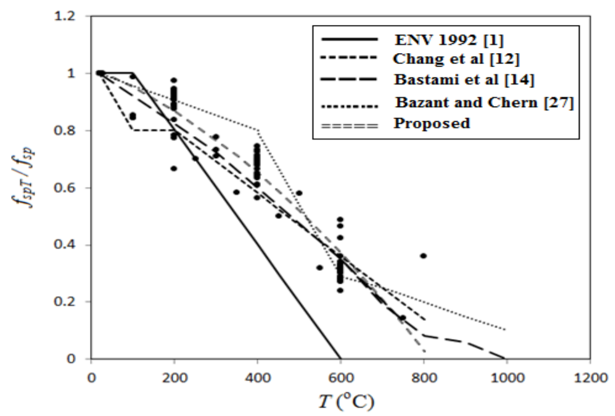

Fig. 9: Test and Calculated FSPT / FSP Variation with Temperature.

5. Conclusion

Based on this research study the following conclusions can be made

Scatter of data related to the residual compressive strength is higher than those for splitting tensile strength and elastic modulus. Accordingly, the correlation between the splitting tensile strength and exposure temperature and between the elastic modulus and temperature are higher. Accordingly, the quality of most of the proposed models for predicting the splitting tensile strength and elastic modulus is better.

There is some difference among proposed equations for calculating the residual compressive strength, splitting tensile strength and elastic modulus. The equation given by the ENV 1992 Code for the residual compressive strength is accurate and safe. There is a safety related to the tensile strength equation and the prediction is somewhat accurate, but that given for the elastic modulus was found both not accurate and not safe.

There is a good chance to use the equations proposed in this investigation for calculating the three mechanical properties of concrete subjected to the elevated temperature. The proposed equations may be utilized for fire safety design of concrete structures and repairing damaged members subjected to high temperature.

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