EXPERIMENTAL INVESTIGATION OF THE ELASTIC MODULUS OF HIGH STRENGTH CONCRETE AT ELEVATED TEMPERATURES

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Abstract
Concrete is susceptible to damage caused by physical-chemical processes during heating, resulting in the reduction of the elasticity modulus, which decays monotonically. After cooling, the elastic modulus is lower than for the heated concrete. After fire concrete heated above 300°C is commonly removed, but cooler concrete is often maintained in the rehabilitated structure. Therefore, the temperature-dependency of the elasticity modulus of a high strength concrete after exposure to elevated temperatures (in casu heating up to 225°C) is studied through the non-destructive technique of excitement impulse. In this method, the elastic modulus is measured by obtaining a natural vibration frequency from a mechanical impulse received by an acoustic sensor. The results indicate a considerable reduction of elastic modulus, in the range of 30%-35% after heating to 225°C.

Keywords: elevated temperatures, concrete, elastic modulus, non-destructive testing.

1 INTRODUCTION

Concrete has advantages when exposed to high temperatures in comparison to other building materials such as wood and steel, including the non-emission of toxic gases and the characteristic of being an incombustible material. According to Wendt (2006), citing Mehta & Monteiro (1994), concrete is also capable of maintaining its strength over a period long enough for fire rescue operations. However, concrete is susceptible to permanent damage caused by physical-chemical processes during heating, including: loss of compressive strength, reduction of the elasticity modulus, cracking due to thermal stresses, destruction of the adhesion between the cement paste and the aggregates, and the loss of adhesion between the concrete and the steel (Wendt, 2006).

The modulus of elasticity, or Young's modulus, is a measure of the stiffness of a material. The greater the modulus of elasticity, the less deformable the material is. Subject to high temperatures, the modulus of elasticity behaves similarly to most of the mechanical properties of concrete. In general, the resistance, modulus of elasticity and tensile strength decrease considerably, in addition, its decay is monotonic, and after cooling, its value is lower than that of heated concrete (Xiao and König, 2004). Also according to these authors, the type of aggregate has a great influence on the elasticity module. Young's modulus values decrease more significantly for cured concrete submerged in water and it [illegible] erature reached during heating.

After fire, concrete heated above 300°C is commonly removed (Ni and Gernay, 2021). The permanent damage after exposure to lower elevated temperatures is, however, not yet fully understood. Therefore, an experimental investigation is made into the elastic modulus of concrete during heating up to 225°C and subsequent cooling. This investigation is intended to highlight the need for further investigations into the possibility of continued use post-fire of concrete heated to relatively low temperatures (i.e. lower than 300°C).

The non-destructive technique of impulse excitation coupled to an instrumented oven is implemented in this work to determine the variation of the modulus of elasticity as a function of the increase in temperature. In this method, the modulus of elasticity of the material is measured by obtaining its natural frequency of vibration from a mechanical impulse, captured by an acoustic response sensor (ATCP - Physical Engineering). According to PEREIRA et al (2015), non-destructive tests allow obtaining information regarding the defect content of a given product, the technological characteristics of a material, or even, the monitoring degradation in service of components, equipment and structures.

2 MATERIALS AND METHODS

2.1 Materials

With the aid of the Experimental Structure Analysis Laboratory (LAEES) of the Federal University of Minas Gerais (UFMG), a 90 cm long, water-cured concrete beam, with a 30x15 cm cross-section was made for this test. For the production of concrete, CP V ARI PLUS cement was used with a characteristic resistance at 28 days (f_{ck}) equal to 30 MPa. Table 1 shows the concrete composition used to make the concrete.

Table 1: Concrete composition used to make the tested beam

CP V ARI PLUS (Kg)	Coarse Natural Sand (m³)	Pebble (Kg)	Water (L)	Muraplast FK 118 (Additive) (mL)	Factor Water / Cement	Density (Kg /m³)	Mortar content (%)
1,47	3,42	3,41	1	11,71	0,68	2281	0,589

The specimens were extracted from the concrete beam. The specimens were made in rectangular formats with dimensions of approximately 15,0 x 3,0 x 1,0 cm, in three cutting planes: XY, XZ, YZ, according to Fig. 1.

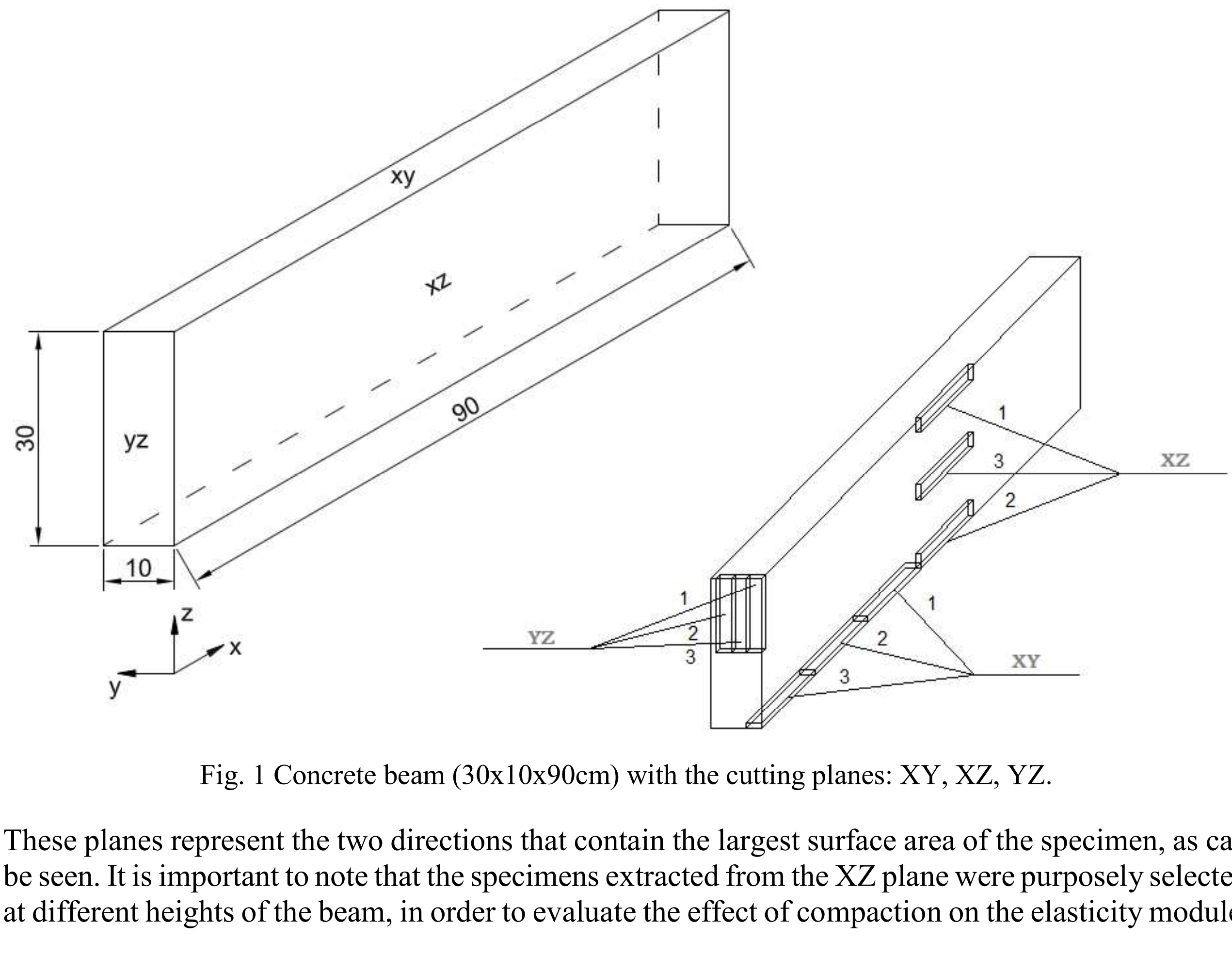

Fig. 1 Concrete beam (30x10x90cm) with the cutting planes: XY, XZ, YZ.

These planes represent the two directions that contain the largest surface area of the specimen, as can be seen. It is important to note that the specimens extracted from the XZ plane were purposely selected at different heights of the beam, in order to evaluate the effect of compaction on the elasticity module.

2.2 Equipment

To characterize the elastic modules as a function of temperature, the instrumented oven HT1150 of the Sonelastic line was used, developed by ATCP - Physical Engineering and by the group of Physical Engineering and Materials Microstructure (GEMM). The oven works in conjunction with an automatic pulsator and a directional microphone for high temperatures.
In addition, the oven allows continuous use of temperature up to 1150 ºC, having a derivative integral proportional controller (PID) with 3 ramps and 3 levels, with internal dimensions of 100x150x200 mm, hence the need to extract the specimens in the above measures.
From its use, the modes of flexural vibration (where the modulus of elasticity was obtained) and torsional (from which the modulus of shear) were obtained as a function of the temperature of the samples. In this case, the work in question was concerned with the study of the modulus of elasticity.

3 METHODOLOGY

The non-destructive tests were performed at the Laboratory of Experimental Analysis of Structure (LAEES) of the Federal University of Minas Gerais (UFMG). The method of impulse excitation, used in the data acquisition equipment used in this test, is based on the ASTM E1876 (2006) standard, which addresses the evaluation of the modules of elasticity and damping of materials from the natural frequencies of vibration of the test specimens.
The basic principle of operation of the Sonelastic equipment is the application of a mechanical pulse of short duration, through the pulsator, in the specimen that responds with vibrations in its natural frequencies, according to the imposed conditions, which are obtained by the acoustic capturer (both located outside the specimen). The Sonelastic software identifies what these frequencies are and their respective damping and, thus, analyzes the transient vibrations, from which it extracts the frequencies for the calculation of the elastic modules and the respective attenuation rates for the calculation of the damping (PEREIRA, et al. , 2015).
Performing this procedure at different temperatures, dynamic elastic modules for different temperatures are calculated. In the case of the test performed, the maximum temperature reached was 225 ºC due to technical limitations of the specific equipment used.
Before starting the test, the nodal lines of the specimens located at 0.224L (where L is the specimen length) of each end are delimited. These nodal lines are defined for the vibration mode equal to 1 which defines the maximum amplitude in the center of the specimen and at its ends (COSSOLINO & PEREIRA, 2010). In this way, the specimens are positioned with the modal lines on the supports and the point of impact in its center. Thus, transversal and flexional vibrations are obtained.
The modulus of elasticity (E) is then determined by the frequency of flexural vibration, while the transverse strain module (G) is determined by the frequency of torsional vibration (ASTM E1876).
For this purpose, the processing unit was programmed to acquire data per minute, the oven temperature being increased by 5°C at each time interval (per minute). The initial temperature of all tests was at room temperature and the maximum temperature reached by the oven was set at 225°C, as already mentioned, for 1 hour. Note that the procedure does not ensure that a uniform temperature is reached within the specimen. This was done to obtain assess the relevance of more elaborate and costly testing whereby slower heating will be used to ensure more uniform temperatures.
In addition to the configuration of the processing unit, the Sonelastic software was also programmed for measurements at continuous high temperature, taking readings regarding the flexional and torsional vibration mode with estimated Poisson coefficient.

4 RESULTS ANALYSIS

The obtained variation of the modulus of elasticity as a function of temperature for the three tests in each of the three planes can be seen in Fig. 2 to 4.

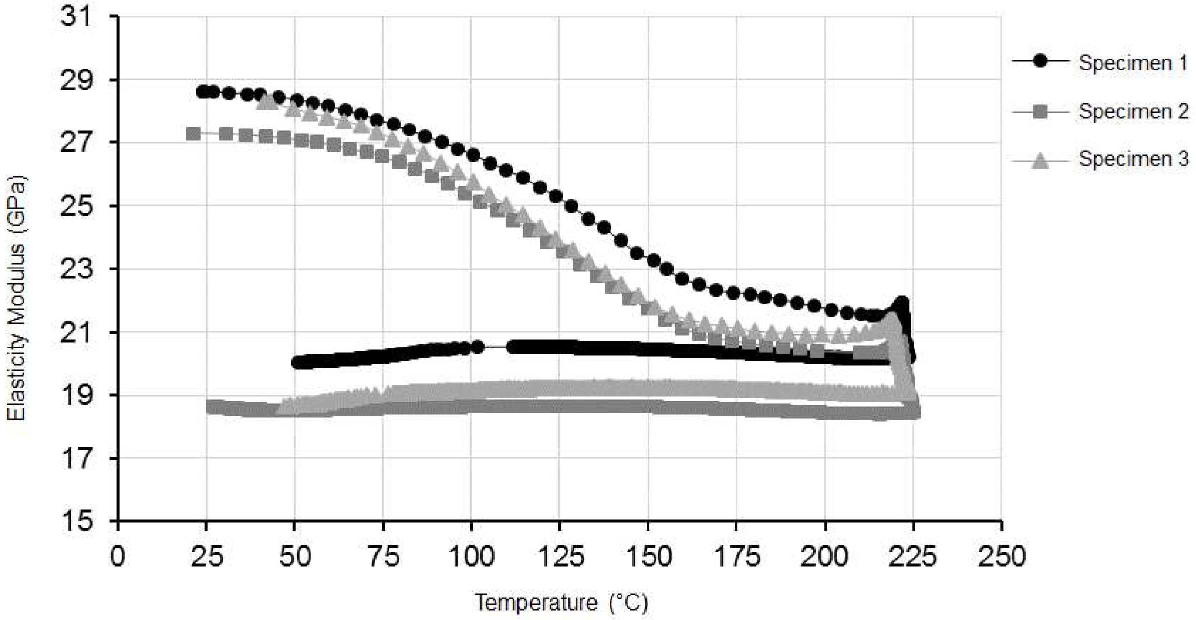

Fig. 2 Variation of the modulus of elasticity for the specimens in the XY plane.

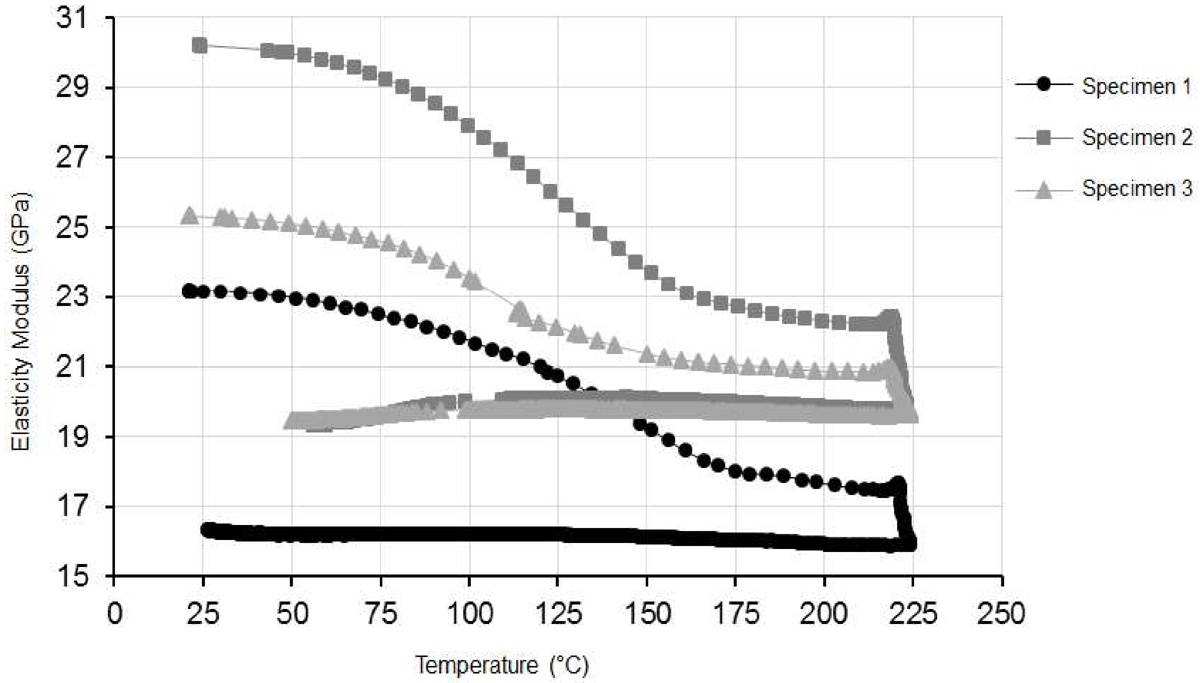

Fig. 3 Variation of the modulus of elasticity for the specimens in the XZ plane.

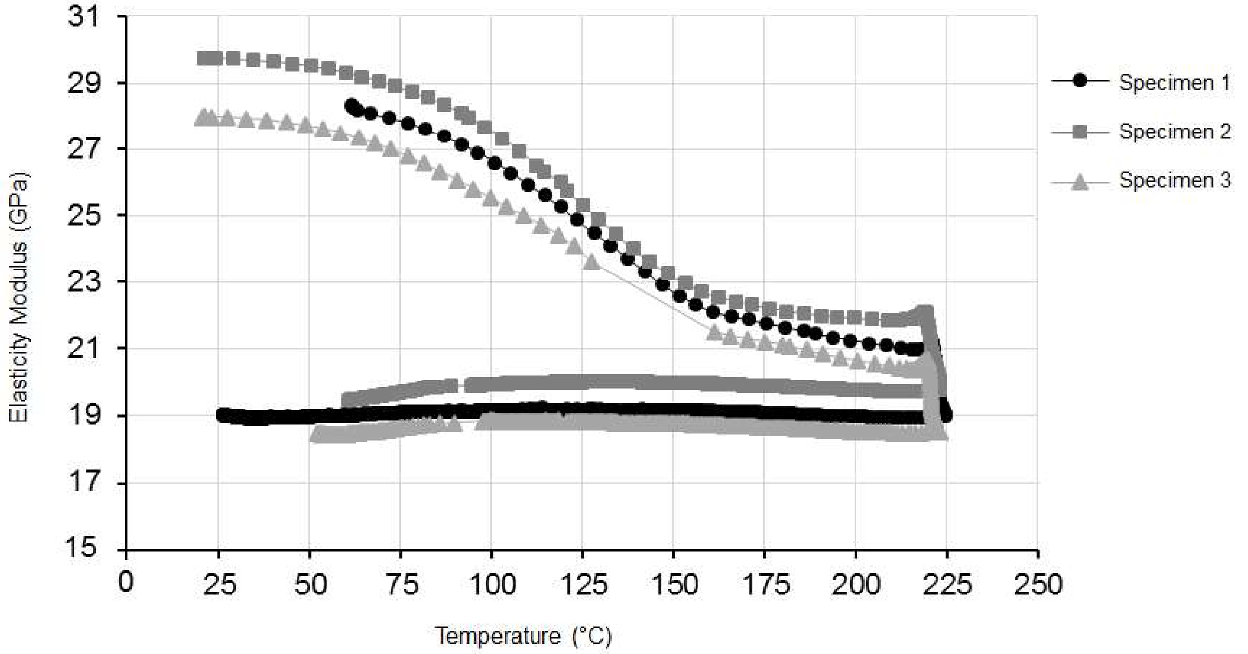

Fig. 4 Variation of the modulus of elasticity for the specimens in the YZ plane.

It is observed that with the increase in temperature there is a sharp drop in the elasticity modulus and when decreasing the temperature the specimen does not recover its modulus of elasticity, this fact occurs in all cases.

It is observed, in all the graphs presented here, that there is considerable scatter for the elastic modulus at the start of the test. It can be seen that with the increase in temperature, all specimens showed the same loss of rigidity behavior. In percentage, the losses were very similar, presenting, at the end of the test, a loss of approximately 33% (Fig. 5).

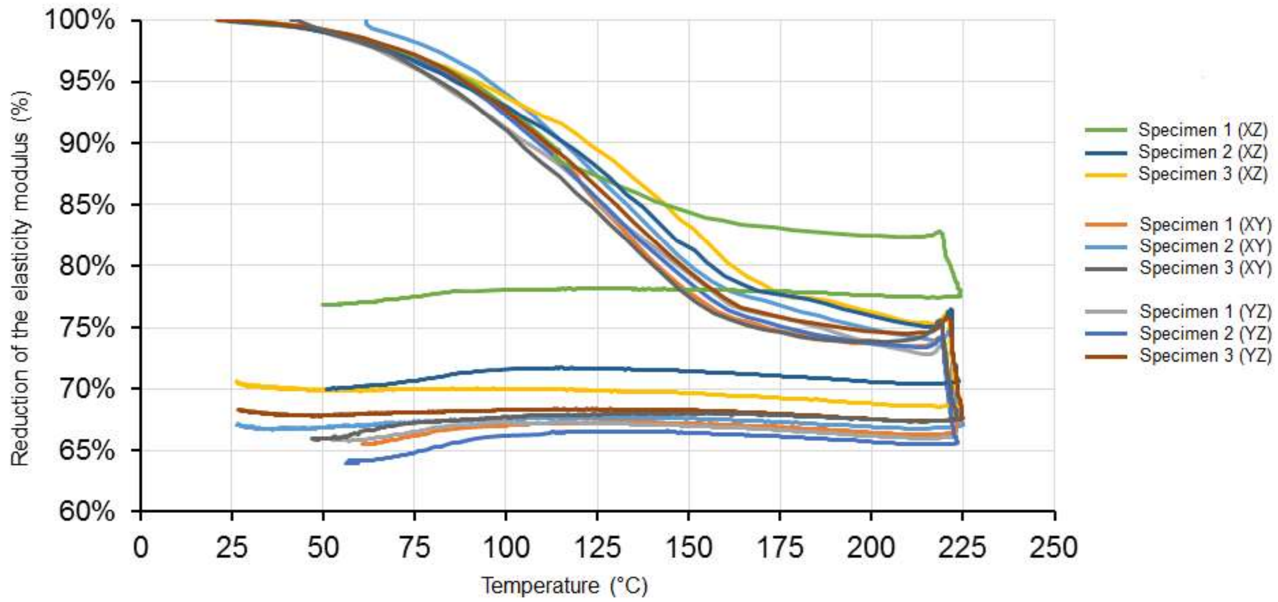

Fig. 5 General comparison of the elasticity modulus decay curves due to temperature.

Considering the above figures, different regions for the loss in the modulus of elasticity can be observed. There appears to be first region between room temperature and 160°C with a fast decrease of in the elastic modulus. In this region, the evaporation of all free water occurs, as well as the start of the loss of the chemically bonded water. According to Wendt (2006), this corresponds with an increase in permeability and total degradation of ettringite, a component responsible for the initial grip and resistance, as well as an increase in the concentration of calcite.

A second region between 160 and 220°C is observed where the decrease in elastic modulus is markedly slower. Note, however, that the transient nature of the tests (no uniform temperature) makes definite conclusions difficult. While maintaining the temperature at approximately 225°C for 1 hour a further reduction in the elastic modulus is recorded. During cooling, the modulus of elasticity is approximately constant. It should be noted that it does not recover with the reduction in temperature, and that for some specimens a further reduction in elastic modulus is recorded.
The figures highlight that the XY and YZ planes have less variability in the elastic modulus when compared to the XZ plane. This issue can be explained by the fact that it is precisely this plane where the extraction of the specimens took place at different heights of the beam. In other words, it is perceived that different heights refer to different levels of compaction and, consequently, different elasticity modulus values. Thus, these results suggest that the better the compaction, the greater the modulus of elasticity and vice versa. Some effect on the percentage reduction of the modulus of elasticity at elevated temperatures is observed. This issue further emphasizes the importance of compaction control when making concrete
The results can be compared with those obtained by Bilow & Kamara (2008). Considering the aggregates used and the initial modulus of elasticity of approximately 28 GPa, the results of Bilow and Kamara referring to the siliceous aggregates are considered. From (Bilow & Kamara, 2008) it can be seen that for the temperature at which the test was performed, 235 °C or 437 ºF, a reduction of the elasticity modulus to a residual value of approximately 60% is expected. In the current study, a residual value of approximately 67% has been observed, a slightly higher retention than expected, probably due to the characteristics of the concrete composition and the heating regime.

5 CONCLUSIONS

An exploratory experimental study was conducted into the elastic modulus of concrete during heating to 225°C and subsequent cooling. Even for these small temperature increases, significant permanent reduction in the elastic modulus was observed (approximately 33%). The decrease in elastic modulus already starts at very low temperatures (below 100°C). This may have important implications for the continued use of concrete after heating.
The applied non-destructive test method, i.e. continuous acoustic test during heating and cooling, was found very promising. The obtained results were furthermore in line with selected results published in literature. The preliminary investigation has shown both the relevance and the importance of this type of study. Follow up studies using an adjusted heating regime are recommended.

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