**Environmental Engineering and Management Journal**

*March 2015, Vol.14, No. 3, 601-605*
*http://omicron.ch.tuiasi.ro/EEMJ/*

***"Gheorghe Asachi" Technical University of Iasi, Romania***

# MATHEMATICAL MODELLING OF MECHANICAL BEHAVIOUR OF CELLULOSE-BASED FIBRES EXPOSED TO GAMMA RAYS AND HYDROTHERMAL TREATMENT

**Angelica Olaru[1], Teodor Măluţan[*2], Maria Geba[1], Cristina M. Ursescu[1*], Corina Măluţan[2]**

*[1] "Moldova" National Complex of Museums, 1 Piaţa Ştefan cel Mare şi Sfânt Str., 700028 Iaşi, Romania*
*[2] "Gheorghe Asachi" Technical University of Iasi, 73 Prof. Dr. docent Dimitrie Mangeron Str., 700050 Iasi, Romania*

## Abstract

The deterioration of the natural polymers is a very complex process, and a problem that can be best addressed through modelling. The approach for modelling the rheological behaviour of different cellulose-based textile fibres (*cotton*, *hemp*, *flax*) when subjected to a hydrothermal treatment, followed by exposure to different doses of gamma-rays (5, 10, 15 and 25 kGy) is presented here. In order to predict the optimum radiation dose limit and hydrothermal aging time, the mathematical model was developed using MATLAB computational technique.
To study the mechanical behaviour of the tested fibres, tensile tests were carried out using a TINIUS OLSEN dynamometer H5KT according to ISO 2062 norm. The model of correlation between the mechanical properties of the fibres and the independent variables was based on a polynomial second-degree equation, with the Least-Squares fitting approach that led to the coefficients of the mathematical model.

*Key words:* cellulose-based textiles, gamma rays, mathematical modelling, rheological behaviour

*Received: November, 2014; Revised final: March, 2015; Accepted: March, 2015*

## 1. Introduction

As the level of environmental degradation is nowadays a rising hazard, physical treatments such as exposure to ionizing radiation (gamma rays or electron beam) prove to be the environmentally friendly methods both for reducing biological contamination and as mean of modifying polymers for different purposes. In industrial irradiators, the standard sealed sources of isotopes are subjected to national and international regulations (ASTM, 2006; ISO, 2000; ISO, 2006a; ISO, 2006b) that provide the legal basis for environmental radiation monitoring (Ionescu et al., 2012).

Although used mainly for the sterilization of medical devices and pharmaceutical products or food products decontamination, gamma-rays treatment was taken into consideration for the last fifty years as a less noxious mass-treatment for disinfestations or micro-organisms inactivation in historical collections (Kennedy et al., 2000; Katušin-Ražem et al., 2009; Van der Sluijs and Church, 2013). The main advantage in applying this treatment resides in the high penetrating power of this type of ionizing radiation, which allows a product to be treated even inside its package, while it leaves no residues on the object. As regards the conservation of textile heritage collections, the radiation dose should be selected according to the chemical and physical properties of the materials (Geba et al., 2014; Panzaru and Malutan, 2012).

The exposure to gamma rays requires thorough investigation concerning the long term effect of radiation doses (Machnowski et al., 2013;

[*] Author to whom all correspondence should be addressed: e-mail: thmalu@tuiasi.ro; marta_ursescu@yahoo.com

Takacs et al., 1999) on the mechanical properties of the natural fibres during aging (Olaru et al., 2013) in their future environmental conditions.

In the present study, the mechanical behaviour of cellulose-based fibres exposed to gamma rays and hydrothermal treatment was investigated, followed by empirical mathematical modelling, developed to establish the effect of both increased exposure to irradiation and hydrothermal treatment on the physical-mechanical characteristics of fibres.

## 2. Experimental

### 2.1. Materials

This study was carried out on fibres from commercial fabrics made of *cotton*, *flax* and *hemp*. Textile samples subjected to a hydrothermal treatment and irradiated at increasing doses of gamma radiation were analysed.

### 2.2. Weathering procedure

The tested fibres were placed in a laboratory chamber (Angellantoni Ind., Italy) and exposed to the hydrothermal treatment, to climatic conditions set at 40°C and 60 % R.H., in order to reproduce the influence of the main agents of deterioration within the museum environment. The samples were kept in the climatic chamber for 0, 24, 48 and 120 hours.

### 2.3. Irradiation procedure

The Technological Radiation Centre IRASM/IFIN-HH in Magurele, Ilfov, Romania provided the exposure to gamma-rays doses of: 5, 10, 15 and 25 kGy, with a Dmax/Dmin=1.14 dose uniformity, in an SVST Co-60/B type irradiator.

### 2.4. Tensile tests

Tensile tests were carried out using a TINIUS OLSEN dynamometer H5KT, according to ISO 2062 norm. The main tensile properties, namely breaking force (inN) and relative elongation (%) were analyzed.

## 3. Results and discussion

The behavior of the tested samples of cotton, flax and hemp under the radiation treatment may be different from the pure cellulose, due to the changes already induced through fibers manufacturing (i.e. temperature, chemicals, stretching, raw materials type as cellulose source for processing the fibers) and the exposure to or the fluctuation of environmental agents (i.e. temperature, light, relative humidity). Using an appropriate mathematical model in studying the rheological behaviour of the tested textiles, one can estimate the optimum domain of the radiation doses, as well as the durations of the hydrothermal treatment that should lead to the adequate physical-mechanical characteristics. In order to establish the effect of both increased exposure to irradiation and hydrothermal treatment on the physical-mechanical characteristics of the cellulose-based fibres, an empirical mathematical second order rotational model was developed (Măluţan, 2009). Therefore, results on physical-mechanical tensile tests were subjected to mathematical modelling by means of the Least-Squares fitting approach, for the purpose of obtaining a correlation equation.

The independent variables considered in the proposed model were: time of exposure to hydrothermal treatment and gamma radiation dose. The dependent variables taken into account were the values of the measured mechanical characteristics: breaking work, breaking force and relative elongation. The model of correlation between the mechanical properties of the fibres and the independent variables was based on polynomial second-degree equations such as Eq. (1).

$$y(x) = b_0+b_1x_1+b_2x_2+b_{11}x_1^2+b_{12}x_1x_2+b_{22}x^2 \quad (1)$$

The Least-Squares fitting approach and the adequate modelling of the experimental data related to physical-chemical characteristics of the cellulose-based textile materials led to the coefficients of correlation in Table 1. The different local forms in modelling the real response surfaces $Y = f(X_1, X_2)$ are shown in Figs. 1-9.

For the *cotton* samples exposed to hydrothermal treatment and radiation, the evolution of the breaking force leads to the conclusion that, under hydrothermal treatment of the same duration, the value for the breaking force decreases when the radiation dose increases. This trend is more obvious for doses higher then 15 kGy. The hydrothermal treatment up to 60 hours leads to the decrease of elongation whith the increase of radiation dose to 25 kGy.

**Table 1.** Coefficients of correlation for the mathematical model

| | ***Cotton*** | | | ***Flax*** | | | ***Hemp*** | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Coefficients*** | ***Breaking force, N*** | ***Elongation, %*** | ***Breaking work, J*** | ***Breaking force, N*** | ***Elongation, %*** | ***Breaking work, J*** | ***Breaking force, N*** | ***Elongation, %*** | ***Breaking work, J*** |
| $b_0$ | 2.481 | 2.8948 | 0.0039 | 26.6931 | 3.3382 | 0.0395 | 20.5696 | 3.6842 | 0.0314 |
| $b_1$ | -0.013 | -0.0014 | -5.89e-6 | -0.2776 | -0.0566 | -0.0010 | -0.0983 | 0.0046 | -5.14e-4 |
| $b_2$ | -0.006 | 0.0187 | 1.142e-5 | -0.0374 | 0.0127 | 7.895e-5 | 0.3255 | 0.0287 | 5.16e-4 |
| $b_{11}$ | -1.16e-4 | -0.0011 | -1.87e-6 | 0.0048 | 0.0015 | 2.042e-5 | -0.0069 | -0.0003 | -3.15e-6 |
| $b_{12}$ | 8.22e-6 | 4.248e-4 | 4.664e-7 | 0.0003 | 0.0001 | -2.51e-6 | -0.0015 | 0.0004 | 3.98e-6 |
| $b_{22}$ | 4.81e-5 | -1.35e-4 | -7.48e-8 | 0.0001 | -0.0001 | -5.03e-7 | -0.0022 | -0.0002 | -3.71e-6 |

After 120 hours of exposure, the elongation is increasing while breaking force is decreasing, which proves a pronounced deterioration of the cellulose-based material. These tendencies correlate to the evolution of the work at break, with similar trend up to 60 hours of hydrothermal treatment (Figs. 1-3). For the *flax* fibres exposed to hydrothermal treatment and radiation, under hydrothermal treatment of the same duration the breaking force decreases when the radiation dose is increasing for the entire 0-25 kGy range of doses.

Studying the elongation, the conclusion is that under a hydrothermal treatment up to 60 hours, the elongation reaches a maximum value when the radiation dose belongs to an exposure to 10-15 kGy and the duration of the hydrothermal treatment is between 30 and 80 hours. For other values of radiation or durations of treatment, the elongation decreases (Figs. 4-6).

When exposing to hydrothermal treatment and radiation the *hemp* fibres the breaking force is continuously decreasing, in the whole gamma-rays exposure domain (0-25 kGy) and at the same duration for the exposure at hydrothermal treatment.

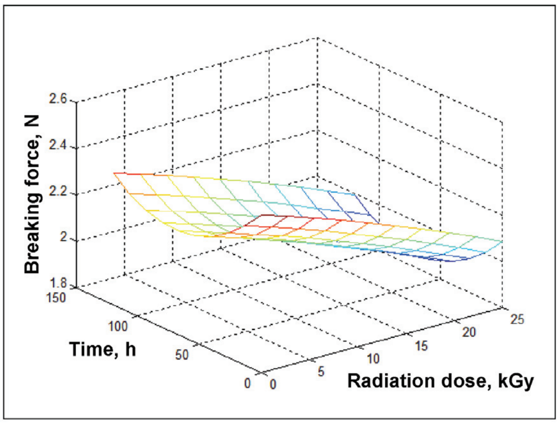


**Fig. 1.** Surface plot for the variation of the breaking force as a function of duration of the hydrothermal treatment and radiation dose in *cotton* samples

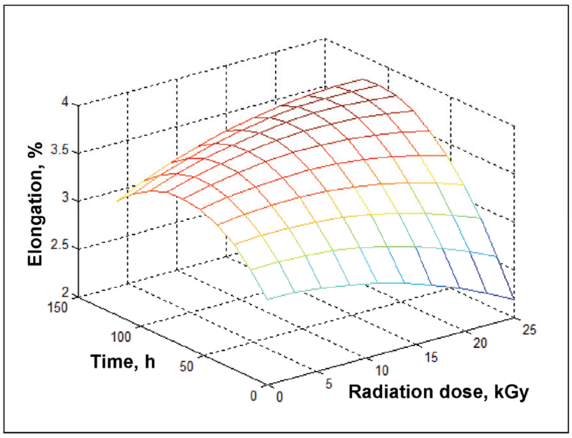


**Fig. 2.** Surface plot for the evolution of the elongation as a function of duration of the hydrothermal treatment and radiation dose in *cotton* samples

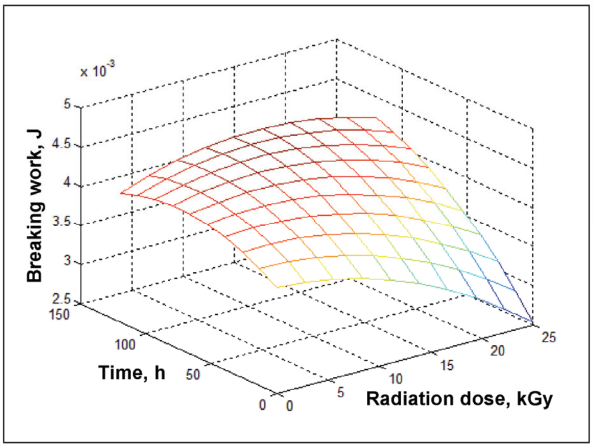


**Fig. 3.** Surface plot for the evolution of the breaking work as a function of duration of the hydrothermal treatment and radiation dose in cotton samples

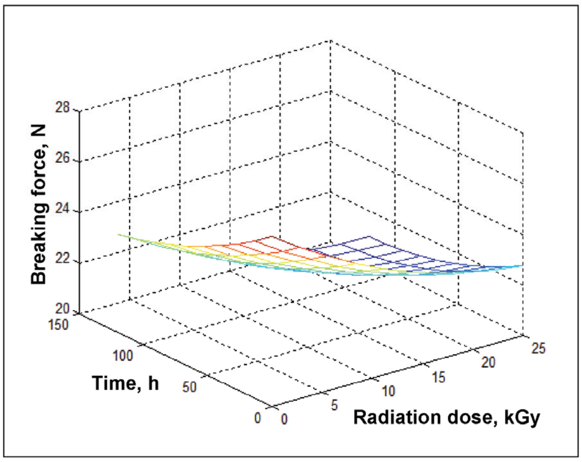


**Fig. 4.** Surface plot for the variation of the breaking force as a function of duration of the hydrothermal treatment and radiation dose in *flax* samples

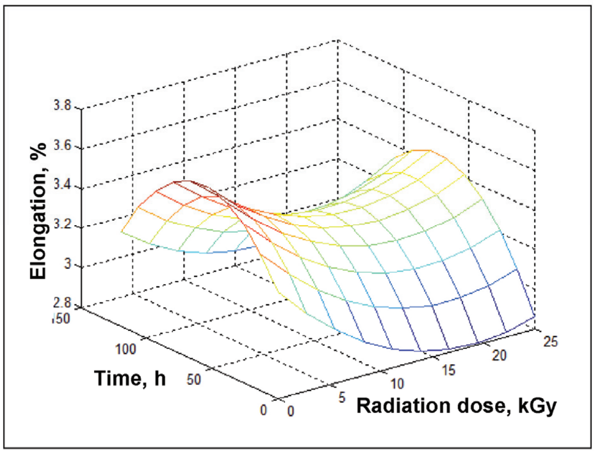


**Fig. 5.** Surface plot for the evolution of the elongation as a function of duration of the hydrothermal treatment and radiation dose in flax samples

The elongation is depicting a maximum gain at around 30–80 hours of hydrothermal exposure for an irradiation dose between 10 and 15 kGy For the overall domain of ionizing radiation or hydrothermal exposure, the elongation seem to be decreasing (Figs. 7-9).

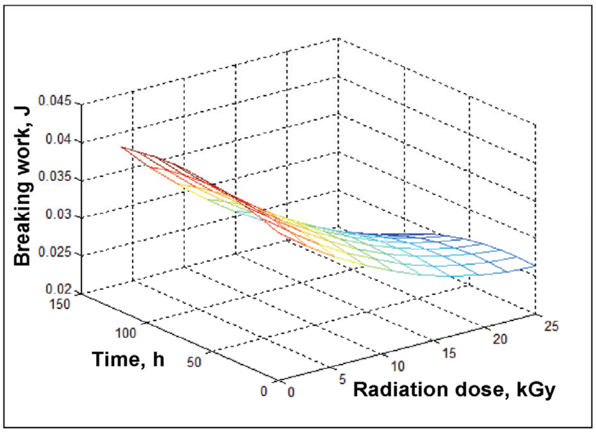


**Fig. 6.** Surface plot for the evolution of the breaking work as a function of duration of the hydrothermal treatment and radiation dose in *flax* samples

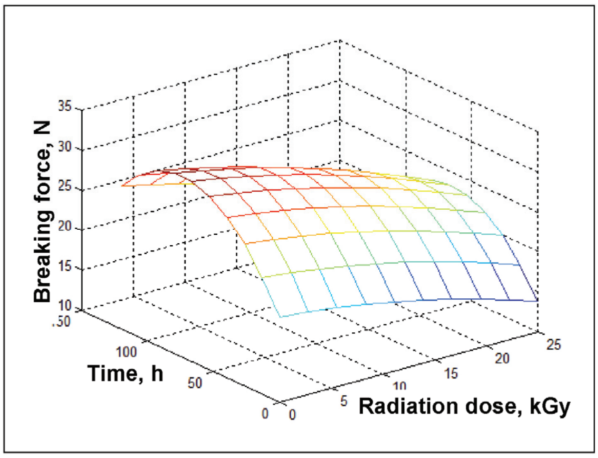


**Fig. 7.** Surface plot for the variation of the breaking force as a function of duration of the hydrothermal treatment and radiation dose in hemp samples

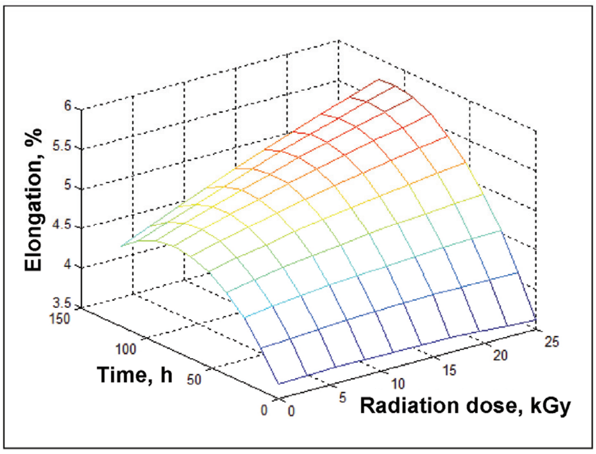


**Fig. 8.** Surface plot for the evolution of the elongation as a function of duration of the hydrothermal treatment and radiation dose in hemp samples

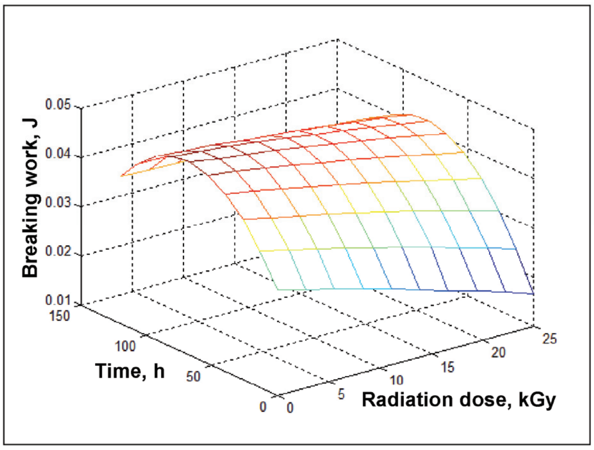


**Fig. 9.** Surface plot for the evolution of the breaking work as a function of duration of the hydrothermal treatment and radiation dose in hemp samples

## 4. Conclusions

Ongoing research performed to assess the impact of gamma-ray treatments on historical materials is essential, in order to determine the lowest possible dose that provides decontamination with minor side effects on the cultural heritage objects, stored in the most appropriate environmental conditions.

According to mechanical tests results on dose-dependency effects, low impact on the tested natural fibres was found at radiation doses below 15 kGy.

Along with experimental data on changes in the physical-chemical properties, the proposed mathematical model may lead to the proper selection of the maximum radiation dose allowed for the treatment in the particular case of historical textile objects.


## Acknowledgements

Part of this work was supported by the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) through the project TEXLECONS, *Improvement of Occupational Environment Quality in Cultural Heritage Deposits. Validation of Gamma Radiation Treatment of Textile and Leather Cultural Goods,* PN-II-PT-PCCA-2011-3-1742, contract no. 213/2012.


## References


ASTM, (2006), *Standard Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing*, ISO/ASTM 51261, Annual Book of ASTM Standards, American Society for Testing and Materials, 970-988, USA, New York.

Geba M., Lisa G., Ursescu C. M., Olaru A., Spiridon I., Leon A. L., Stanculescu I., (2014), Gamma irradiation of protein-based textiles for historical collections decontamination, *Journal of Thermal Analysis and Calorimetry*, **118**, 977-985.

Ionescu C., Sbirna L.S., Mateescu M.D., Moldovan C.S., Sbirna S., (2012), Evaluation of gamma radiation doses in soil using the Monte Carlo simulation, *Environmental Engineering and Management Journal*, **11**, 1355-1361.

ISO, (2000), Sterilization of Medical Devices – General Requirements for Characterization of a Sterilizing Agent and the Development,Validation and Routine Control of a Sterilization Process for Medical Devices, ISO-14937(E), International Organization for Standardization, Geneva, Switzerland.

ISO, (2006a), Sterilization of Health Care Products – Radiation – Part 1: Requirements for the Development, Validation and Routine Control of a Sterilization Process for Medical Products, ISO 11137-1, International Organization for Standardization, Geneva, Switzerland.

ISO, (2006b), Sterilization of Health Care Products – Radiation – Part 2: Establishing the Sterilization Dose, ISO 11137-2, International Organization for Standardization, Geneva, Switzerland.

Katušin-Ražem B., Ražem D., Braun M., (2009), Radiation treatment for the protection and conservation of cultural heritage artefacts in Croatia, *Radiation Physics and Chemistry*, **78**, 729-731.

Kennedy J.F., Hassan W.H.W., Robson M., (2000), The induction and control of biodeterioration of cellulosic materials in worldwide heritage, *Cellulose Chemistry and Technology*, **34**, 253-260.

Machnowski W., Gutarowska B., Perkowski J., Wrzosek H., (2013), Effects of gamma radiation on the mechanical properties of and susceptibility to biodegradation of natural fibers, *Textile Research Journal*, **83**, 44-55.

Măluţan T., (2009), *Analysis*, *Modeling and Synthesis of Processes* (in Romanian), On line at: http://omicron.ch.tuiasi.ro/~thmalu/asmp.htm.

Olaru A., Leon A.L., Geba M., Ursescu C.M., Lisă G., Ciovică S., (2013), Changes in cellulosic materials from heritage textiles during ageing treatments, *European Journal of Science and Theology*, **9**, 179-188.

Panzaru A.E., Malutan T., (2012), Flowthrough acid hydrolysis of rapeseed stalks, *Environmental Engineering and Management Journal,* **11**, 2313-2318.

Takacs E., Wojnarovits L., Borsa J, (1999), Effect of gamma-radiation on cotton-cellulose, *Radiation Physics and Chemistry*, **55**, 663-666.

Van der Sluijs M.H.J., Church J.S., (2013), The effect of quarantine-level gamma radiation on cotton fibre and its subsequent textile processing performance, *Textile Research Journal*, **83**, 197-207.