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## Effect of solar radiation and synergism of the effect of UV radiation, temperature and moisture on the distraction of polymer composite materials in a cold climate

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### Abstract

The influence of solar radiation as a factor of climatic impact on polymer composite materials has not been studied enough. Under the influence of the ultraviolet component of solar radiation, even in cold climates, the surface of materials undergoes destruction and micro-cracking. This destruction is enhanced by capillary condensation of moisture, which at low climatic temperatures increases internal stresses, leading to the formation of microcracks, because of which the strength of polymer composite materials decreases. An algorithm for modelling of polymer composite material aging in cold climates and for identification of significant environmental factors is proposed. Expansion and systematization of experimental data on properties of polymer composite materials exposed to various climatic conditions, including in a cold climate, are anticipated to develop application of extrapolation methods.

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## 1. Introduction

The influence of solar radiation as a factor of climatic impact on polymer composite materials (PCM) has not been studied enough. Collings (1986) argued that solar radiation impacts could be neglected, since its ultraviolet (UV) component penetrates only into a thin surface layer. Indeed, Awaja (2016) found that UV radiation activates reactions of destruction, oxidation, and crosslinking of polymer matrices. In the work of Chin (2007) exposed to natural climatic conditions PCM samples showed alterations of surface color and gloss, liming, spalling, micro-cracking, blistering, removal of polymer resin from the surface without fiber exposure, complete exposure and peeling of fibers and surface layers. Belec (2015) confirmed the destruction of the DGEBA-based epoxy matrix by analysis of photo-oxidation products (amines, ketones, and quinones) in the surface layer of fiberglass (FG) both during exposure under natural tropical conditions and in a climatic chamber equipped with a UV source. No photo-destruction was detected in the inner layers of the FG. Exposure to intense thermal humidity without exposure to ultraviolet radiation did not lead to the destruction of the surface layer in the climatic chamber.

### Nomenclature

$\sigma$	limit strength
$E$	elastic modulus
$k_R$	relative retention rate
CFRP	carbon fiber reinforced polymers
FG	fiber glass
PCM	polymeric composition materials
UV	solar ultraviolet

## 2. Role of UV components of solar radiation and synergistic effects

Kummar (2002) found by the analyzing of the reasons of change in the retention rates of mechanical properties of IM7/997 CFRP, that the destruction of the surface of the samples under the combined action of UV irradiation at 60 °C and saturated water vapor at 50 °C is more intense than with their successive action (synergism). Herein each type of ageing caused a decrease in the strength of the samples cut in the transverse direction, but the maximum loss of limit strength was 29% after UV-moisture cycling. Physical degradation mechanisms resulting from different environmental exposures were monitored by weight loss and/or gain, and by micrographic observations of the composite surface. The CFRP samples lost 0.27% of the weight after 500 hours of UV exposure. The sample weight increased by 0.89% after exposure to humid environment. Humidification after UV exposure showed the similar results (the weight reduction by 0.25% after 500 hours of UV exposure and the weight gain by 0.8% after exposure to humid air). Thermal-humidity cycling with UV exposure showed a small initial growth and weight reduction up to 1.2% after 1000 hours of testing. Microscopy and infrared spectroscopy revealed that the combination of UV and moisture caused the synergistic effects of extensive erosion, leading to micro-cracking of the epoxy matrix, violation of the matrix-fiber boundary, and void formation.

The similar result was obtained by Lu (2016, 2018) in the study of destruction of 6 grades of FG based on vinyl ester and epoxy matrices after exposure to UV radiation in dry and humid climates. Destruction of the FG surface during the cyclic regime was more intense than that under effects of other factors. Destruction products of polymer matrices were removed from the surface of exposed fibers at cycling stages of wetting, and the surface of the samples became more accessible for effects of UV radiation.

Kablov (2017) detected the synergistic effects of temperature, moisture and UV radiation by the change in the mass of the FG and CFRP samples exposed to natural climatic effects. Herein the destruction of polymer matrices was accelerated by superimposed thermal cycles simulating “the take-off-landing” mode of an airplane. Two-year exposure of the materials to effects of moderately warm climates took 470 thermal cycles (an hour-exposure at minus 40 °C and the subsequent one-hour-heating at 100 °C). Precipitation (rain) had significant impacts on PCM

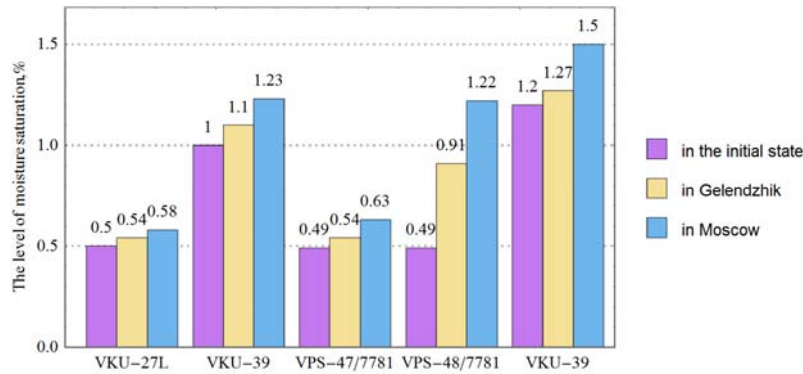


Fig. 1. Water saturation in FG and CFRP in the initial state and after one-year-exposure in Gelendzhik and Moscow.

moisture saturation. Joint effects of solar radiation and thermal cycles increased the number and sizes of surface micro-cracks of the samples, where free and capillary condensed moisture accumulated and was retained during rain. This moisture was removed from the volume of micro-damage during one-hour-heating of the samples at 100 °C, while sizes of micro-damages expanded faster, as compared with those not affected by thermal cycles.

The increased moisture content in volume of five types of PCM after one year of exposure in Gelendzhik and Moscow that was obtained by Slavin (2018) could explain a combination of surface layer destruction, variable humidity, precipitation, and climatic thermal cycles (Fig. 1). Herein the destruction of the surface layer which depth is proportional to the dose of solar UV radiation during exposure was observed in all the five types of PCM. According to the data of a microscopic 3D analysis, an average range of heterogeneities on the PCM surface under climatic impacts increased from 10 to 30%, revealing a higher degree of destruction in Gelendzhik, as compared with that in Moscow. However, the moisture content of the FG and CFRP samples exposed in Moscow was 7–34% more than that of the samples exposed in Gelendzhik. Such a phenomenon was due to effects of low temperature thermal cycles (air temperature in Moscow decreased below zero °C 46 times in a year). Higher levels of internal stresses occurred, increasing micro-defects and the sorption capacity of moisture-saturated PCM samples under low-temperatures.

The similar result was obtained by Starzhenetskaya (1996). Herein three cycles (water absorption at 20 °C and drying at 60 °C) resulted in the increased maximal water absorption from 3.7 to 4.6% in the Organit 7TL OP and from 1.4 to 1.7% in the KMU-3 CFRP. Inclusion of the cycles “cooling (–60 °C) and heating (+60 °C)” into those modes increased the water content of OP up to 6.5% and that of CFRP up to 17%. Thus, the increase of PCM defectiveness at freezing was proved.

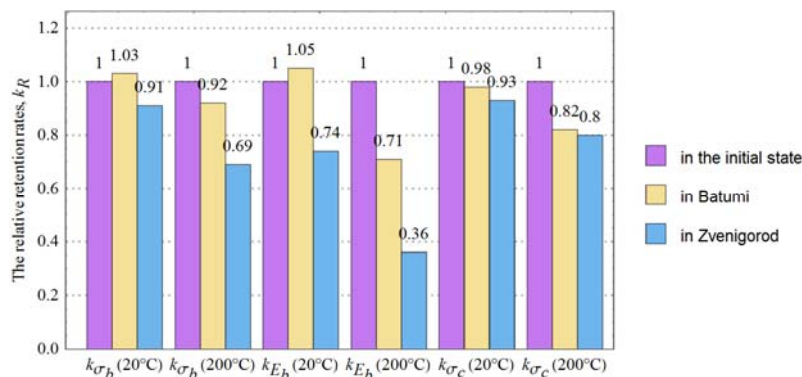


Fig. 2. KMU-1u CFRP retention rates  $k$  after 10-year exposure to natural atmospheric conditions in Batumi and Zvenigorod.

One more example of abnormal alterations of PCM mechanical properties under climatic effects is given in Fig. 2, where  $k_R = R_t / R_0$  of the KMU-1u type of CFRP after 10-year ageing in subtropical Batumi and moderately continental Zvenigorod (in the suburbs of Moscow) are compared by Vapirov (1994). The initial values  $R_0$  in the CFRP sample are bending strength  $\sigma_b = 480/300$  MPa, bending modulus  $E_b = 88/70$  GPa, compressive strength  $\sigma_c = 260/160$  MPa (numerator at 20 °C, denominator at 200 °C). According to data by Kablov (2017), physical and chemical transformations in PCM polymer matrices were more active in warm humid climates, as compared with those in moderately cold climates. However, low winter temperatures in Zvenigorod, on arrival of the Arctic air when the temperature dropped to -25 – -30 °C, affected more significantly damage in the PCM epoxytriphenol matrix, than subtropical temperatures and humidity did during the similar period of tests.

From these modern studies of the mechanisms of PCM aging under various climatic conditions, the dominant mechanism of PCM aging in a cold climate can be distinguished. Namely, the synergism of the effect of temperature, moisture, and solar radiation activates such physicochemical transformations in polymer matrices of PCMs that promote capillary condensation of moisture and subsequently under low climatic temperatures increase internal stresses and form microcracks, which reduce the strength of PCM.

### 3. Modelling of PCM ageing in cold climates

Our analysis has shown that even in cold climates, the surface of PCM is subject to destruction and microcracking under UV effects, increasing the number of sources of internal stresses. Seasonal and daily thermal cycles deteriorate mechanical properties of composites, notably, if freezing water accumulates in their pores and capillaries. Considering this regularity, we can consider possibilities of modelling of PCM ageing in cold climates.

Prediction of  $k_R$  rates applying strictly physical models is likely to be impossible, due to a great number of significant factors of impacts and insufficiently studied effects of synergism of seasonal and daily temperature fluctuations, humidity, and solar radiation. In our opinion, extrapolation methods should be applied to predict PCM mechanical properties.

A model based on the assumption of the linear damage accumulation rule under external effects was proposed to extrapolate results of PCM tests under natural environmental conditions by Bulmanis (1998). According to this approach, tests under natural environmental conditions and accelerated tests were conducted, resulting in identification of ultimate states of the material under study (the maximal degree of hardening, ultimate levels of plasticizing effects, internal stresses, destruction, etc.) with varying modes and duration of ageing. Modelling of mechanical rates of  $R$  via temporal dependence was shown

$$R = \eta(1 - e^{-\lambda t}) - \beta \ln(1 + \chi t) + R_\infty, \quad (1)$$

where  $\eta$  and  $\beta$  are the parameters of materials, defined by accelerated methods in the laboratory,  $\lambda$  and  $\chi$  are the characteristics of materials and the environment. The adequacy of the dependence (1) was verified and confirmed for various sets of experimental data obtained by exposure in various climatic zones.

It is appropriate to expose the PCM under study to various climatic conditions and to model PCM mechanical properties applying the multi linear regression by Startsev (2016) to consider synergy effects with simultaneous impacts of several aggressive factors

$$R_{in} = B_{in0} + \sum_{k=1}^k B_{ink} x_{nk}, \quad (2)$$

where  $R$  is the task response (calculated mechanical rate of PCM),  $x$  is the climatic factors included in the function (1): the air temperature, relative air humidity, temperature of the sample surface, total flux density, and UV component of solar radiation to a horizontal surface and a surface at an angle of 45 degrees to the horizon, pressure, rainfall, wind speed and direction, declination angles, and the height of the Sun above the horizon, measured over a selected period of time  $i$ ;  $n$  is the location and conditions of exposure (open stand, warehouse, canopy in various climatic zones),  $B_{ink}$  is the variable model parameters, the search for which was based on singular decomposition of matrices and ranking of independent variables in the descending order of their impacts on response and exclusion of insignificant variables.

The correlation between the factors  $x$  was estimated via the regression (2), thus facilitating the possibility of identification of factors significantly affecting  $R$  rates. Examples of effective usage of the regression (2) to predict surface temperatures of PCM exposed to natural climatic conditions were given by Startsev (2016, 2017).

#### 4. Conclusions

Exposure of PCM to cold climates reveals weaker processes of plasticization, swelling, hydrolysis, curing, destruction of their polymer matrices under impacts of temperature, humidity, and solar radiation, as compared with those in the tropics and subtropics. The major factor affecting deterioration of PCM properties is a low temperature.

Physical and chemical transformations in PCM polymer matrices activated by temperature, moisture, and solar radiation contribute into capillary condensation of the moisture capable of turning into a solid phase at temperatures below 0 °C and being a source of additional internal stresses that cause new damages and a decrease in the PCM strength.

Modelling of PCM ageing in cold climates is feasible applying methods of extrapolation and quantification of rates of physical and chemical transformations of a binder (destruction, plasticization, post-curing, structural relaxation, and accumulation of microdefects), and deformation and strength indicators of PCM with various combinations of meteorological factors and adjustable levels of temperature, moisture, and UV radiation.

Expansion and systematization of experimental data on properties of PCM exposed to various climatic conditions, including in a cold climate, are anticipated to develop application of extrapolation methods.

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