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A proposal of a new material for greenhouses on the basis of numerical, optical, thermal and mechanical approaches

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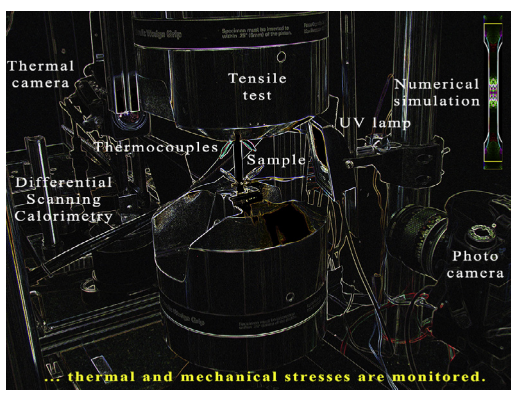
HIGHLIGHTS

- Endothermic events were discovered both in pure and modified HDPE samples.
- A pseudo-static matrix reconstruction algorithm applied to IRT data was used.
- Thermocouples monitored the temperature variation in time during the tensile tests.
- The UV optical transparency in the modified HDPE increased after the tensile test.
- Numerical and experimental temperature variations follow similar trends in time.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of recycled paper in HDPE (High Density PolyEthylene) matrix composites has recently been introduced as an interesting alternative to traditional recycling process for paper. HDPE is also used as double wall greenhouse glazing because panels are easy to install, UV stabilized, and affordable. These type of products must also be strong enough and durable in order to react under tensile loads provided by wind and harsh weather conditions.

An interesting idea may be the insertion via injection moulding of chopped basalt and waste paper – *i.e.*, two natural products – in pure HDPE samples. It completely follows the environmental sustainability concept centred on the triple "*re*", *i.e.*, *re*cycle, *re*use and *re*duce.

The research presented herein starts with a Differential Scanning Calorimetry (DSC) inspection of pure HDPE and HDPE mixed with 5% by weight of waste paper plus 5% by weight of chopped basalt as fillers in order to obtain an insight related to the temperature at which possible thermal events (endothermic or exothermic) occur. The dog-bone samples were also inspected under UV conditions (380 nm) before and after tensile tests. The latter approach was simulated firstly by Comsol Multiphysics® computer program, and secondly recorded in real time via thermographic inspections.

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The temperature variation in a region of interest (ROI) selected at the centre of the samples was mapped in the time during the inspection by infrared thermography (IRT) method using a pseudo-static matrix reconstruction algorithm realized in Matlab® environment. Instead, the combined use of thermocouples aimed at emphasizing the knowledge of the heat transfer in the time due to the mechanical stress applied at the borders of the inspected samples.

The aim was to understand whether modified HDPE can (or cannot) be a valid competitor of pure HDPE for the production of semi-transparent and robust panels.

1. Introduction

Recycling, mainly driven by economic and regulatory factors, is performed to retrieve the material content of used and nonfunctioning products [1]. Materials to be recycled are either brought to a collection center or picked up from the curbside, then sorted, cleaned, and reprocessed into new materials bound for manufacturing. Recycling can also be defined as a process to convert waste materials into new products, to prevent waste of potentially useful materials, to reduce the consumption of fresh raw materials, energy usage, both air and water pollution by diminishing the need for conventional waste disposal, and lower greenhouse gas emissions as compared to plastic production [2]. Recycling is a key component to the recent processes of waste management and is the third component of "*Re*duce, *Re*use and *Re*cycle". Reusing materials minimizes the need for further raw materials and this inherently prevents damage to the environment and deterioration of the natural balance due to consumption of resources, which is rising up in line with increasing population [3]. In this case study, the authors refer to indirect recycling, *i.e.*, the recycling of waste paper and chopped basalt into additional forms of materials other than paperboard and tiles, respectively.

The idea was to maximize the mechanical and thermal performance of double wall greenhouse glazing without deny the passage of the ultraviolet (UV) radiation (*i.e.*, one of the optical properties to be considered) through the material. It can be accomplished via *a priori* knowledge and *a posteriori* destructive (tensile test), non-destructive and numerical simulations making use of cues from previous studies. In particular, the aim of the authors is to improve the current state-of-the-art proposed to the scientific community by eminent research groups, such as *Skozrit* et al. [4], *De Finis* et al. [5], *Hagman* and *Nygårds* [6], *Wang* et al. [7], *Zhifeng* et al. [8], *Torres* et al. [9], *Le Cam* et al. [10], *Terekhina* et al. [11], *Yamashita* et al. [12], *Iziumova* et al. [13], *Harizi* et al. [14], *El Yagoubi* et al. [15], *Montesano* et al. [16], *Murariu and Lozanović Šajic* [17], *Pitarresi* et al. [18], *Lisle* et al. [19], *Majidi* et al. [20], *Romhány* et al. [21], *Bekas* et al. [22], *Koudelka* et al. [23], and *Fernandes* et al. [24].

Considering the above mentioned research works and the semi-transparent nature of the materials under inspection, the present study was implemented by performing reflected and transmitted UV inspections, as well as an in-depth and preventive analysis conducted in Comsol Multiphysics® [25] environment, which was focused on the thermal and mechanical aspects brought to light during the tensile test. In practice, the idea was simulating the mechanical action of the wind, which either elongates or contracts the external structures realized in HDPE, at high velocity. This explains why two thermocouples were introduced along the test samples, above and below the initial point of delamination, and why a thermal camera continuously monitored the elongation phase both of pure HDPE and of modified HDPE. A comparison of the results obtained was done, while the pros and cons of the prospected composite material product were explained.

2. Brief history and main concepts of greenhouses

The idea for greenhouses, and the need for year round crops despite their normal growing season started with the Roman emperor Tiberius, who insisted on having fresh cucumbers at all times. The first true greenhouse, named "the botanical garden", was built in Italy, in the 13th century, to protect many exotic tropical plants explorers brought home from the explorations abroad. Early greenhouse gardeners learned to adjust their methods to the suns natural movements and used southern exposure to ensure the most sunlight and warmth reached their plants. In the 15th century Italian glass makers from Murano, near Venice, came up with a transparent glass, which was soon used to create glass roofs for the orangeries and other early greenhouse structures [26]. This invention changed the history of greenhouses, which were soon after that named "glasshouses" or "conservatories". In the 19th century public conservatories became popular places in which to study plant life and botany. One of the most famous conservatories was the Crystal Palace, built in 1851 in Hyde Park in London, England, to house the Great Exhibition. This enormous cast-iron and glass structure was made of around 84,000 square meters of glass and had full-size mature elm trees growing inside it. The Crystal Palace was an exercise in designing a greenhouse that was strong, durable and simple and fast to build. Towards the end of the 19th century greenhouse became fairly common and many gardeners were experimented with design, heating, ventilation and construction materials. Throughout all the experimenting these gardeners continued to use southern exposure of the glass windows to warm up the greenhouse by the passive solar power just as their predecessors had done. The last century has seen many technological advances that have been used to construct more efficient and cheaper greenhouses, which in turn has made them available to the ordinary gardeners [27]. The invention of large sheets of polyethylene revolutionized the greenhouse construction and today more than 90% of greenhouses are built using poly sheets. Many new materials, like fibreglass, acrylic and polycarbonate panels are also used to make greenhouses more efficient and cheaper. The material proposed herein is also partially eco-friendly.

In practice, a greenhouse is a building that is heated with solar radiation and insulated to prevent loss from convection, conduction and radiation, such that it can stay warm without external heating even during cold days of winter. Such a building is used to grow plants during the winter. Physically speaking, light from the Sun passes through the material of the greenhouse to heat the plants and ground inside. Objects heated by sunlight emit infrared (IR) radiation. The IR radiation emitted is then absorbed or reflected by the material of the roof of the greenhouse which traps the thermal energy inside instead of letting it escape. There is no heat transferred to the outside by air convection. Although the HDPE used for a greenhouse allows visible light and short wavelength IR radiation to pass through it, it does not transmit the longer IR wavelengths. This means the radiation is prevented from escaping, causing a loss of heat. Typically, the material of the greenhouse transmits solar radiation of wavelengths between