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A study of the behavior of bi-oriented PVC exposed to ionizing radiation and its possible use in nuclear applications

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HIGHLIGHTS

- Bi-oriented PVC specimens have been irradiated with γ rays and β particles.
- Up to 100 kGy mechanical properties of bi-oriented PVC are practically unchanged.
- A numerical simulation allows estimating PVC piping minimum lifetime.
- Achieved decontamination factors of PVC piping are satisfactory.
- Results suggest bi-oriented PVC piping is suitable for nuclear applications.

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ABSTRACT

The paper discusses whether bi-oriented PVC, obtained by modifying the structures of polymers chains to enhance the mechanical properties of unplasticized PVC, could successfully replace metallic materials in industrial applications where radioactive fluids are processed and an intense field of ionizing radiation is present. Tests have been carried out in order to study the behavior of a commercial bi-oriented PVC when exposed to ionizing radiations. A numerical simulation allows comparing the effects of radiation expected on the pipe in nuclear industry applications with those resulting from the irradiation tests. Contamination and decontamination tests of bi-oriented PVC in contact with a radioactive solution have been performed too. Results show that the bi-oriented PVC can withstand high β and γ radiation doses (up to 100 kGy) without showing significant degradation in mechanical properties; bi-orientation of polymers chains in the bulk of material is not affected even to much higher doses (250 kGy); the decontamination of the material is satisfactory. The results suggest that tested commercial bi-oriented PVC could be considered in nuclear industry applications.

1. Introduction

In the last years piping made with plastic materials have progressively replaced in many industrial applications metallic piping. Reasons for this replacement include lower costs in production, installation and maintenance and better resistance to chemical corrosion. In addition, underground piping networks made with plastic materials do not require cathodic protection or the use of other techniques to control the corrosion over the entire piping lifetime.

With respect to metallic materials, the major limitation for a wide use of plastic materials in industrial applications is related to low temperatures and pressure that these materials can withstand. However, typical applications of plastic piping extend to systems processing fluids at low temperature and pressure, and include firewater networks, sewer networks for collecting oily and contaminated waste water, process systems of corrosive fluids.

Among plastic materials, Polyvinyl Chloride (PVC) is by far the most widely used in industrial applications: in the last years the attention of PVC producers has focused on processes that, by the modification of the structure of polymers chains, aim at the enhancement of the mechanical properties thus allowing to broaden the field of possible applications. In the family of the

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modified PVC's, one of the most promising materials is represented by the so called bi-oriented PVC that, due to its peculiar orientation of the polymer chains in the bulk material, has a yield stress more than twice than unplasticized PVC, is less fragile and better withstands to shocks, thus overcoming the most common drawbacks that limit the use of PVC in many industrial applications.

It is worth questioning whether the enhanced mechanical properties of commercial bi-oriented PVC are affected when the material is exposed to ionizing radiation: this information is important to assess whether this material could be successfully employed as a possible replacement of metallic materials also in industrial applications where radioactive fluids are processed and ionizing radiation is present. In order to provide a first answer to this question, an experimental campaign was conducted with the aim of assessing the behavior of a commercial bi-oriented PVC when exposed to an intense field of β and γ ionizing radiation. In addition, preliminary contamination and decontamination tests of bi-oriented PVC in contact with a radioactive solution have been carried out. Our aims are to point out the possible applicability of PVC-BI in nuclear industry neglecting a deep insight into molecular alteration in order to focusing on the macroscopic behaviors.

1.1. The bi-oriented PVC

Polyvinyl Chloride (PVC) is a thermoplastic material that has been used since many decades for a wide numbers of applications. Approximately one half of the world's polyvinyl chloride resin manufactured annually is used for producing pipes and fittings for municipal and industrial applications (Rahman, 2007). Its light weight, low cost, good chemical resistance to corrosion and workability make it very attractive. With a chlorine content of 57%, PVC is much less dependent on the limited supply of gas and oil than other polymer products. Since the 70's the attention of PVC producers has focused on overcoming the major limits of the product, like fragility, low resistance to shocks and low crack propagation resistance. One interesting solution is the bimolecular orientation of PVC material. Bimolecular orientation is a process whereby, by applying mechanical deformation to a pipe previously extruded, a substantial modification of its mechanical properties is produced: mainly an increase of the allowable tensile strength, a better resistance to impacts, an improvement to creep, a better resistance to crack propagation, an increase of the Young module (Chauffoureaux, 1981). Orientation is achieved by drawing or stretching the PVC pipe previously extruded, under appropriate temperature and deformation speed conditions, so that a strain (deviation from originally formed dimensions) is induced in the bulk of the material to produce an alignment of the molecules in the direction of strain. After the orientation process, the pipe is cooled down quickly to ambient temperature. A number of patents have been development to produce Bi-Oriented PVC pipes. The pipes for the study were provided by GDS-SIRCI, Italian leader in the field of plastic materials pipes for building and industry applications. Bi-oriented pipes are produced with an innovative system that stretches and orients PVC pipe with air instead of water. This method was introduced in 2008 by Molecor, a Spanish technology development Company. The bi-orientation process is very sensitive to high temperature. If bi-oriented PVC is re-heated at a temperature greater than the glass transition temperature ($\approx 80\ ^{\circ}$C), the bulk material completely looses the bi-orientation and returns to the original shape it had before the orientation process took place, i.e., its thickness approximately doubles, and its diameter halves. This phenomenon is known as ‘reverse’ and it is particularly critical since for a pipe it implies, along with unacceptable dimensional changes, the complete loss of enhanced mechanical properties. The bi-oriented PVC-U pipes for the experimental irradiation tests were produced in GDS-SIRCI Plant, Levate (BG) in Italy. Table 1 shows the pipe's formulation with concentration in phr (parts per hundred resin) and the trade name of each material.

Table 1
Bi-oriented PVC composition used for the tests.

Material	phr (parts per hundred resin)	Trade name
PVC	100	Ineos chlorvinyls – Norvinyl S6806
Organic stabilizer	3.2	Reagens-Reapak G-TU/1068
Calcium Carbonate	3	Nicem-Carb BCM 20
Pigment	0.8	Chimar-White CP r 31/08

The axial orientation coefficient λ_a, defined as the ratio of the lengths of PVC-Bi pipes and the pre-formed pipes,. is approximately 1.0 whereas the tangential orientation coefficient λ_t approaches 1.8 and is defined as:

$$\lambda_t = \frac{D1 - e1}{D2 - e2}$$

where $D1$ and $D2$ represent the mean external diameter of PVC-Bi pipes and pre-formed pipes respectively, $e1$ and $e2$ are the mean thickness of PVC-Bi and pre-form pipes. The preform pipes have a nominal diameter of 77.6 mm and nominal thickness of 7.6 mm, so the pipes after the stretch of 1.8 have a diameter of 140.1 mm and a nominal thickness of 3.9 mm, in accordance to ISO 16422 for Pressure Class 16. The preform pipes are extruded with an Argos 93 Cincinnati Battlefield extruder; the molecular orientation is achieved by applying Molecor Tecnologia patent's process conditions.

2. Experimental procedure

2.1. Numerical simulation

In view of the possible application of bi-oriented PVC in nuclear plants, a preliminary numerical simulation was carried out. The objective of the simulation was to assess the dose on the pipe wall due to the contact, over a specified time period, with a stream containing radioactive nuclides, with a specified concentration. In such a way it is possible to compare the effects that are expected in a possible industrial application, when the pipe, during its entire lifetime, conveys radioactive fluids, with those resulting from the irradiation tests that have been experimentally carried out.

The first assumption is that the pipe shall be used to convey streams containing β and γ sources. Then, it is assumed that the pipe is completely filled with an aqueous solution containing β and γ emitters homogeneously distributed.

For sake of simplicity, two different mono-energetic β and γ sources, having respectively energy equal to 174 keV and 661 keV, have been considered. These values correspond respectively to the average energy of the β particle and the characteristic energy of γ radiation emitted during the decay of Cs-137 that for its long half-life is assumed as the dominant radioactive contaminant that most likely could be contained in radioactive liquid waste streams in many industrial applications.

As a first step, the range of β particles in water has been assessed by means of the following empirical formula (L'Annunziata, 2003):

$$R_{max} = 0.11\left(\sqrt{1 + 22,4E^2} - 1\right)$$

where E (MeV) is the end-point energy β decay, and R_{max} (cm) is the range of β particles. With E equal to 0.512 MeV (end-point energy of