THERMOPLASTIC COMPOSITE MATERIALS FOR HIGH VOLTAGE INSULATOR APPLICATIONS

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Abstract

Thermoplastic composites represent a promising class of materials for high voltage insulator applications due to their potential for high production speeds, volatile organic compound (VOC) free processing and recyclability compared to state of the of art glass fibre-reinforced epoxy-based insulators. In order to determine the most suitable thermoplastic composite material for glass fibre reinforced insulators, polypropylene (PP), polyamide 12 (PA12), polycarbonate (PC), polyethylenterephthalat (PET) and polyetherimid (PEI) have been evaluated as matrix materials. The dielectric properties, porosity and thermal breakdown behaviour of the materials were investigated according to the International Electrical Commission (IEC) testing procedures. The results indicated that PET is the most suitable of the considered commingled thermoplastic candidate materials for insulator applications. PEI performed better than the epoxy reference in terms of thermal degradation but failed to meet the standards in other aspects such as porosity. This study also showed the correlation between material properties such as porosity and electrical breakdown strength and highlighted the importance of processing conditions to obtain the best performing material.

1. Introduction

With energy demand increasing worldwide, the technology to ensure efficient power transport is moving towards ultra-high voltages (UHV). This necessitates the development of manufacturing techniques to produce insulators with increased length and cross-sections. A composite insulator consists of a fibre-reinforced rod that carries the mechanical loads, a silicone housing that protects the rod against the environment and metallic end fittings, which connect the insulator mechanically to the electrical conductor and tower [1]. Today, thermoset pultrusion using glass fibre and epoxy resin is the state of the art manufacturing technology for reinforcing rods. However, the large diameter rods required to carry higher voltages makes utilizing current technology difficult due to the exothermic behaviour of thermoset resins leading to defects initiated by thermo-mechanical stresses [2]. To overcome the challenges associated with thermoset pultrusion, the viability of non-reactive thermoplastic composites as insulator rod materials are being evaluated.

Thermoplastic composite pultrusion is expected to reduce the potential for defects caused by exothermic reactions of large cross sections using thermoset resins [3], whilst increasing the production speed [4]. Thermoplastic composites also offer the benefits of being weldable, reformable and recyclable. In addition, the high fracture toughness of thermoplastics is advantageous in insulator applications, due to their need to withstand high impact and seismic loads. On the other hand, because of the high viscosity of thermoplastic materials and therefore difficulty to impregnate reinforcing fibres, traditional pultrusion based on fibre bath or injection technology is not suitable for the production of thermoplastic profiles with large cross sections. Thus, the use of intermediate materials such as commingled yarns are exploited in order to reduce impregnation distance during production. Compared to other intermediate materials like tapes, they require longer processing times at higher pressures to achieve full impregnation due to the inhomogeneous distribution of polymer and glass fibres, but offer a better selection of matrix polymers without the prohibitively high costs of fully impregnated tapes. Polymers typically used for electrical insulation include: polyethylene, fluorocarbons, nylons, polyvinylchloride, polyesters, polystyrenes, and epoxies due to their excellent dielectric properties [5]. Their most common applications are as encapsulants and insulation materials for electric transformers, motors, coils, relays, and electrical cables [6]. In hollow core insulators, polyethylenterephthalat (PET) was reported to be the most promising material due to its good ageing behaviour, followed by polyoxymethylen (POM) and polyetherimide (PEI) as higher performance, but more expensive alternatives [7]. Ethylene vinyl acetate (EVA) is commercially used by TE Connectivity as a high voltage insulation material for railway applications [8]. At presence, no examples of commercialized long rod insulators based on thermoplastic composite rods were found to be available. This work investigates the potential of thermoplastic composites for high voltage insulator applications, using commingled thermoplastic glass fibre yarns as intermediate materials.

2. Materials and methods

2.1. Processing

To determine a suitable thermoplastic material for insulator applications, commercially available thermoplastic polymers have been evaluated based on different properties like acid resistance, dielectric behaviour and thermal stability according to the relevant IEC standards. PEI has been selected showing the highest potential in all fields, but would be difficult to commercialize because of its high price. Of the engineering polymers, PC has been chosen due to its high glass transition temperature (T_g), PA12 for its impact resistance, PET for its good chemical resistance and PP as a lower cost alternative.

The manufacturing of thermoplastic composites to replicate the unidirectional (UD) fibre orientation of a pultruded rod requires a combination of filament winding, pre-consolidation and compression moulding as can be seen in Fig. 1. After being wound onto a frame using a filament winder, the fibres are dried and heated just over melt temperature in an oven as a preconsolidation step. This allows for their relative ease in handling for placement in a rectangular-shaped closed mould such to maintain their orientation. In the final compression moulding step, the stack of UD-fibres is heated at a rate of 4K/min, while being simultaneously compressed at a rate of 0.5 bar/min up to 30 bar and then held for 90 minutes at the processing temperatures shown in table 1. The temperatures are chosen as high as possible to minimize viscosity while preventing degradation. The manufactured sample plates with a size of 200x80x20mm are then air cooled at the same pressure to room temperature with 2K/min and cut into the sample geometries specified for the individual IEC tests.

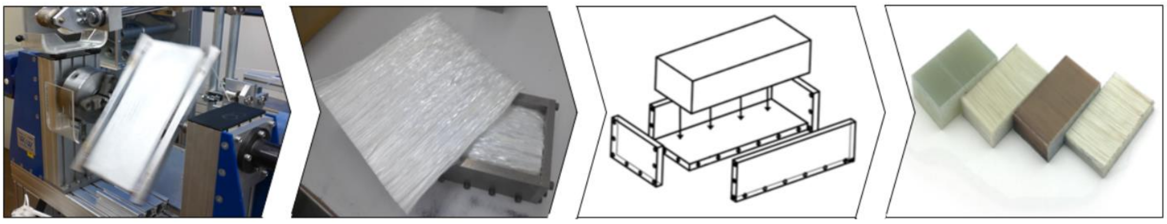

Figure 1. Processing steps of sample manufacturing.

Table 1. Material properties of the investigated polymers.

	PP	*PA12*	*PC*	*PET*	*PEI*
Processing Temperature (°C)	200	220	250	260	350
Glass Transition Temperature (°C)	-10	50	150	76	210
Melt flow index (g/10min)	75	30	32	n.a.	19
Degradation Temperature (°C) (N_2 atmosphere)	260	350	380	370	480

2.2. Testing

In order to effectively develop composite core materials for insulator applications, the following tests from the International Electrotechnical Commission (IEC) are considered:

2.2.1. Dye penetration test (IEC 62217)

To assure good insulation properties of unidirectional composites, the material should be void free to prevent ingress of moisture and humidity that can lead to electrical breakdown due to formation of conductive channels. The dye penetration test incorporates a low viscosity solution composed of 1 % (by weight) Astrazon BR 200 dye and methanol, to infiltrate any channels present in the sample along the fibre through capillary action. The testing specimens are 10 mm long (in fibre direction) and can have variable dimensions in transverse direction to the fibre. They are then placed with the fibre direction being vertical onto a steel grid in a vessel as depicted in Fig. 2. The specimens remain in the dye bath for 15 minutes. Any dye exposure on the top surface of the specimens is indicative that the porosity of the material is too high and thus the material fails the test.

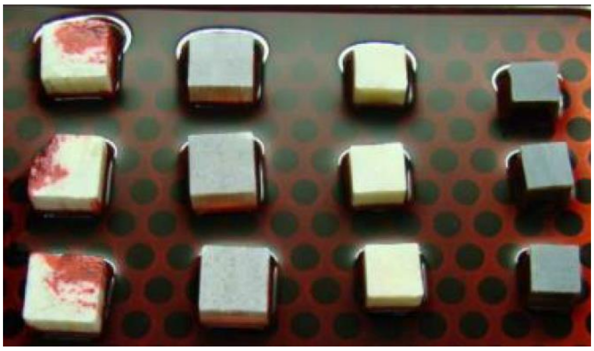

Figure 2. Different UD thermoplastic composite samples showing different degrees of dye penetration.

2.2.2. Water diffusion test (IEC 62217)

The water diffusion test investigates the electrical breakdown strength of the material under conditions mimicking insulators in humid or highly polluted environments. The 30 mm long specimens (in fibre direction) are boiled in a closed, stainless steel vessel for 100 h ± 0,5 h in deionized water with 0,1 % by weight of NaCl. After boiling, the specimens are removed from the vessel and placed in a container with tap water until their temperature reaches ambient conditions. Immediately before the voltage test, the specimens are removed from the container and any liquid on the surface is removed with filter paper. Each specimen is then put between two electrodes as seen in Fig. 3. The test voltage is increased at approximately 1 kV per second up to 12 kV. The voltage is kept constant at 12 kV for 1 minute and then decreased to 0 kV at the same rate. During the test, no puncture or surface flashover shall occur. The current during the whole test shall not exceed 1 mA (r.m.s.).

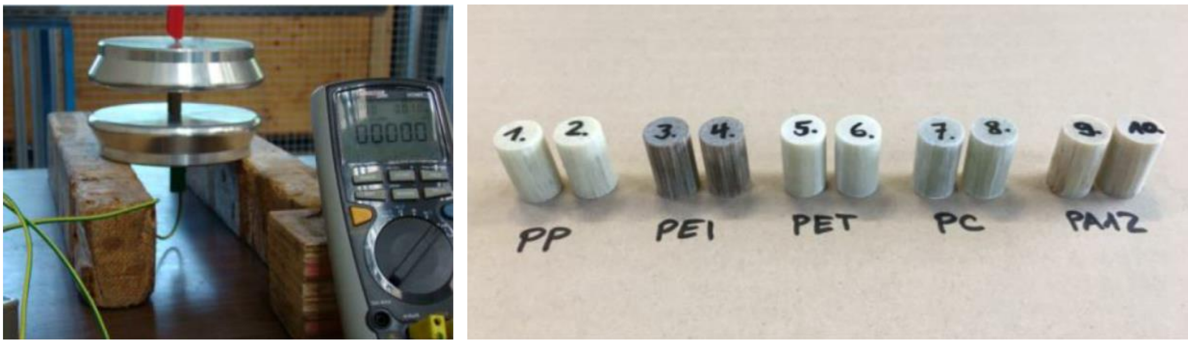

Figure 3. Voltage test set up (left) and 30 mm long Ø20 mm water diffusion test samples (right).

2.2.3. HL-test (High voltage low current arc resistance test, IEC 61621)

The HL-test imposes an electrical arc on the surface which is indicative of the resistance of the composite material against erosion and degradation. The specimens are flat thermoplastic composite plates with dimensions of 30x100x3 mm onto whose surface two tungsten electrodes are placed at a distance of 6.35 mm as depicted in Fig. 4. The arc occurs intermittently between those two electrodes until the material degrades and becomes conductive. The tests are performed at a voltage of 12,5 kV in both the longitudinal and transverse direction to the fibre. The severity of the test is increased by successively raising the duration of the arc from 1/8 s to continuous operation, while also increasing the current in 10 mA steps form 10 mA to 40mA. The time until the arc disappears and the material becomes conductive is indicative of the quality of the material for composite insulator application. Housing materials directly exposed to the environment should resist a minimum of 180 s to be qualified as a suitable housing material and should not show any flames or other signs of self-combustion. Since rod materials are embedded inside the housing material, no minimum requirement is given. Therefore, test results of the state of the art rod materials are applied as reference.

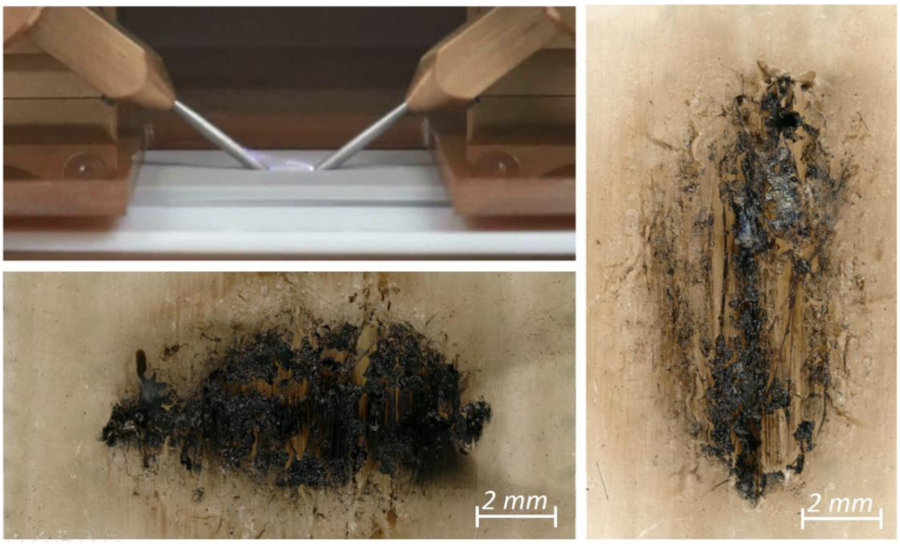

Figure 4. Experimental HL- test set up with two arcing electrodes (top left), PA12 samples after the HL test in fibre direction (right) and transverse fibre direction (left).

3. Results & Discussion

The optical micrographs of the compression moulded commingled yarn materials showed fibre volume contents ranging from 0.3% for PP to 0.9% for PEI which are well within the range of the thermoset material at 0.7%. The micrographs of the thermoset reference material and the compression moulded PA 12 composite can be seen in Fig. 5. Note that the smaller dark spots are the result of shattered glass fibres caused by the polishing process and do not constitute actual voids. It can be appreciated that the fibre volume content of the investigated thermoplastic composites is between 50 and 54 % compared to 60 % of the thermoset reference. The performance of the individual thermoplastic polymers according to the IEC testing procedures is presented in this section.

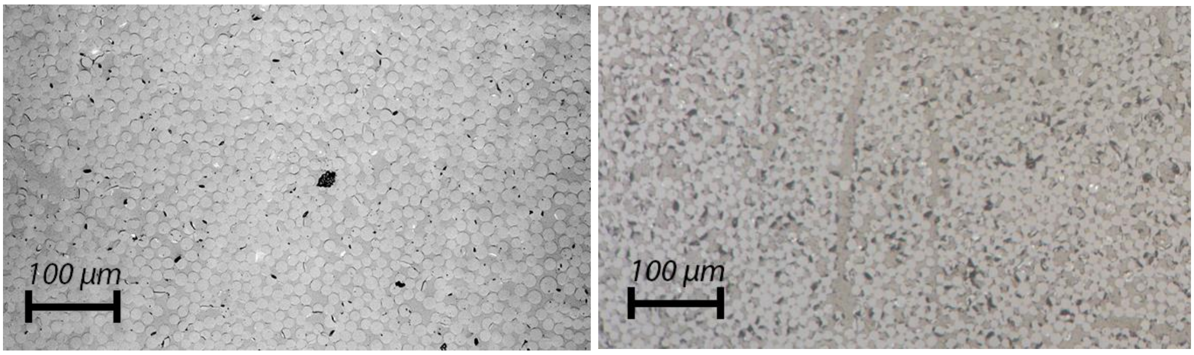

Fig. 5: Micrographs of thermoset EP reference rod material (left) with 0.7% voids, and thermoplastic PA12 material (right) with 0.8% voids.

3.1. Dye penetration test

The dye penetration behaviour of the consolidated materials is illustrated in Fig. 6. The increased concentration of surficial dye present is indicative of the longitudinal porosity present in the materials. PET shows no signs of dye penetration while PC, PA12 and PEI show evenly distributed porosities over the whole surface of the sample. PP shows minimal dye penetration except one large defect, which only appeared on one sample situated close to the border of the plate where the matrix pressure is lower during processing.

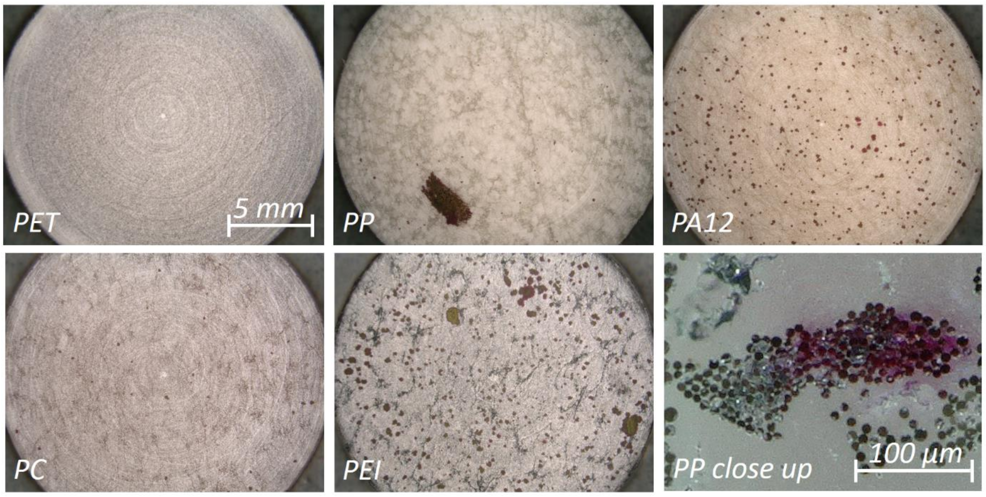

Figure 6. Dye penetration analysis of: PET, PP, PA12, PC, PEI.

The equal distribution of the spots on all samples as well as their size are indicative that cracks related to thermal stresses or machining can be eliminated as the source of the dye penetration. Also hollow glass fibres can be excluded as the spot pattern would be identical for the materials coming from the same supplier and using the same glass fibre type, which is not the case. Through micrographs, the areas showing dye penetration could be identified as partially impregnated glass fibre bundles as can be seen for the PP material in the magnified view of Fig. 5. Those areas were not detected prior to the dye penetration through micrographs during the void determination as they are very localized and not clearly distinguishable from fully impregnated fibre bundles due to their elevated local fibre volume content. These fibre agglomerations originate from inhomogeneities in the commingling quality of the yarns, where tightly packed glass fibre bundles are not fully impregnated by the thermoplastic resin. The variation in dye penetration behaviour of the investigated materials suggest a correlation to their viscosities at processing temperature as described in table 1. PEI having the highest viscosity is showing the strongest dye penetration, while PC and PA12 show improved behaviour and PP only a few localized signs. As the processing temperatures have been selected just below the degradation temperatures of the polymer to minimize the viscosity, the processing pressure currently limited by the mould to 30 bars could be further increased, to reduce the porosity of the material and therefore improve the dye penetration behaviour of the materials.

3.2. Water diffusion test

The results of the voltage test depicted in Fig. 7 indicate a direct correlation with the results of the dye penetration tests. Porosities detected by the dye penetration constitute a pathway for electrical currents in the presence of a conducting medium. Therefore, high dye penetration values observed for PEI translate into high currents of 800 µA just satisfying the acceptance criteria. PA12 and PC with minor dye penetration show currents around 130 µA whereas PET with no dye penetration shows comparable values to the thermoset reference. PP fails the water diffusion test at flashover voltages of 10 kV below the limit of 12 kV and is not represented in the diagram. One possible reason could be the high thermal stress exerted through the boiling onto the PP material and matrix fibre interface, having a far lower T_g and melting temperature than the other polymers.

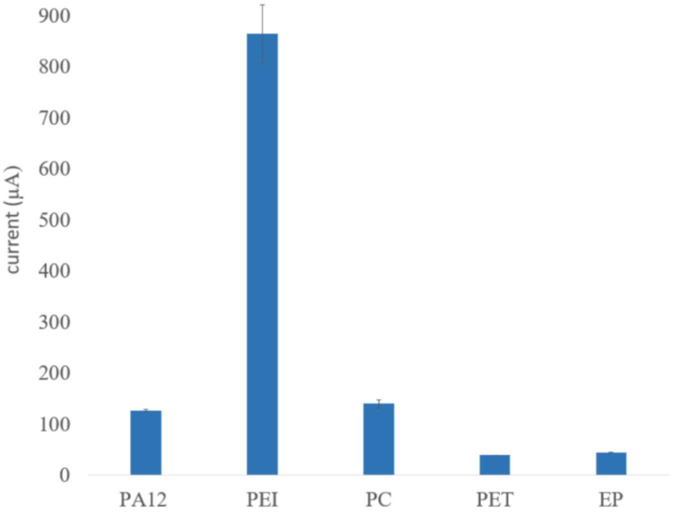

Figure 7. Electrical current at 12 kV constant voltage for 60 seconds of different polymer composite materials.

3.2. HL-Test

The results of the HL-test seem to be closely related to the thermal stability of the polymer, as the material is subjected to extensive heat in proximity of the electrical arc. PP having the lowest degradation temperature according to performed TGA analysis depicted in table 1 offers the least resistance to the high thermal loads caused by the electrical arc as can be seen in Fig. 8. PA12, PC and PET with higher degradation temperatures show an improved performance. This also applies to PEI, that exceeds the epoxy reference while having the highest temperature stability. The different results in fibre and transverse direction of the thermoplastic materials compared to the thermoset can be potentially explained through a lower fibre matrix adhesion of the thermoplastic materials, which has been observed through microscopic analysis of sample surfaces. The thermal and mechanical loads of the electrical arc causes glass fibres to break out of the matrix material and expose the thermoplastic matrix, which has a far lower resistance to the heat of the arc. Also the presence of air between fibre and matrix facilitates the formation of electrical arcs and degradation of the material. As the fibres are held in place at transverse direction, this effect is far less pronounced in the other direction. This effect is also known from investigations on the electrical breakdown of internal interfaces e. g. in cable accessories [9].

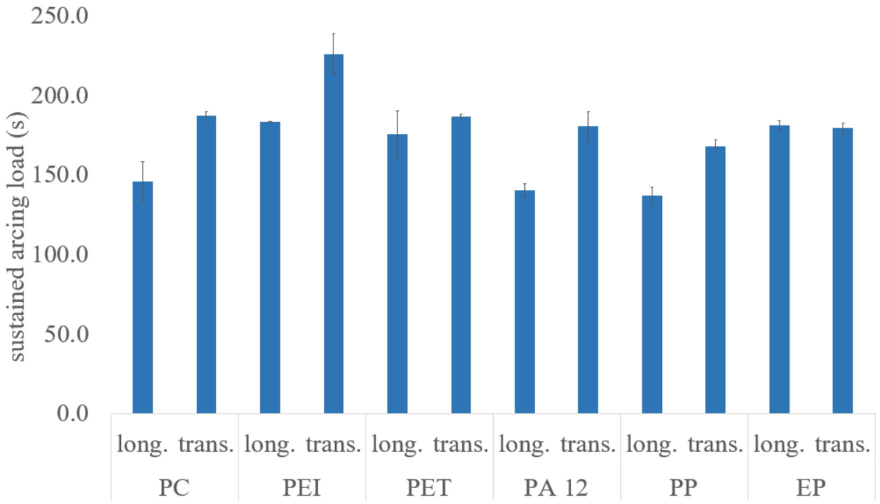

Figure 8. HL-test: Sustained arcing load in seconds before breakdown of the material for different thermoplastic composites compared to the thermoset reference material (Epoxy, EP).

Conclusion:

This investigation demonstrates that thermoplastic composite materials based on commingled yarns show promising results for their use in insulator applications according to IEC standards as can be seen in table 2. The dye penetration test revealed porosities in the PP, PA12, PC and PEI materials due to the combination of inhomogeneous commingling and high viscosity polymers which is currently limiting the performance of the respective polymers and need to be further investigated. The dye penetration behaviour seems to directly influence the performance of the polymers in the water diffusion test where increased porosity promotes conductivity of the material leading to leakage currents.

Table 2. IEC test results for all tested polymers.

	Water diffusion	*Dye penetration*	*HL-test*
PP	Failed	Failed	Passed
PA 12	Passed	Failed	Passed
PC	Passed	Failed	Passed
PET	Passed	Passed	Passed
PEI	Passed	Failed	Passed

The HL-test showed a good performance for all thermoplastic composites and the results suggest this is a relation to the thermal stability of the polymer. PP underperformed all of the other candidates specifically in regards to the voltage test. This is likely due to inferior fibre matrix adhesion in combination with an insufficient thermal stability of the polymer and therefore infiltration of water into the interface. PA12 and PC showed good performances in the water diffusion and HL test while PEI outperformed the reference material. PET shows overall the best results with comparable or better values than the thermoset reference and constitutes the most suitable thermoplastic composite material for insulator applications.

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