High Performance Thermoplastic Cable Insulation Systems

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ABSTRACT

Crosslinked polyethylene (XLPE) has a successful history as a cable insulation material. Nevertheless, its main constraint is a limitation to operate below ~90°C. This limits both continuous, peak and emergency cable ratings and constrains network flexibility. This paper concentrates on the development and assessment of thermoplastic alternatives, which can be actively designed with improved properties and performance. These have particular benefits over XLPE as the upper continuous temperature limits for their operation approach 130°C with correspondingly longer short term maximum temperatures being possible.

INTRODUCTION

Crosslinked polyethylene (XLPE) has been widely used in power cable electrical insulation systems for different electrical transmission and distribution system applications for many years. While crosslinking confers improvements in high temperature thermo-mechanical properties compared with the base low density polyethylene (LDPE), the maximum continuous operating temperature is nevertheless limited to ~90 °C, because the material softens dramatically as the material approaches and goes through the melting transition. This limit impacts both on the continuous, peak and emergency cable ratings and has therefore implications for power network operational flexibility particularly in future energy scenarios heavily influenced by distributed renewables generation and variable load and source storage technologies.

While high density polyethylene (HDPE) has a higher melt temperature than XLPE, giving potential operating temperature headroom, its mechanical and electrical properties are inferior. This programme of work has examined the use of thermoplastic blends, which are actively designed with improved properties and performance, taking advantage of each component's individual properties, and the beneficial effects of blending these components due to the different morphologies achievable.

In this paper we describe the principles underpinning the new and patented thermoplastic insulation systems arising from this work. This will be illustrated in various embodiments involving polyethylene and polypropylene blends. The benefits to the materials properties are presented and the potential implications discussed should these materials be applied to existing networks, particularly with respect to network flexibility in emergency situations.

EXPERIMENTAL

During the course of this work, blend systems were produced and characterised on a laboratory scale. From these options, blends were selected for upscaling to mini-cable production for larger scale trials and characterisation.

Plaque sample preparation

The materials discussed in this paper were as follows:

(i) An HDPE:LDPE blend utilising Dow HDPE 40055E and a non-commercial grade LDPE system.
(ii) A polypropylene blend utilizing the isostatic polypropylene (iPP), Dow H358-02 with various propylene: ethylene copolymer systems from Dow's Versify TM range.

Blended pellets were produced using a laboratory scale extruder, with the appropriate melt temperatures and screw speeds. Typical antioxidants were used in the production of these pellets, at commercially recommended levels. The preparation of these pellets has been reported elsewhere [1-2]. Samples were produced from these pellets as required for the characterisation tests – typically, plaques of varying thickness.

Mini-cable production

Cable samples were manufactured using a 25 mm^2 aluminium conductor, for both PE and PP blends. The cable samples were extruded on a Troester triple extrusion line, with differing operational conditions but with the same conventional structure, of conductor, semi-con, insulation. For comparative purposes, an XLPE reference was produced in the same way – although taking account of the need for additional crosslinking and degassing. The production of these cable samples is also described in more detailed in other published works [1-2].

Characterisation

A number of techniques were used in this work to characterise the plaque and mini-cable samples. Some of these methods are summarised briefly in the paragraphs below and results included in the following section.

Microscopy

Use of optical and scanning electron microscopy (SEM) has proved a powerful tool in the examination of these blends. Visualisation of material morphology gives an early and easy indication of the suitability of the material to this application, through examination of the amount of

phase separation, if any, and the crystal structure of the blend. Surfaces have been etched prior to examination using standard procedures [3-4].

Thermal Analysis

Differential scanning calorimetry (DSC) has been used to determine sample melt temperatures and examine the percentage crystallinity of samples. This has also been applied to prepare samples at known cooling rates to examine the impact of this on the morphology and resulting properties of the materials.

Dynamic mechanical analysis (DMA) has also been used to examine the blends mechanical moduli as a function of temperature.

Thin-film breakdown testing

Pellets were pressed into ~85 µm thick disks at 180 °C. After applying a pressure of 4 ton, the sample was quenched into distilled water and transferred, still in its aluminium foils, into a hot stage. It was then held at 200 °C for 2 min to enable any residual stresses to relax. The samples were finally either quenched immediately or following cooling in the hot stage from 130 °C to 90 °C at the required cooling rate (0.5 ^{o}C min^{-1} to 10 ^{o}C min^{-1} here). When cooling from 200 °C to 130 °C, the minimum instantaneous cooling rate was at least 20 ^{o}C min^{-1}. The foils were removed and the thickness of each disk was measured at each breakdown testing site.

The above samples were then inserted in a specially designed electrical breakdown testing chamber containing Dow Corning 200/20cs silicone fluid. The chamber was in turn placed in an oven, partly immersed in a tray of silicone fluid of sufficient thermal capacity to provide a stable temperature. The electrodes took the form of two vertically opposed ball bearings; these were replaced each time the disk was changed in order to preclude electrode pitting from affecting the data. All quoted temperatures correspond to the measured temperature of the silicone oil. A 50 Hz voltage was applied to the sample with a peak-peak amplitude ramp of 141 V s^{-1} ± 4 % until breakdown. The data were analysed using a two parameter Weibull distribution [5-6]; appropriate parameters were calculated using the maximum likelihood estimation method. Likelihood ratios were used to generate 90 % confidence intervals for the data.

Mini-cable breakdown testing

Ideally, both thin film and mini-cable breakdown testing would have been undertaken using either ac or dc stress. However, this proved doubly impracticable. From the point of view of thin film testing, the dc breakdown strength of these materials is several times higher than the ac strength; a compensatory decrease in sample thickness would lead to prohibitively large uncertainties in the applied field.

Conversely, it was not possible to probe the ac breakdown strength of the mini-cables due to the onset of significant surface discharge activity at ~100 kV. Although this could have been overcome through the use of appropriate terminations, this was not viable given the large number of samples that needed to be tested. Whilst it is admitted that dc breakdowns do not provide a direct comparison to the ac thin film studies [7], this does not negate the value of the dc tests in validating the use of these blends in cables. Room temperature dc testing was performed. For each specimen, five 6 m (± 2%) loops of cable were cut. The conductor was connected to the HVDC supply; a trough of tap water formed the ground electrode. Each of the cable types was divided into two batches, each of five samples. The first batch was tested as removed from the cable drum, while the other was mechanically stressed prior to testing. For this, an extreme procedure was deliberately chosen, that involved wrapping the cable around a mandrel, 120 mm in diameter, for 2 h before removing it and allowing it to relax for >36 h prior to testing. Voltage ramps were applied in a stepwise fashion: 1.75 kV s^{-1} +/- 13% rises followed by 30 s dwells, leading to an overall ramp rate of 370 V s^{-1} +/- 7 %. For safety reasons, it was not possible to apply a voltage greater than 400 kV to the cables. The laboratory temperature throughout the tests remained constant at 14 - 15 °C.

RESULTS

The first part of the programme of work involved identification of the ideal processing conditions for these types of blends, to achieve the morphologies, and therefore targeted electrical and mechanical properties. In addition to this, the materials chosen for use in the blends also required examination for the optimal chemical features, such as ethylene content of copolymer in the PP blends.

Once the ideal blends had been identified and characterised, mini-cable samples were produced. These were tested in comparison with XLPE to identify possible benefits that might be seen in operation.

Information from these tests were fed into the system constraints assessment to identify the real benefits of utilising cables with thermoplastic insulation on the network, in real case studies.

Blend Optimisation

In the production of these materials, two factors were found to have significant impact on the achieved morphologies of the blends, and subsequently their electrical and mechanical performance.

Firstly the cooling rate, which applied to both PE and PP blends. In the knowledge that there exists a temperature window of ~6 ^{o}C for the PE blend within which isothermal

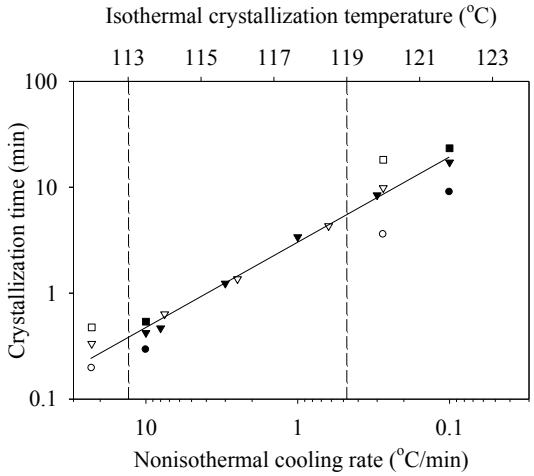

Figure 1: Crystallization time comparison for isothermal (upper abscissa) and non-isothermal (lower abscissa) crystallization for a 20:80 wt% HDPE:LDPE blend. Circles, triangles and squares: 10, 50, 90 % conversion.

crystallization leads to enhanced electrical properties, it was decided to consider the viability of non-isothermal analogues. An initial estimate was obtained by comparing crystallization times for isothermal and non-isothermal crystallization. Samples of the blend, ~5 mg in mass, were analyzed by DSC. Each sample was held at 200 °C for 2 min to erase its thermal history, before being crystallized to completion at a chosen isothermal temperature or subjected to the required non-isothermal temperature profile. The resulting crystallization exotherms were integrated with respect to time and compared in terms of their 10th, 50th and 90th percentiles; these data are summarized in Figure 1.

From this analysis, a non-isothermal cooing rate range window of 0.5 - 10 °C min^{-1} was estimated to correspond to the isothermal temperature window of 113 – 119 °C. However, while this approach serves as a useful initial guide, it is by no means certain that equivalent morphologies form under isothermal and non-isothermal conditions. Pertinent factors include the temperature dependence of nucleation and growth rates [8], lamellar fold surface free energies [9] and possible preordering in the melt [10]. Consequently, it was necessary to confirm that the enhanced ac ramp breakdown strengths obtained following isothermal crystallization are mirrored when samples are crystallized non-isothermally.

The effect of cooling rate on morphology can be seen in Figure 2, which compares SEM images taken of PE blends cooled at different rates (0.1 °C min^{-1} and 10 °C min^{-1}). Both the images show development of a space-filling lamellar texture, suggesting that cooling within this relatively wide range. As such, both the enhanced short term breakdown behaviour and the improved treeing resistance that have previously been associated with the existence of a space-filling lamellar texture

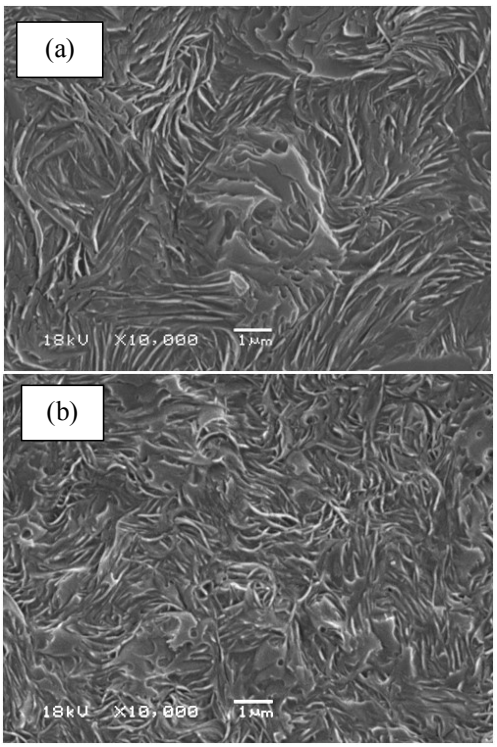

Figure 2: SEM micrograph showing the morphology of the polyethylene blend prepared using a cooling rate of (a) of 0.1 °C min^{-1} and (b) 10 °C min^{-1}.

should be accessible when crystallization occurs anywhere within this two orders of magnitude range provides the required microstructure, assuming that this morphological characteristic is indeed the source of enhanced performance.

This conclusion is further enhanced by the breakdown results obtained from these blend samples, crystallised at different rates. Figure 3 shows the Weibull plots for

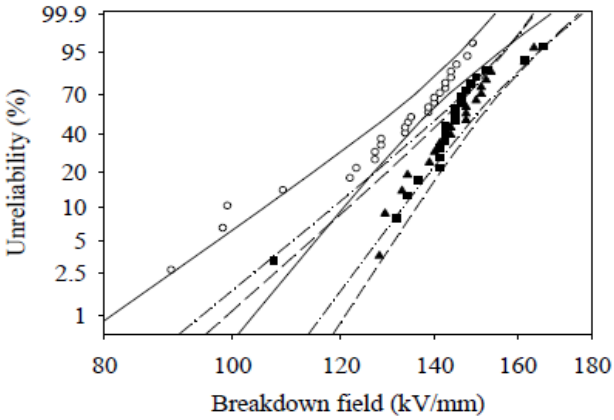

Figure 3. Weibull plots for the chosen blend following quenching (hollow circles,) and non-isothermal crystallization at 10 °C min^{-1} (squares) and 0.5 °C min^{-1} (triangles.). Two-sided 90 % confidence bounds in breakdown strength: dash-dot: 10 °C min^{-1}, long dash: 0.5°C/min, unbroken line: quench.

quenched samples compared with those obtained from samples crystallised 0.5 °C min^{-1} and 10 °C min^{-1} . Since the data for 0.5 °C min^{-1} and 10 °C min^{-1} are indistinguishable from each other, yet distinct from the quenched data, we can infer that the true non-isothermal rate window is at least as wide as that provided by the initial DSC estimate. In fact, the assumption of Weibull behaviour is in this case a conservative one; the significance of the four outliers in the quenched sample is underestimated by the maximum likelihood algorithm, assuming a Weibull background population.

Breakdown testing was undertaken on the PE blend thin film samples as a function of thermal history (quench and 10 °C min^{-1}) and testing temperature. The shape parameter increases with testing temperature. At temperatures up to 64 °C, the data fit well to a Weibull distribution; as far as the confidence bounds are concerned, there is only one outlier. At 97 °C, a different failure mode is suggested based on the 10 °C min^{-1} dataset. However, in short term ramp to failure tests, the Weibull distribution can only provide a statistical indication, rather than a robust discriminator for hypothesis testing of changes in failure mode.

The second factor influencing the blend morphology is observed in the PP blends, where the second component is a propylene/ethylene copolymer. In these blends the ethylene content plays an important role in achieving the required blend morphologies as incompatibilities between blend components can cause detrimental phase separation. This is exemplified in Figure 4, which shows SEM images taken from PP blends containing different copolymer components.

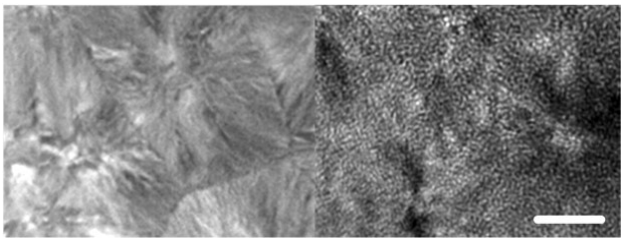

Figure 4. High magnification images showing samples of PP blends, S2200/50 (left) and S2400/50 (right) after isothermal crystallization at 126°C. Scale bar 20 µm.

In the case of the S2200/50 system, relatively slow isothermal crystallization, as occurs at 126°C, results in the formation of a well-defined spherulitic texture, which appears comparable to that of the homopolymer [12]. In contrast, S2400/50 exhibits clear evidence of a superimposed texture that results from phase separation due to a degree of melt phase incompatibility between the two components of the blend. Breakdown testing was performed on the PP blends utilizing different component ratios as well as test temperatures. From these results an optimal composition of 50wt% iPP is apparent for all blends, regardless of test temperature. This composition produces high electrical breakdown strength and good dielectic and mechanical properties. At higher copolymer compositions, the behaviour of the blends is dominated by the electrical characteristics of this component, which is generally poor.

Mini-cable characterisation

Mini-cables have been manufactured using both the PE and successful PP blends. The morphologies of the blends were examined once more for this larger scale extrusion production process as well as examination of the breakdown performance.

In the PE mini-cable, the morphologies of transverse sections were examined. A good bond is observed between the semi-con layer and the insulation. No morphological differences were observed between the inner and outer sections of the insulation, implying that higher heat loss from the top surface due to conduction is not significant compared with the conduction of heat around the cable.

For the PP blend, the cooling rate appears to have been greater at the outside of the cable than adjacent to the conductor and greater still on the upper surface, presumably due to enhanced convective cooling. However, this conclusion is based solely on the uniformity of the morphology, observed by SEM, and consequently must be somewhat tentative, since shear forces acting in the extruder may have served to promote homogenization of the blend.

HVDC breakdown data were obtained from all of the mini-cables produced, with five tests undertaken per cable type.

Table 1. Breakdown voltages for the cables with and without applied bend radii (C indicates did not breakdown)

Cable	Breakdown voltage (kV)				
	Test 1	Test 2	Test 3	Test 4	Test 5
XLPE (no bent radius)	184	168	224	196	196
XLPE (bend radius)	212	196	196	184	212
LDPE (no bend radius)	C	408	352	C	C
LDPE (bend radius)	C	352	C	C	352
PE blend (no bend radius)	C	C	C	C	C
PE blend (bend radius)	C	C	C	C	C
PP blend (no bend radius)	>400	>400	>400	>400	>400
PP blend (bend radius)	>400	396	388	270	>400

Cables were examined after no external stresses (i.e. unbent) and after a bend radius had been applied. HVDC breakdown data are listed in Table 1. The following conclusions can safely be drawn from the results. First, the non-crosslinked cables outperform the crosslinked reference cable. Second, none of the cables based upon the PE blend failed. Third, the data suggests that applying the artificial bend radius does not lower the breakdown strength dramatically. Finally, the PP blend cables outperformed the XLPE reference, despite the non-optimal use of an ethylene based semi-con.

SYSTEM CONSTRAINT STUDIES

Ratings study work was carried out by Southampton Cable Ratings Group as a part of this program of work. The primary objective was to quantify the rating enhancements as well as the impact on the surrounding environment by operating a cable circuit at 120 °C and 150 °C at its core. Three deployment schemes were studied as part of this project – Directly Buried Cables, Direct Buried Cables with Water Cooling and Cables in Tunnels.

The outcomes of the work suggested that by running the cable core higher than 90 °C, higher continuous rating can be achieved for Directly Buried schemes with and without water cooling, but not for cable systems installed in tunnels due to restrictions imposed on tunnel air temperature. But the main advantage seems to be in the emergency rating capability. For instance, for a Directly Buried scheme, if the new technology cable were operated as a conventional XLPE cable with the same conductor size and its preload restricted to 75%, the 6 h emergency rating at 150 °C could be around 50% higher than that for conventional XLPE. In addition, if the conductor temperature were limited to 120 °C, the 6 h emergency rating of XLPE cable can be extended to 24 h. Similar benefits can be expected from a cable system installed in a tunnel where the 6hr emergency rating is 47% higher than that of a XLPE system installed in tunnel.

A National Grid report, which was part of the development, examined system constraints and potential benefits of new material cables in the existing HVAC electricity transmission network. It provided a good starting point for consideration of the issues and potential benefits of alternative technologies to XLPE. In addition to the potential capital gains and environmental performance, it was recognised that having a cable system that offers much higher short-term ratings could have substantial system operation benefits especially in managing constraints and emergency situations.

CONCLUSIONS

This paper reports on the successful development of thermoplastic cable insulation, from laboratory scale materials to mini-cable test samples. The investigation has resulted in a thorough understanding of both the optimisation of processing conditions and blend component selection leading to optimal morphologies and, subsequently, targeted improvement of electrical breakdown strength.

The experimental outcomes of the work has been fed into theoretical system constraint studies, where network performance benefits can be achieved with regards to the increased flexibility offered to network operators, particularly with regard to increasing emergency ratings.

Acknowledgments

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