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USE OF NANOFILLERS IN HIGH PERFORMANCE OF MV CABLES UNDER FIRE CONDITIONS

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ABSTRACT

Currently, most new specifications of MV flame retardant cables request for a high performance under fire conditions, low smoke production and good mechanical properties. Indeed, this is due to fire safety issues which are increasing its level of demand. This performance is difficult to obtain via traditional technology. The authors present two different achievements of the General Cable group where nanotechnology is used.

The paper describes the most important properties of the oversheath nanotechnology compounds, which make them the most suitable material to use in MV flame retardant cables.

KEYWORDS

Nanofillers, Fire performance, MV cable, HFFR material.

INTRODUCTION

As it is well known, the main feature of the oversheath of a MV cable is to protect the core (including inner screens) from potential outer damages: mechanical shock, humidity diffusion as well as soluble ions which can flow from the earth. Lately, in many cases, MV cables technical requirements ask for higher mechanical properties of the oversheath (1) in order to avoid problems during rough installation conditions (abrasion). Furthermore, the cable shall comply with fire propagation and low smoke emission issues. In this article two real cases are considered where the use of nanotechnology has allowed achieving an optimum design.

The first cable considered (case 1) is a MV cable (rated voltage up to 18/30 kV) used in tunnel applications. Actually there was no previous design because of two issues related to the oversheath that couldn't be properly balanced: flame retardancy and high mechanical properties (tensile strength and elongation at break). The use of these new materials has shown a rather good behaviour. It complies with the requirements of flame propagation test on bunched cables (IEC 60332-3-23 Category B) demonstrating an improved performance (slow combustion and low smoke emission) due to the effect of char formation (fire barrier) produced by the nanofillers combined with good mechanical properties that ensure abrasion resistance.

The second cable (case 2) is, as well, a medium voltage cable (rated voltage up to 18/30 kV) designed for fixed installations such as distribution networks or industrial installations. The new sheathing compound substitutes the previous double-layer design (oversheath and fire barrier) for a single flame retardant oversheath. In the same manner as the former case the high fire performance is achieved by the improvement in fire retardancy but especially by means of the char formation effect. In this case it passed the fire propagation test (IEC 60332-3-24 Cat. C).

CABLE DESIGNS

Some cable prototypes were manufactured in order to carry out the research presented in this paper. The following table shows the basic information and the comparison between the previous designs (case 1 and 2) and the final ones improved using materials with nanofillers (case 1+ and 2+):

	Cross section (mm²)	Rated voltage (kV)	Construction Standard	Over-sheath	Fire Barrier
1	1x240	12/20	UNE 211620-5E (DMZ2 Type)	TPO-01	Yes
2	1x150	12/20	IEC 60502-2 (ST8 Type)	TPR-05	Yes
1+	1x240	12/20	UNE 211620-5E (DMZ2 Type)	TPO-03	Yes
2+	1x150	12/20	IEC 60502-2 (ST8 Type)	TPR-19	Not necessary

Table 1: Basic features of each cable design

It is important to highlight the difference between the oversheath materials in both cases. ST8 type (see IEC 60502-1 Table 18) is considered a "soft" material (low mechanical properties) whereas DMZ2 is more suitable for rough installation conditions. In this case, the cable is subjected to potential damage, cracks, due to abrasion or tear.

ST8 TYPE

ST8 type flame retardant materials are not new, in fact, very well known. The balance between moderate mechanical properties and quantity of fillers (mostly mineral flame retardants) needed to pass the fire tests it's relatively easy to achieve. The main objective of the work presented in this paper (case of study 2) was to develop a high performance material in terms of flammability, HRR, heat of combustion, char formation…good enough to pass the fire tests bearing in mind to:

- Minimise the thickness of oversheath
- Remove the extruded fire barrier
- Reduce the overall diameter

Furthermore, this material can be compounded in-house and extruded at a high velocity.

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DMZ2 TYPE

Developing a good DMZ2 flame retardant material is a real challenge and an outstanding achievement from the point of view of R+D. In this case, the balance between the required mechanical properties (very demanding) and flame retardancy seemed a setback in advance. Moreover, the cable considered had to pass Category B fire propagation test which demands high fire performance (especially for MV cables where the amount of insulation is a serious problem).

TPO-03 is the result of vast amount of work carried out by the research chemists of General Cable. Compared to its former equivalent material (TPO-01), it has a unique performance either under fire conditions or mechanically speaking. Actually, TPO-01 was only developed initially to have very good mechanical behaviour and to pass mainly the flame propagation test on single cable but not to be used in fire tests which demand a high performance such as IEC 60332-3-23 category B. In this sense, it can be considered as a next step in MV FR cables design. The most important properties are highlighted in the following table (for further information see UNE 211620-5E, table annex 7):

	DMZ2 Req.	TPO-03
Mechanical properties before ageing: - Tensile strength (MPa) - Elongation at break (%)	Min 12.5 Min 300	**> 15** **> 400**
Mechanical properties after ageing in air oven (240h – 110ºC): - Elongation at break (%)	Min 300	**> 370**
Mechanical properties on complete cable ageing (168 h – 110ºC) - Elongation at break variation (%)	Max ±25	**< 15**
Pressure at high temperature (6h – 110ºC, K=7) - Penetration value (%)	Max 50	**< 20**
Tear resistance (20ºC) - Resistance value (N/mm)	Min 9	**> 18**

Table 2: Summary of the most outstanding mechanical properties of TPO-03 compared to the standard requirements

MATERIALS

BACKGROUND

Regarding the nanotechnology used, it has been the classical solution (2) of the Montmorillonita (hydrated sodium calcium aluminium magnesium silicate hydroxide $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2\cdot nH_2O$) modified using quaternary ammonium compound combined with classical flame retardants such as magnesium hydroxide.

The polymer-clay nanocomposites contain Montmorillonite clay where the sodium ions have been removed by ion-exchange with various alkyl ammonium salts. This modification renders the usually hydrophilic clay organophilic. The exchange of the long alkyl-ammonium cations into the gallery of the Montmorillonite "separates" the layers. There is a molecular swelling of the Montmorillonite. The so-modified Montmorillonite (organoclay) is more compatible with the polymers than the original filler.

The clay nanocomposites can be synthesised via polymerization of the polymer in the presence of cation exchange Montmorillonite clay (3) or by melt-processing. In the present work the method used is the melt-processing, where the polymers have been mixed with the clay and the fillers in a Buss Kneader machine. The main consequence when using nanocomposites is the formation of a char. This char acts as a physical fire protection which doesn't fall or drip when a flame is applied. As well, it has the function of shielding the polymer against heat flux and reduces the permeability of burnable gases from the polymer degradation to the flame. Its use allows to design cables with a reasonable oversheath thickness (almost no oversizing, which actually means optimizing its cost) while complying with all the requirements.

CONE CALORIMETER DATA ANALYSIS

The analysis of Cone calorimeter curves (ISO 5660) is a powerful tool to assess the performance of these materials in FR cable designing. Although this particular type of data doesn't have always complete correlation with the full scale test, at least provides a first approach and a qualitative comparison between candidates which can be rather useful in the short term. The cone calorimeter data, indicates, for example, the heat release rate, as the main parameter and can be described as the "driving force" of a fire (4).

Apart from Cone calorimeter data, there are other variables that shall be considered. Some of them are important but difficult to quantify, for example, issues concerning the overall complete cable such as the manufacturing process and geometry (construction).

TPO-03 vs TPO-01

Observing the two curves, it is obvious that these two materials are rather different. TPO-01 (without nanocomposites) burns quite fast, almost entirely, in a short period of time with a high HRR peak value whereas TPO-03 is consumed very slowly showing a smooth and regular burning pattern (very low peak). Such differences are then clearly confirmed during the full scale fire test.

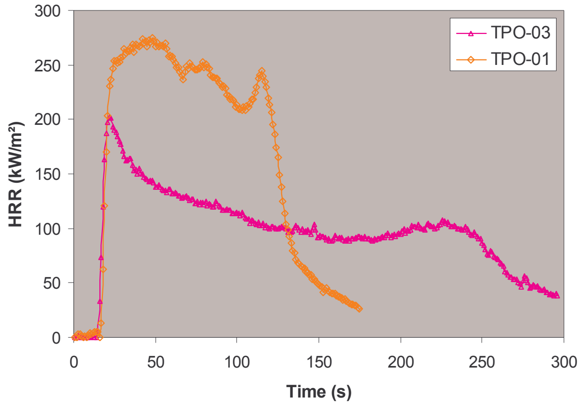

Figure 1: HRR vs time curves (50kW/m²)

for TPO-03 and TPO-01

TPR-19 vs TPR-05

Both curves differ slightly in comparison with the great differences observed in the former case. The pattern is similar. Indeed, these two materials are very close as type of compounds than the two used in case 1 / 1+. However, in the full scale test, the behavior is quite different. This is the reason why a fire barrier must be used underneath in case 2. On the other hand TPR-19 provides enough protection to

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avoid the use of another layer.

Looking at the HRR plots, the main pattern changes can be found in the first half of the graph. Despite that the two HRR peaks are very close in value, TPR-05 burns in a shorter amount of time (first 60 seconds) in comparison withTPR-19 that lasts until 130 seconds. Two peaks are present in both materials. The first one is the initial burning with the formation of the char. Once it is produced, the HRR remains steady (like a “valley”) which means a low combustion. Therefore, it’s clear that TPR-19 has good performance as the char remains for approximately 50-60 seconds whereas in case of TPR-05 the char is destroyed by the fire and the combustion gases in the first 60 seconds showing no “valley” at all.

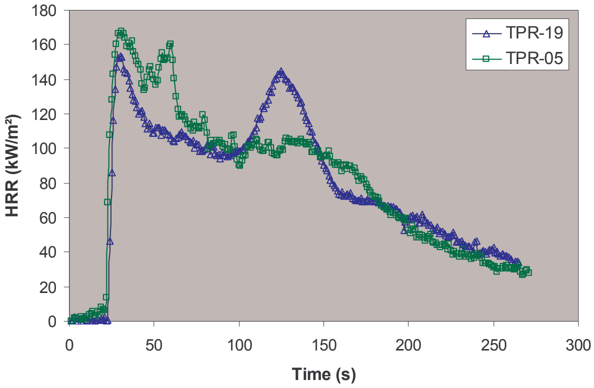

Figure 2: HRR vs time curves (50kW/m²)

for TPR-19 and TPR-05

TESTS

FIRE TESTS

All of them referred to reaction to fire issues. See the following table:

	Standard	Conditions	Requirements
Vertical fire propagation on bunched cables	EN 50266-2-3 (eq. to IEC 60332-3-23)	Category B 3.5 l/m 40 min	Maximum burned length of 2.5 m above the burner line
	EN 50266-2-4 (eq to IEC 60332-3-24)	Category C 1.5 l/m 20 min	
Vertical flame propagation test on single cable	EN 60332-1-2 (eq. to IEC 60332-1)	1 kW burner, time depending on diameter	Max 540 mm and min 50 mm from upper support
Smoke opacity on cables under burning conditions	EN 50268 (eq to IEC 61034)	27m³ chamber, aprox. 40 min	Minimum light transmittance required 60%
Corrosive and acid gas emission	EN 50267-2-1 EN 50267-2-2 (IEC 60754)	Tube furnace and bubbling	pH > 4.3 Conductivity < 10 (µS/mm)

Table 3: Summary of fire tests

Flame propagation test on single cable simulates the beginning of a small fire whereas the fire propagation reproduces the effect of a real fire in a full scale scenario. The cable is attached to the rugs of a standard ladder (maximum width of 300 mm). It’s important to bear in mind that the cable pieces are attached spaced. This is in fact a rather good approach because MV are installed separated on a regular basis in order to increase the current transport capacity as well as to ensure a proper heat evacuation during the heating cycles. In both cases the main parameter measured is the burned length (only charred portion) above the line of the burner.

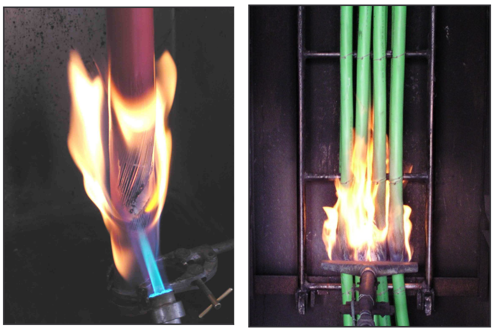

Figure 3: Pictures of flame propagation on single cable (left) and fire propagation (right)

The smoke opacity test is very well known. In this case it doesn’t reproduces the exact installation conditions but it has demonstrated to be very useful to assess how potentially opaque It is used to measure how opaque would be the smoke released during the period when the cables are burning (normally 40 minutes). Clear smoke allows the people evacuating to see the escape routes and the light signals. It’s called the “static smoke measurement”. The loss of light transmittance is the only parameter measured. Normally a value of not less than 60 or 70% (tunnels) is considered to be suitable in terms of fire safety, enough to evacuate people and firemen extinguish the fire. The test is carried out in a 27 cubic meter chamber (3x3x3). See picture below (figure 4).

Figure 4: Picture of the smoke

opacity 27m³ chamber

Typical minimum light transmittance values are: 75-90% for HFFR materials (both thermoplastic and thermosetting versions) and 20-30% for PVC, not suitable for this particular application. The pattern of the transmittance curve is always quite similar with a small drop in a first stage, a steady behaviour in the middle zone and a final sudden drop when the fire source is consumed and the cable extinguishes. See figure 5.

Finally, the measurement of the corrosive and acid gas emission is used to assess the potential damage to the lungs and breathing capability of people when evacuating from a fire. For HFFR materials the two main parameters measured are pH and conductivity (part -2-2 of the standard) and a titration for PVC (part 2). The test is performed on a

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small piece of material which is burned in a tube furnace during 20 minutes with air inlet. The combustion gas released is then bubbled into wash bottles in order to get absorbed in an aqueous solution (see figure 6). Indeed, there's a strong relationship between halogenated materials and the production of obscure smoke.

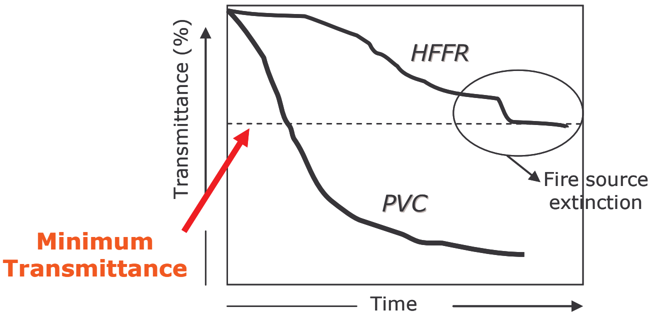

Figure 5: Typical curves for PVC and HFFR materials

Figure 6: Equipment used for corrosive and acid gas emission test

RESULTS

Regarding the fire and smoke tests:

	FLAME TEST	FIRE PROPAGATION TEST		SMOKE OPACITY TEST		
	Burned Length (mm)	Burned length (m)	Self-extinction time (min)	Minimum light tran. (%)	pH	Cond (µS/ mm)
1	140	> 2.50 (Fail)	-	75	7,1	0,22
1+	99	0.53	3	85	5,7	0,32
2	96	0.42	1	86	5,9	0,16
2+	127	0.53	15	82	6,5	0,28

Table 4: Summary of fire test results

FLAME TEST

The slight differences appreciated (40 mm for case 1 and 30 mm for case 2) confirm that the use of nanofillers improves the condition of non-flammability , and therefore, less vertical propagation of the flame. However, the values are quite similar (see Table 4), almost the same for both cases 1 and 2. When considering cables with great overall diameter (for example MV or HV cables) the values are usually very close to each due to the heath absorption capability. The great difference is only appreciated when the oversheath is not a FR material.

FIRE PROPAGATION TEST

Case 1 / 1+

Apart from this data, some remarks shall be taken into consideration concerning the fire propagation test:

- For case 1 first droplets of material appear in minute 3, for case 1+, minute 27 (strong correlation with HRR curves).
- Great differences in the evolution of the flame growth. In case 1+ the burning is steady, low and controlled during the 40 minutes of the test whereas in case 1 there's a sudden change in minute 30. After that the flame grows dramatically. When the test finished the cable is not yet burned (2.0 m) but then it has no capacity of self-extinguishing and it finally burns it all rather fast. See Figure 7.

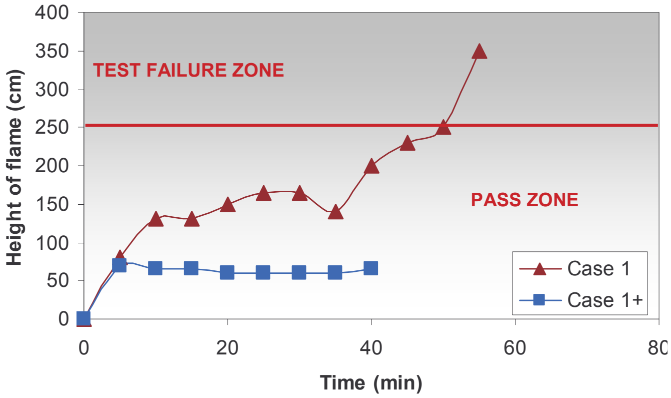

Figure 7: Flame height evolution during the test.

- Almost the same results when looking at the inner chamber temperature profile. This temperature is an average value of 3 thermocouples, one on top of the front door (to measure the heat flux to the front walls due to radiation) and two more positioned at 1.5 and 2.5 m above the ground and behind the ladder. These ones are used to check the fire growth all along the cable surface. See figure 8. The temperature profile of case 1+ is flat and smooth. Case 1 has the first sensible increase (nearly 100ºC) between minutes 15 and 30, afterwards (min 27) the XLPE insulation starts burning accelerating the combustion of the cable. This is the reason why the final part of the profile follows an exponential model from minute 30 until minute 40. At this point there's a sudden drop because the burner is switch off (see Figure 8).

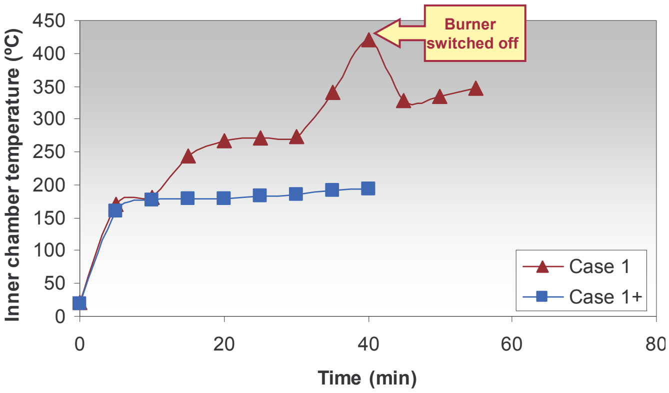

Figure 8: Temperature profile in the chamber.

Case 2 / 2+

The same behaviour was found for both cables during the fire propagation test (see Table 4): small burned length and low combustion. The increase of self-extinguishing time is due to the use of a single layer in case 2+. In fact, 15 minutes is considered a good value in terms of fire safety. This parameter is not a requisite of the standard to conclude whether the cable passes or fails the test.

SMOKE EMISSION TEST

Generally speaking, values for thermoplastic HFFR materials are almost similar for all the types (in a range of 75 up to 90%). Definitely, apart from the material itself, the overall diameter of the cable is, as well, an important parameter. It shall be taken into account because it influences the final result of the smoke test. Indeed, the smaller the diameter the better the result (higher light transmittance). This is to avoid oversizing the thickness of either the oversheath or fire barrier.

The slight difference in light transmittance (10%) between case 1 and 1+ is due to the different burning behaviour of the nanofillers (see Table 4).

ACID AND CORROSIVE GAS EMISSION TEST

Exactly the same as in the former point but in this case there is no strong relationship with design parameters (cable construction). Indeed, it is mostly related to the material itself and its compounds.

OTHER TESTS ON COMPLETE CABLE

For the particular case 1+ (TPO-03) a couple more additional tests were conducted in order to check the material with positive result:

- Abrasion test (20 kg, 8 motions) - *HD 605 part.2.4.22*
- UV resistance - *HD 605 part.2.4.23*

CONCLUSIONS

CASE 1 VS 1+

The improvement of the oversheath material using nanofillers has changed completely the results of the fire propagation test (from fail to pass). Furthermore, TPO-03 provides a controlled, low combustion which guarantees repeatability of results and, indeed, the quality and the safety of the product during its service life.

The optimum design has not yet been achieved but there has been a noticeable reduction of thickness. This implies less overall diameter (4.2%) and less manufacturing cost.

All these positive aspects regarding to fire issues have been achieved without the sacrifice of any of the chemical properties required (mostly referred to mechanical resistance). And what is more important, the new oversheath is mechanically robust (before and after ageing). It has good abrasion and tear resistance and preserves its properties at high temperature too. In fact, this is a way to demonstrate that the cable will withstand rough installation conditions typical of MV cables (buried or even inside a tunnel).

CASE 2 VS 2+

The new material with nanofillers does not have a direct consequence on the result of the test. The former design passed the test as well with a low and smooth combustion. However, the crucial point here is the importance of removing the fire barrier which means reducing the overall diameter (5.4%). This fact involves simplifying the manufacturing process: the use of only one material and only one extruder. Summing up, all these advantages have a direct effect on the cost of the cable. The design and manufacturing of a MV cable that passes IEC 60332-3-24 (category C) with only one FR sheath (and a quite reasonable thickness) shall be considered as a remarkable success.

GENERAL

Both cases presented in this paper widely demonstrate that the use of nanofillers in HFFR thermoplastic oversheath materials allows the achievement of an outstanding fire performance without losing high mechanical properties, providing as well, a cost reduction of the cables concerned.

Regarding fire reaction issues on electrical cables, it is foreseen that nanotechnology will be one of the main solutions in the nearest future.

MISCELLANEOUS

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GLOSSARY

HFFR: Halogen Free Flame Retardants
FR: Flame Retardant
PVC: Polyvinyl chloride
HRR: Heat Release Rate
THR: Total heat released
MV: Medium Voltage
XLPE: Cross linked polyethylene
TPO: Internal denomination of GENERAL CABLE for halogen free flame retardants with high mechanical properties
TPR: Internal denomination of GENERAL CABLE for halogen free flame retardants with low mechanical properties