U.P.B. Sci. Bull., Series C, Vol. 72, Iss. 4, 2010 ISSN 1454-234x

FAN MOTORS SUPPLY CABLES FOR GASES EVACUATION FROM TUNNELS DURING FIRES

Constantin STOICA[1], George MAREŞ[2], Simona PĂSĂREANU[3], Petru V. NOȚINGHER[4]

Deoarece cablurile de alimentare a motoarelor ventilatoarelor din tunelurile de cale ferată trebuie să corespundă unor cerințe de securitate deosebite (funcționare la o temperatură de 400 ^oC şi vibrații cu o frecvență de 0 ÷ 5 Hz timp de 2 h), pentru realizarea acestora s-a propus utilizarea unei izolații multistrat, cu o componentă minerală şi alta polimerică. Pentru estimarea duratei de viață a izolației polimerice (XLPE), în lucrare, s-a propus o metodă simplă şi rapidă bazată pe determinarea energiei de activare şi a unei îmbătrâniri accelerate termice la 155 ^oC a acesteia. Se prezintă, pe larg, modelul de calcul al temperaturii într-un canal de cabluri în cazul unui incendiu şi verificarea rezultatelor numerice obținute. Experimentele efectuate au arătat că, datorită vibrațiilor, în zonele de prindere ale cablurilor pe pereții tunelurilor, mantalele cablurilor trebuie să fie acoperite cu un manşon din țesătură de sticlă impregnat cu Sibralit A.

Since the fan's motors supply cables for railway tunnels must meet high safety standards (working at temperatures around 400 ^oC and vibrations with the frequency of 0 ÷ 5 Hz for 2 hrs), the use of a multi-layer insulation – with a mineral component and a polymeric one – seem to correspond at safety constraints. In order to assess the polymeric insulation (XLPE) lifetime, a simple and rapid method based upon the determination of the activation energy and its accelerated thermal ageing at 155 ^oC was proposed in this paper. Temperature computation model in a special cable canal in presence of fire and the experimental validation of the obtained results are thoroughly presented.

The performed experiments showed that, due to vibrations, cable jackets must be covered with a glass-texture collar impregnated with Sibralit A in the fixing areas onto the tunnel walls.

Keywords: railway tunnels, fire, power cables, XLPE, ageing, Sibralit A

1. Introduction

The catastrophic tunnel fires produced since the year 1999 and a series of accidents in some tunnels in the summer of 2001 triggered extensive discussions

[1] PhD Student, TUC RAIL D-HV Belgian Rail Engineering, Bruxelles, Belgium, email: constantin.stoica@tucrail.be
[2] Researcher., SC Eurotest SA, Bucharest, Romania, email: george.mares@eurotest.ro
[3] MS chem., SC Eurotest SA, Bucharest, Romania, email: simona.pasareanu@eurotest.ro
[4] Prof., Electrical Engineering Faculty, University POLITEHNICA of Bucharest, Romania

and proposals concerning tunnel safety. When a fire occurs in a tunnel, and in absence of sufficient air, large quantities of smoke are generated, filling the vehicles and any space available around them. Unless a strong flow is created and maintained, hot gases and smoke migrate in all directions. If the airflow is weak, the smoke forms a layer along the tunnel ceiling and can flow against the direction of the forced ventilation, interfering with people evacuation.

The ventilation of tunnels is necessary in order to remove pollutants emitted by vehicles and to control smoke in the event of fire. In short tunnels, the airflow induced by the moving vehicles (piston effect) is usually sufficient to drive fresh air in and push polluted air out of the tunnel [1]. However, in long tunnels mechanical ventilation systems, such as jet fans and exhaust shafts are essential in addition to the piston effect to augment the airflow inside the tunnel to keep the level of toxic gases within safety limits [2]. Studies showing how the heat release rates of the fires were affected by the ventilation in tunnels were done by several authors [3-5]. It was found that forced ventilation had a greater enhancing effect on the heat release rates of heavy goods vehicle fires, but had little effect on those of car fires.

It has also been demonstrated that the failure of the ventilation system could lead to the most damaging situation, which could be avoided by using (of) smoke removal equipments. There were cases of fires in tunnels and underground facilities that led to several recommendations to improve the evacuation procedure, ventilation system and warning mechanism for vehicles entering tunnels [6].

The fire smoke can not only reduce the visibility and cause slower evacuation, but toxic gases from the smoke can also be fatal in time. The hazards caused by a fire smoke are more critical in long tunnels that may be densely occupied by vehicles and people at times. The smoke extraction cannot do by a partial transverse ventilation system that might be composed of different numbers of smoke extraction openings [7-8].

Knowledge of heat and smoke development in vehicular tunnels in the case of fire is of crucial importance for the design of ventilation systems, for the achievement of safety, for emergency management and even for training purposes. The main concern is to maintain an escape route with low temperature intensity and safe levels of smoke concentration, because of the impact these factors have on human life. For road tunnels, it is therefore vital to understand fire propagation and to develop ventilation mechanisms to control it; for example, the elements that lead to the formation of a striking stratified layer of hot combustion products which flow in the opposite direction of the ventilation stream [9-12].

Tunnel ventilation can be provided by mechanical systems, by natural means, or even by the so-called traffic-induced piston effect. The type of ventilation installed in a tunnel will depend on variables such as tunnel length, traffic type (one- or two-directional) and traffic density. For short tunnels, for example, experience points to natural ventilation as the preferred mechanism. However, this may not be an appropriate system in the event of fire, when particular conditions will develop. Although mechanical ventilation could be considered as an alternative for critical conditions, blowing smoke can be hazardous if the tunnel is two-directional [9].

In order to avoid fire disasters (like the one from Baku subway in 1995 - where over 300 people died, the one from Viamala Tunel, Switzerland – where 9 persons died- etc), long tunnels must be provided with powerful ventilating fans that will begin to function when the fire occurs and evacuate the produced smoke. The fans are triggered by powerful asynchronous motors which, according to the standards (specific for each domain where the power of the ventilating fans is established) must function for two hours at 400 ^{o}C, temperature that would be produced by a fire with a standard power of 14 MW, inside the tunnel [13,19 - 22].

In this paper, aspects concerning the fabrication and testing of feeding cables of the motors fixed on the ceiling of a railway tunnel (two-directional, for high speed trains) 10 km long are presented. The tunnel was provided with two fan batteries positioned one at 300 m and the other at 500 m from the tunnel end, at both sides of the tunnel entrance. Each battery is formed of 5 groups motor-fan supplied individually at 1 kV, 50 Hz placed on tunnel ceiling at 200 m distance of each other. When a fire occurs in a wagon of the train passing through the

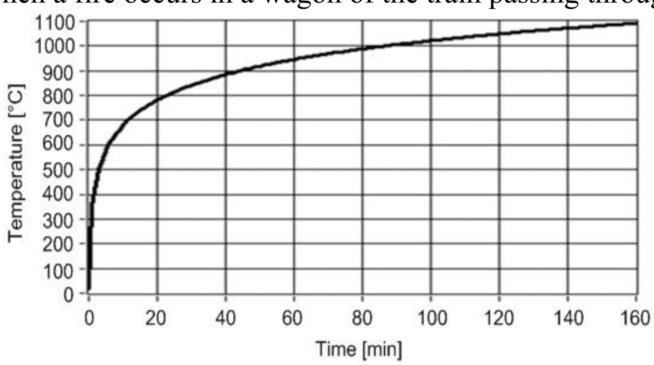

Fig. 1. Normalized ISO curve for temperature increases in testing oven.

tunnel, the railway traffic is stopped, the fans begin to function so that the people in the train are less exposed to smoke and high temperatures and the people are evacuated.

The electric power supplying cables of the engines are arranged in cable channels (positioned near the tunnel walls) made of concrete flags. The cable segments (for cables used at 1000 ^{o}C) from outside of cable channels, sustained with clamps that have been fixed on tunnel walls are subjected to higher thermal stress and vibrations with frequencies between 1÷50 Hz in fire case (the vibration sources are the fans and earthquakes). ISO 834 and NBM 713-020 [20] state that all cables in channels can function 2 hrs at 1000^{o}C. Temperature evolution in fire area is considered to be standard (Fig. 1) [21].

The paper also presents a computation model for the temperature repartition in the tunnel, the choice of a cable structure, the lifetime estimation for the cable insulation and its testing at high temperatures.

2. Temperature computation in cable channels

In order to determine temperature T repartition inside a cable channel - if a fire occurs nearby - it was considered a parallelepiped channel having the dimensions presented in Fig. 2. The slit on the upper side of the channel corresponds to the "actual handling slits" that the used concrete flags present.

Assuming that the channel length is much bigger than the dimensions of the transversal section of the channel, the temperature calculation implies solving – in a two dimensional domain (Fig. 3) – the Fourier equation:

$$\gamma c_p \partial T / \partial t = \mathrm{div}(\lambda \mathrm{grad} T), \quad (1)$$

where γ represents the density, c_p – isobar specific heat and λ - thermal conductivity.

For the concrete flags it is known: the density (2400 kg/m^3), the water content (48 kg/m^3), the convection coefficients for exposed areas (25 W/mK) and unexposed areas (4 W/mK) and the temperature variation in time (for the upper and lateral sides) which is given in Fig. 1 and follows the equation:

$$T(t) = 345 \log_{10}(8t+1) + 20. \quad (2)$$

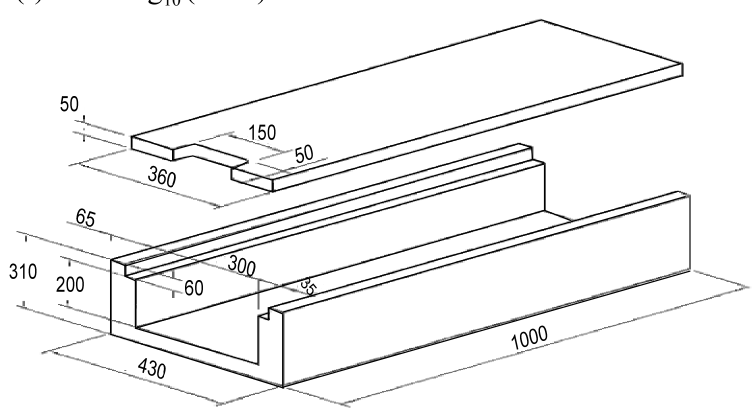

Fig. 2. Geometry of the cable channel

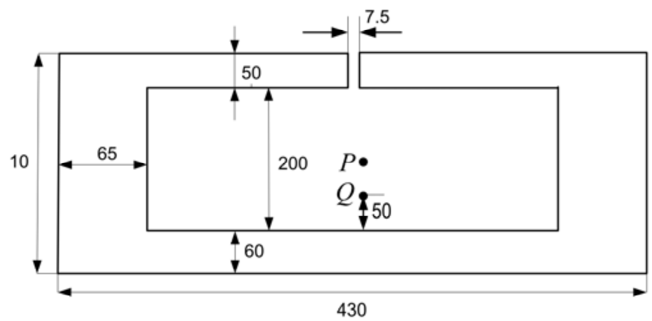

Fig. 3. Two-dimensional model for temperature computation in transversal section of a cable channel

The software used for the temperature computation (SAFIR) was elaborated by Liege University [21]. The time evolution of the temperature in the central point *P* and in a point *Q* (at 50 mm from the canal bottom) corresponding to the cables surfaces (inside the channels) is given in Fig. 4. It can be seen that, after 120 minutes since the thermal stress begun, the calculated value of the temperature in the middle of the computation domain is approximately 530 ^{o}C, and at the cable level is less or equal to 350 ^{o}C. Consequently, the cables set in this tunnel must be able to work for 2 hours in case of fire at least 350^{o}C, when the outside temperature of the cable channel wall is 1000 ^{o}C [23].

In order to verify the numerical results, a parallelepipedic thermal box has been designed and it has been made of concrete panes (similar to the ones used to realize tunnel cable channels) of equal section with the one used for computation and 3 m long. The box has been placed in a thermal testing chamber, and the temperature has been raised to 1000 ^{o}C according to the curve showed in Fig. 1 and, using two thermocouples, the temperature has been measured in the box center (corresponding to the point *P*, Fig. 3).

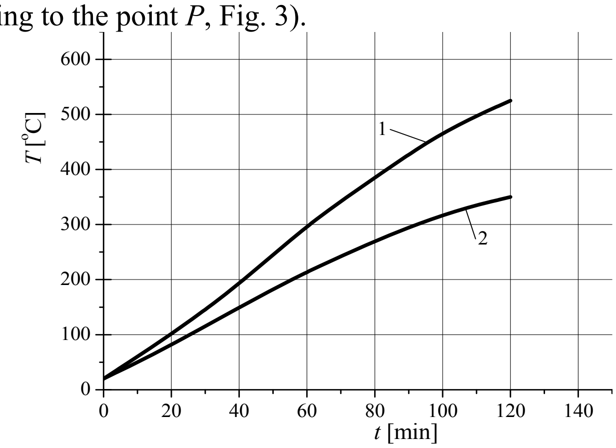

Fig. 4. Temperature *T* versus heating time *t*, in a central point *P* (1) and in the point *Q* (at 5 cm from the canal bottom) (2)

The calculated and measured temperature is shown in Fig. 5. It can be seen that the measured values are very close to the calculated ones, which confirms the accuracy of the numerical computation.

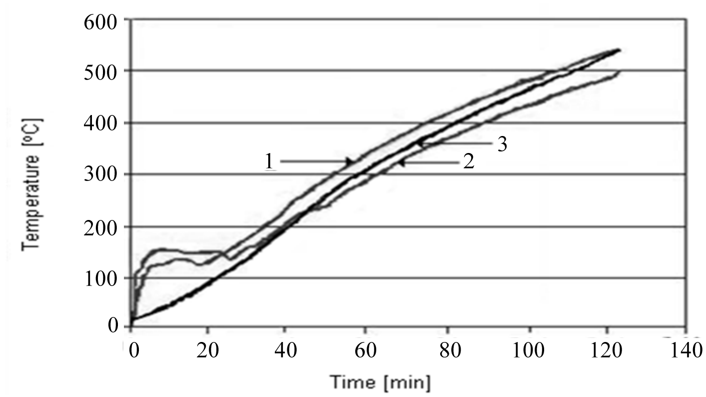

Fig. 5. Temperature versus time, calculated with SAFIR software (3) and measured with thermocouples 1 (1) and 2 (2)

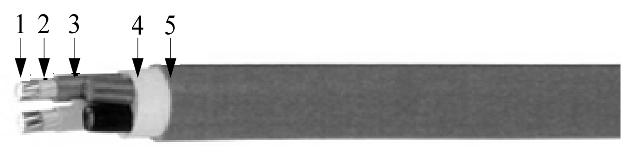

Fig. 6. Cable structure for motor alimentation: 1 – copper conductor; 2 – mica band; 3 – XLPE insulation; 4 – fireproof halogen-free filler; 5 – thermoplastic halogen-free jacket

Assuming that the temperature of the cables in the channels is below 350 ^{o}C and that the imposed temperature for the cables situated outside the channels is 400 ^{o}C, a cable having the structure presented in Fig. 6 was chosen. For the cable insulation (crosslinked polyethylene - XLPE), filler and jacket were chosen halogen-free materials and the conducting wire was covered with a mica layer (2), so that, in case of fire, even if the polymeric insulation would be completely destroyed (becoming conductor) it remains an insulating layer which can prevent short-circuits between cable phases and/or between phases and ground.

3. Lifetime estimation

Giving that the predominant stress of the cable electrical insulation is the thermal stress, the lifetime of the insulation has been estimated. Assuming that the chemical reaction rate of degradation satisfies Arrhenius equation, the lifetime $L(T)$ of an insulation aged at a temperature T is given by the equation:

$$L(T) = A.\exp(\frac{E}{RT}), \qquad (3)$$

where A is the preexponential factor, R – the perfect gas constant and E - the activation energy of the degradation reaction [16].

From equation (3) it results the regularly used lifetime equation:

$$y = a + bx, \qquad (4)$$

where $y = \ln L(T)$, $a = \ln A$, $b = E/R$ and $x = 1/T$.

If the a and b parameters values are known, the lifetime of insulation $L(T)$ at a working temperature T can be estimated.

To draw the lifetime curve $L(T)$ it is necessary to test the insulation at three temperatures chosen according to [16]. Because the ageing times, for XLPE are relatively long to low ageing temperatures, in the present paper it was preferred to do one ageing at a higher temperature and using the activation energy E (determined by chemiluminescence method [15]). As diagnosis factor the elongation at break and the life-end criteria to be the 3.21 % value of the elongation at break were used.

4. Experiments

4.1. Thermal ageing

The 100 dumbbell samples with 20 mm gauge length have been made from the XLPE electrical cable insulation. The initial relative elongation at break was measured for a group of 16 samples (with Monsanto 10E traction device with electronic extensometer and pneumatic gripping). The obtained average value is 321.2 % and the corresponding standard deviation is 29.39 %.

Before the thermal ageing test, a thermal analysis of XLPE was conducted for XLPE samples (with STA 409PC equipment produced by Netzsch Geratebau Gmbh). The thermal stability domain has been determined from TG, DTG and DSC diagrams, the maximum allowed temperature being of 266 ^{o}C. Then, a group of 75 samples have been thermal aged in a WS 200 oven (with forced air circulation, 14 evacuations per hour) with ±1 ^{o}C tolerance at temperature control. The volume occupied by the samples inside the oven was less than 10 % of the active volume of the oven. The chosen ageing temperature has been 145 ^{o}C and the ageing time τ = 2673 hours.

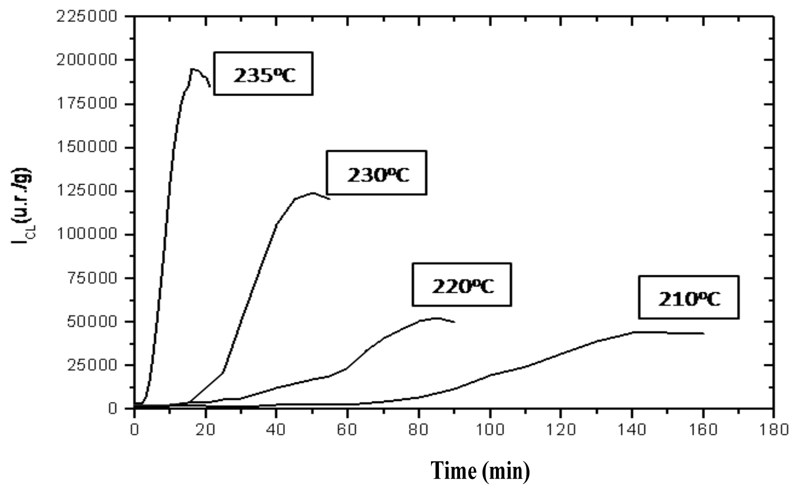

Fig. 7. Time variation of the chemiluminescence signal intensity I_{CL} for XLPE samples

After 2673 hours, the relative elongation at break value ε has been 50.102 %, with standard deviation of 2.65 %. The ε(τ) curve has been continued until it has had reached ε = 3.22 % value, corresponding to τ = 2875 hours; it has been obtained the first point of 145 ^{o}C thermal lifetime curve.

4.2. Evaluation of activation energy

Chemiluminescence measurements were performed [16-17] in order to determine the activation energy *E*. The chemiluminescence diagrams, respectively the time variation of the chemiluminescence signal intensity I_{CL}, obtained for 210, 220, 230 and 235 ^{o}C are presented in Fig. 7. From these diagrams, for each temperature, the time interval t_{ind} after which the signal intensity presents a notable growth (respectively, in the sample the degradation reaction is generating an important growth of ion concentrations) has been determined.

In Fig. 8 is presented the dependence of the natural logarithm of the induction time ($\ln t_{ind}$) of the reverse of the thermodynamic temperature *T* and the confidence level of 95 %. The activation energy value corresponding to the thermal-oxidative ageing is given by the slope of the regression line from Fig. 8 (curve 1). The correlation coefficient of the linear regression is 97.5 % and the activation energy is $E = 228.08 \pm 41$ kJ/mol.

Using the activation energy *E* and the coordinates for the first point of lifetime curve (for 145 ^{o}C), it have been calculated the quantities *b* ($b = 27445.86$ J/mol·K), *a* - with the equation (4) ($a = -53.67$) -, and the preexponential factor *A* – with the equation (3) ($A = 4.891\cdot10^{-24}$ hrs). Taking into account the value of *A*, it can be calculated the lifetime $L(T)$ for 99 % degradation at a given temperature *T*.

During the service life these cables are submitted also to vibrations of frequency f = 1…5 Hz, the experiments showed that for the cable to work correctly in case of fire it is necessary that the relative elongation at break of the insulation will suffer a degradation of at most 99 %, meaning a residual relative elongation at break value of 3.212 % at 266 ^oC. Thus the 266 ^oC temperature can be attained on XLPE insulation surface after more than two hours since the fire

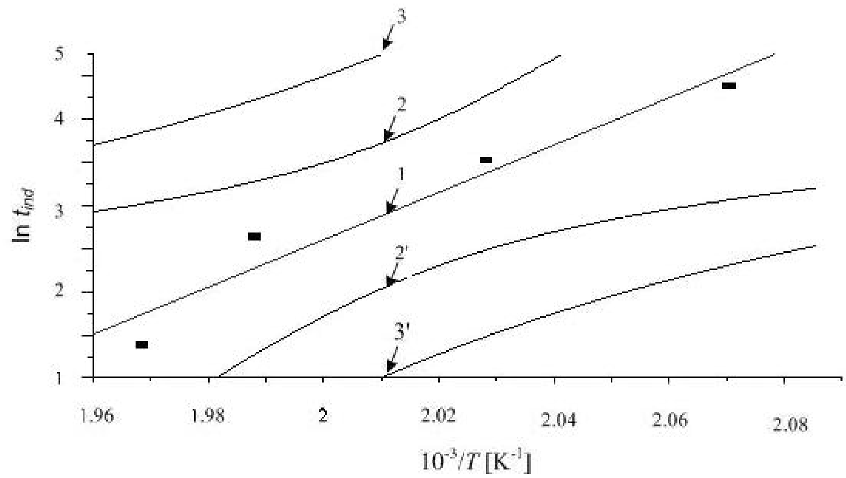

Fig. 8. Induction time variation t_{ind} (in minutes) in function of the reverse of thermodynamic temperature T (curve 1). 2-2' diagrams represent the confidence interval of 95 %, and 3-3' - the confidence interval limit of 95 %

starts. In the case of XLPE tested insulation, from lifetime equqtion (3), an elongation at break value of 3.212 % - for 266 ^oC - has been obtained for τ = 0.0014 hrs. Consequently, the conductors have been covered with a mica layer (Fig. 6).

In addition, in the areas where the cables are fixed on the tunnel walls, because of the vibrations, a complete mechanical destruction of the polymeric insulation and of the mica layers from the conductors may be produced.

4.3. Thermo-mechanical shield

In order to obtain a lower temperature on the surface of the jacket (and thus at the surface of the insulation) and to obtain a better mechanical fixation of the cable and a protection of this one to vibrations, the cable was covered with a Sibralit A layer. This material has a low thermal conductivity and expands its volume when the temperature increases over 120 ^oC, fixing the cable in the attachment clamps and avoiding the mechanical degradation of the insulating layers during the vibration.

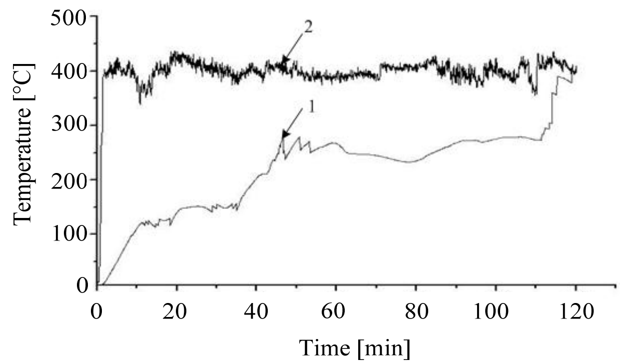

Fig. 9. Temperature versus time on the two sides of Sibralit A layer, measured with thermocouple 1 (curve 1) and 2 (curve 2)

In order to study Sibralit A behavior at high temperatures, a thermocouple (1) was covered with a Sibralit A layer, near this layer a second thermocouple (2) was fixed, and the pack was introduced in a chamber at 400 ^{o}C. The temperature's dependence of time, measured with both thermocouples is shown in Fig. 9. It can be noted that after 50 min the temperature indicated by thermocouple 1 approaches 266 ^{o}C and sometimes goes beyond this value. Thus, in order to improve the thermal characteristics, the cable jacket was covered with a glass tissue impregnated with a much thicker layer of Sibralit A.

4.4. Tests at 400 ^{o}C

The cable - with the jacket partially covered with Sibralit A and supplied at 1000 V - was tested at 400 ^{o}C in an oven at Universite de Liege – Belgium, for 2 hours (Fig. 10).

After 120 minutes, from the outside of the room mechanical shocks were applied on the cable sustaining mounting supports (with a 0.5 kg hammer) using metallic guides (strongly attached to supporting that pass through the ceiling). The shocks had the frequency of 1 Hz and the number of cycles was 60.

It has been observed that during the tests, there were no short-circuits between phases or between phases and ground and that at the end of the testing, although the XLPE insulation was destroyed, the glass tissue with Sibralit A allowed to maintain the cable dimensions and especially the mica layer on the conductors (Fig. 11).

5. Discussions

The use of a software specialized for temperature computation (SAFIR) allowed the determination of temperature values in a cable channel from a railroad tunnel with relatively small errors. Temperature computations were also performed for other channel types and/or characteristics of the concrete flags [18]. On the basis of the numerical results it was designed a three-phased cable structure that corresponds to the demands of the standard [13] for working in case of fire, in the areas where mechanical stresses (vibrations) do not exist.

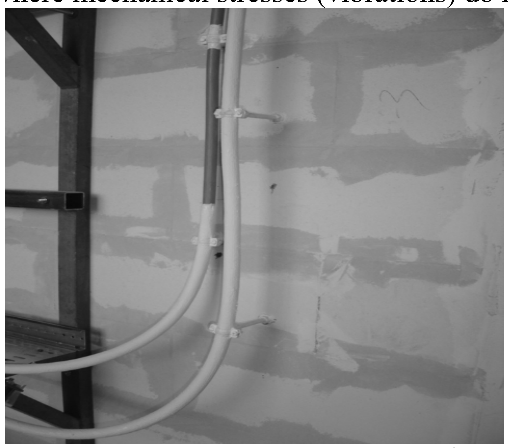

Fig. 10. Cable segment fixed in clams for 400 ^oC tests
(the light grey area is covered with Sibralit A)

Fig. 11. Section through the cable presented in Fig. 4, after the thermal ageing at 400 ^oC for 2 hours: 1 – Sibralit A; 2 - XLPE insulation

The cable lifetime estimation for working at the high temperature produced during the fire is a problem that needs long tests. Because of this, the chemiluminescence measurements made to determine the activation energy of the predominant degradation reaction during the fire led to a considerable reduction of the testing time. On this basis and on the basis of a single test at a higher temperature (145 ^oC) it was possible to estimate the lifetime for a working temperature T = 266 ^oC, for which the elongation at break value does not surpass

3.212 %. This value (2.05 hrs) is sufficient to ensure the cable working during the fire.

By following the temperature growth pattern in a point situated under the layer of Sibralit A (Fig. 9), there can be seen that 266 ^{o}C value is reached in 110 minutes. Thus, the use of a thicker layer of Sibralit A (three times the initial thickness) will reduce the probability of appearance of this temperature at jacket-Sibralit A interface before 2 hours, respectively the new cable can work in good conditions in case of fire.

The consideration of the vibrations [24] imposed the modification of the initial structure of the cable by adding a glass tissue impregnated with Sibralit A. At increased temperature this material expands, filling the spaces between the cables and the attaching clamps on tunnel walls (Fig. 11). This allows keeping the mica layer on the conductors intact and it helps avoiding shortcuts during the fire (that would cause the stopping of the fans and, thus, the evacuation of the gases from the tunnel).

It must be noted that, in the areas near the fire, the temperature of the environment can reach 1000 ^{o}C. For that reason, in the cable channels, above the cables it must place a layer of inorganic material with low thermal conductivity so that the insulation temperature does not surpass 266 ^{o}C [18].

6. Conclusions

The elaboration of a computation model for the temperature in a cable channel in a railroad tunnel of 10 km allowed to compute the temperature at which the jackets and the insulations of the power cables of fan motors are subjected in case of fire. The computations were experimentally validated on a channel introduced inside of oven at 1000 ^{o}C temperature. It was observed that there are close values of the calculated and measured temperatures. It was concluded that the temperature at the surface of the cable jacket situated in the channel is approximately 350 ^{o}C.

The lifetime computation of the cable insulation showed that the insulation which can reach maximum 266 ^{o}C, for the residual elongation at break value of 3.212 %.

The Sibralit A impregnated glass tissue (added over the cable jacket) allows keeping the geometric dimensions and the functional characteristics of the mica layer disposed on the conductors at least 2 hours (standard time for evacuating the train where the fire started).

On the basis of the performed tests and computations, the cable has been used to supply the fan motors of a railroad tunnel of 10 km (between Belgium and Germany). Its use ensures the increase of safety inside the tunnel in case of fire, the supplying of fan motors for harmful gases evacuation being ensured for over 2 hours since the fire started.

REFERENCES

1. *S. Bari, J. Naser*, Simulation of smoke from a burning vehicle and pollution levels caused by traffic jam in a road tunnel, Tunnelling and Underground Space Technology, **vol. 20,** no. 3, pp. 281-290, 2005
2. *E. Casale, J.M. Charvier, G. Lemaire*, Tunnel ventilation system modeling. In: Tunnel Engineering Handbook. Chapman & Hall, New York, pp. 69–81, 1996
3. *R.O.Carvel, A.N. Beard, P.W. Jowitt, D.D. Drysdale*, Variation of heat release rate with forced longitudinal ventilation for vehicle fire in tunnels, Fire Safety Journal **vol. 36**, no. 6, pp. 569–596, 2001
4. *J.P. Kunsch*, Simple model for control of fire gases in a ventilated tunnel, Fire Safety Journal **vol. 37**, no. 1, pp. 67–81, 2002
5. *A. Kashef*, Comparisons of numerical predictions and field tests in a road tunnel, ASHRAE Transactions, **vol**. 115, no. 2, pp. 1-12, 2009
6. *W.K. Chow, J.S.M Li*, Case study: vehicle fire in a crossharbour tunnel in Hong Kong, Tunnelling and Underground Space Technology, **vol. 16**, no. 1, pp. 23–30, 2001
7. *Jojo S. M. Li, W. K. Chow*, Numerical studies on performance evaluation of tunnel ventilation safety systems, Tunnelling and Underground Space Technology, **vol. 18**, no. 5, pp. 435-452, 2003
8. *J. Modic*, Fire simulation in road tunnels, Tunnelling and Underground Space Technology, **vol. 18**, no. 5, pp. 525 - 53, 2003
9. *J. Abanto, M. Reggio, D. Barrero, E. Petro*, Prediction of fire and smoke propagation in an underwater tunnel, Tunnelling and Underground Space Technology, **vol. 22,** no. 1, pp. 90-95, 2007
10. *Jojo S. M. Li, W. K. Chow*, Numerical studies on performance evaluation of tunnel ventilation safety systems, Tunnelling and Underground Space Technology, **vol. 18**, no. 5, pp. 435-452, 2003
11. *A. Beard*, Tunnel safety, risk assessment and decision-making, Tunnelling and Underground Space Technology, **vol. 25**, no. 1, pp.91-94, 2010
12. *C.-J. Lin, Y.K. Chuah*, A study on long tunnel smoke extraction strategies by numerical simulation, Tunnelling and Underground Space Technology, **vol. 23,** no. 5, pp. 522-530, 2008
13. ***Belgian Norm NBN C 33-134, Câbles de tension assignée 0,6/1 kV non armés, sans halogènes, à comportement amélioré au feu et résistants au feu
14. *T.W. Dakin*, Electrical Insulation Deterioration Treated as a Chemical Rate Phenomenon, Trans. AIEE, **vol**. 67, no. 1, pp. 113-122, 1948
15. *R. Setnescu*, Synergistic Effects in Degradation and Stabilization of Polymers, PhD Thesis, University Politehnica of Bucharest, 1997
16. *** IEC PUBLICATION 60216-1, Electrical Insulation Materials – Properties of Thermal Endurance – Part 1: Ageing Procedures and Evaluation of Test Results, Fifth Edition, 2001-07
17. *G. Mareş, R.Setnescu*, The Accelerated Ageing of a XLPE Cable Insulation under the Simultaneous Action of Heat and Stationary Electric Field, Proceedings of IEEE 7th Intern. Conf. on Solid Dielectrics., Eindhoven, Olanda, pp. 62-65, 2001
18. *C. Stoica*, Study of thermoplastic polymers power cable insulation ageing, Ph D Thesis, University Politehnica of Bucharest, 2010
19. *Aurelia Ionescu, P.V. Noţingher, L. Tarko, Sanda Cotescu, Lidia Avădanei, C. Preduţ*, Influence of the Halogen-Free Additives Concentration on Fireproofed Composite Materials Properties, U.P.B. Sci. Bull., Series C, **vol**. 71 , no. 4, pp. 183-192, 2009

20. ***Belgian Norm NBN 713 – 020, Protection contre l'incendie. Comportement au feu des matériaux et éléments de construction. Résistance au feu des éléments de construction,1994
21. *** BS EN 1363-1:1999, Fire resistance tests. General requirements
22. *** Rapport Université de GENT, Ligne LGV L3 – Liège Guillemins – Frontière allemande, Tunnel de Soumagne, Etude numérique de la ventilation naturelle, 2006
23. *** IEC PUBLICATION 60695-6-1-A1: Fire hazard testing - Part-6-1: Smoke obscuration - General guidance
24. *Rochdi El Abdi, Noureddine Benjemaa,* Mechanical wear of automotive connectors during vibration tests U. P. B. Sci. Bull., Series C, **vol. 71**, no. 2, pp. 167 – 181, 2009.