IPPI

Polyolefins Journal, Vol. 8, No. 1 (2021)
DOI: 10.22063/poj.2020.2787.1167

ORIGINAL PAPER

Changes in signal transmission speed in coaxial cables through regulating the foam structure of the polyethylene dielectric section

Milad Moradian, Taher Azdast*, Ali Doniavi

Mechanical Engineering Department, Faculty of Engineering, Urmia University, Urmia, Iran

Received: 11 October 2020, Accepted: 30 November 2020

ABSTRACT

Polyolefins have been widely used in the electrical insulation and cable industry in recent years. One of the main usages of these materials is dielectric insulation in coaxial cables. Low attenuation and high signal transmission speed are among the desired features in coaxial cables. The role of polyethylene foam on signal transmission speed in the coaxial cables is the main focus of this study. In the present study, the velocity factor of coaxial samples with different dielectric structures is investigated in both theoretical and experimental approaches. In theoretical formulation, only the void fraction of foam is taken into consideration and other foam properties such as cell density, cell size, and foam structure are neglected. This is the reason for the difference observed between theoretical and experimental results. In theoretical results, a linear increase in the velocity factor is witnessed with the increase of the void fraction while in experimental results there are some exceptions. The foaming degree of the samples was reached 63% causing a 37.7% decrease in theoretical relative permittivity and consequently a 26.8% increase in theoretical velocity factor. On the other hand, up to 36% increase is observed in the experimentally measured velocity factor of foamed dielectric samples compared to the samples with solid polyethylene dielectric.
Polyolefins J (2021) 8: 41-48

Keywords: Velocity factor; polymeric foam; polyethylene; void fraction; cell density.

INTRODUCTION

Polyolefins are widely used in electrical insulation functions due to their special properties and also their low cost and easy processing. For instance, one of the first commercial usages of low-density polyethylene (LDPE) was in radar cable sheathing during world war II. Since then, these polymers have entered the power and signal transmission cables industry. After years of using paper and oil-impregnated materials, polyolefins became very popular as insulation materials due to their low relative permittivity and high dielectric strength [1-5]. Polyethylene (PE) in particular was implemented in both power and signal transmission cables. However, some major downsides were observed in the use of polyethylene. In power cables, the low

*Corresponding Author - E-mail: t.azdast@urmia.ac.ir

softening temperature and its aging in the time lead to undesirable deterioration in dielectric properties [6]. In telecommunication cables, the main problem was the water absorption of PE which caused an increase in the permittivity of the insulator [7].

To overcome these problems different chemicals, materials, and morphological modifications were performed on LDPE, high-density polyethylene (HDPE), and polypropylene (PP) to enhance their insulation and dielectric properties. In the case of power cables, crosslinking seemed a good solution. Peroxides such as dicumyl peroxide (DCP) were used to cross-link the polyethylene and produce XLPE cables with a high chemical, moisture and temperature resistance. XLPE cables are highly used in high voltage applications [8].

Regarding the signal transmission cables, the adopted solution was to foam the PE to achieve a cellular structure in the core with a rigid shell surrounding it. The rigid shell prevents the water from entering the dielectric material and the cellular core leads to lower relative permittivity of the dielectric material and consequently better signal transmission properties of the cable. Foaming the polymers has also many other advantages such as density reduction, polymer consumption reduction, thermal and sound insulation. Therefore, polymeric foams studies are increasing day by day [9-14]. Many scholars have investigated the foaming process of dielectric material and its influence on the dielectric properties of the material. Standaert [15] studied the relationship between structural properties of poly(tetra fluoro ethylene) (PTFE) foam and its dielectric properties such as relative permittivity. The results showed that as the porosity of foam increased, the permittivity grew lower. Knott [16] investigated the relative permittivity of polystyrene (PS) foams, and they used a theoretical approach to derive the relative permittivity of foam out of the relative permittivities of air and PS. They concluded that the high expansion ratio of the foam can be an indicator of its low relative permittivity. Kim et al. [17] studied the influence of the foaming degree of the composition of HDPE/LDPE on its relative permittivity and dissipation factor. Due to their results, relative permittivity was highly affected by the variation of foaming degree while the dissipation factor did not have a logical relationship with foaming degree. The reduction of relative permittivity with increasing of expansion ratio in different polymers was also observed in the work of Jeon et al. [18], Chu et al. [19], and Zhao et al. [20]. Zhao et al. [20] also compared the results with some theoretical approaches which were in good agreement with experimental results.

The relative permittivity and dissipation factor eventually affect the transmission properties of signal cables. Coaxial cables, in particular, were the subject of many studies of this type. Behravesh et al. [21] investigated the attenuation in the coaxial cables containing a dielectric section with PE foams with different densities. Their results showed that the samples with lower density in the dielectric section had a lower attenuation along the cable due to decrease of relative permittivity by increasing of expansion ratio of the foam. Moradian et al. [22] studied the effect of morphological properties of the foamed polyethylene dielectric of coaxial cables on the attenuation of cable thoroughly. They showed that expansion ratio was not the only significant parameter and other structural parameters of the foamed dielectric section such as cell density and cell size affect the attenuation in the coaxial cable.

However, another important transmission parameter in signal cables which seems to be neglected in previous studies is the velocity of propagation or velocity factor (VF). This parameter indicates the speed of signal transmission through the cables. Therefore, this research aims at investigating the effect of foam properties of the dielectric section of coaxial cables on the velocity factor of the cables. Cables with different dielectric foam structures and theoretical calculations of velocity factor are used to achieve reasonable results.

EXPERIMENTAL

Samples

The experiments were performed on the coaxial cable samples with solid and foamed PE dielectric sections. Coaxial cables are made of copper core covered by a polymeric dielectric section. The second conductor is braided on the dielectric material with a final polymeric sheathing that covers it. Figure 1 demonstrates the different steps of coaxial cable production.

Samples of this study were coaxial cables produced with the same material, the same design, and the same dimensions in all parts except the dielectric section. The dielectric sections of 9 samples of this study were 1 solid PE sample and 8 foamed PE samples with different foam properties. Achieving different structures of foam is possible through changing the dielectric extruding conditions which were thoroughly explained in our previous work [22]. Process and material parameters affect the foam structure. Reaching different foam structures in samples fabricated in the extrusion process is possible through regulating these process and material parameters including injected gas content, gas pressure, nucleation agent content, pressure drop rate in the die output, and die temperature.

Characterization

Foam properties

Foam properties are divided into two categories: density-based properties and structure-based properties. Relative density, void fraction, and expansion ratio are in the first category, while cell density and cell size belong to the second category.

The density-based properties are all calculated using the density of the foam which itself is measured based on the water displacement method (ASTM-D792 test). Relative density (ρ_{ref}) is calculated based on Equation (1) in which ρ_f is the foamed sample density and ρ_p is the solid polymer sample density [13].

$$\rho_{rel} = \frac{\rho_f}{\rho_p} \quad (1)$$

One of the criteria of the foaming rate is void fraction which is computed using Equation (2) [23].

$$v_f = 1 - \rho_{rel} \quad (2)$$

It is noteworthy that the two introduced density-based properties (relative density and void fraction) are dimensionless variables.

The structure-based properties are all derived from the scanning electron microscope (SEM) pictures. The SEM pictures were taken from the gold-coated section of dielectric samples, and the samples were broken inside liquid nitrogen to have a brittle break which does not affect the cross-section. The cell density (N) of the samples was measured by counting the number of cells in the 2D SEM picture. According to the surface area of the SEM picture (A), cell density is calculated as Equation (3) [24].

$$N = \left(\frac{n}{A}\right)^{3/2} \quad (3)$$

The 3/2 power compensates for the error of using area instead of volume in the formulation. Cell size (D) is the next structure-based parameter which indicates the average size value of the cells inside a specific sample. This parameter is calculated by measuring the cell diameter of all the cells present in an SEM picture and then calculation of the average value.

Electrical properties

The electrical property studied in this manuscript is the velocity factor which represents the signal transmission speed in the cable. This factor is calculated relative to the light speed in the free space. The higher this amount, the faster the signal transmitted from one end of cable to the other end. The

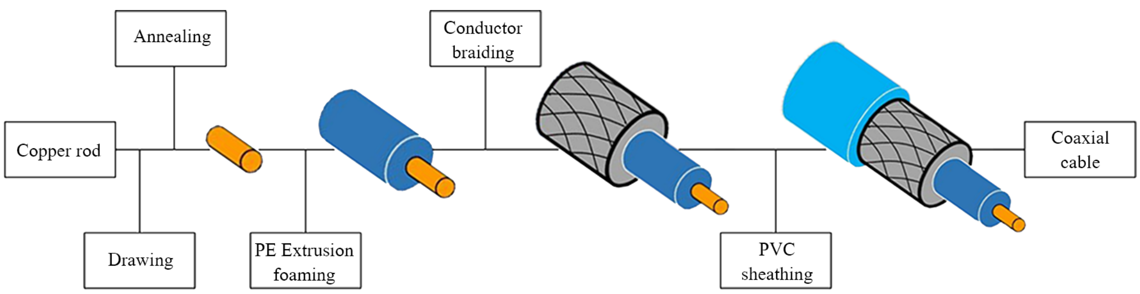

Figure 1. Procedure of Coaxial cable production.

velocity factor was measured experimentally using an E8363C Vector Network Analyzer (VNA) device by Agilent Technologies. The measurements were done based on frequency domain analysis. The VNA device generates and routes different signals to the tested cable and the receiver measures magnitude and the phase angle of signals. The S11 and S22 parameters were both measured. The subscripts indicate the input and output ports number. The S11 parameter represents the signals transmitted from port 1 to port 2 and then returned and received in port 1 [25]. The S11 parameter is also called the return loss and is used to calculate the velocity factor in coaxial cables.

Calculating the velocity factor

Experimental approach

The phase at the end of a signal cable is calculated based on Equation (4) [25].

$$\varphi = \frac{2\pi l}{\upsilon_p} f \tag{4}$$

Where l is the length of the cable, f is the frequency, and υ_p is the velocity of propagation in the cable.

The S11 parameter, measured by VNA, gives us the phase angle value at different frequencies; the frequency range was from 0 to 4 GHz with 50 MHz step.

Plotting the phase angle variation versus frequency increase demonstrates a cycle between -π to π. The slope of the phase angle diagram between -π to π (m) is used to calculate the velocity of propagation through the cable as Equation (5) [25].

$$m = \frac{2\pi l}{\upsilon_p} \tag{5}$$

The velocity factor is the ratio of velocity propagation (υ_p) to the speed of light (c) [26].

$$VF = \frac{\upsilon_p}{c} \tag{6}$$

Theoretical approach

The signal transmission velocity in a cable surrounded by free space is equal to the speed of light (3×10^8 m/s). The velocity of a signal in other mediums is lower than the light speed and is depended on the relative permittivity and permeability of the dielectric around the conductor. The velocity of propagation for a coaxial cable can be calculated as Equation (7) [26].

$$\upsilon_p = \frac{c}{\sqrt{\mu_R \varepsilon_R}} \tag{7}$$

Polyethylene is a nonmagnetic material so we can assume, therefore integrating Equations (6) and (7), the velocity factor of a coaxial cable is equal to [26]:

$$VF = \frac{1}{\sqrt{\varepsilon_R}} \tag{8}$$

The Maxwell-Garnett equation is used to derive the relative permittivities of cellular polymers using Equation (9) [20].

$$\varepsilon_{eff} = \varepsilon_1 \frac{(\varepsilon_2 + 2\varepsilon_1) + 2\upsilon_f(\varepsilon_2 - \varepsilon_1)}{(\varepsilon_2 + 2\varepsilon_1) - \upsilon_f(\varepsilon_2 - \varepsilon_1)} \tag{9}$$

where ε_1 is the relative permittivity of the polymer matrix and ε_2 is the relative permittivity of gas state, and υ_f is the void fraction of the foam. The calculated relative permittivities are used in Equation (9) to obtain the theoretical velocity factor.

RESULTS AND DISCUSSION

The samples of this research were nine coaxial samples with different dielectric sections. The dielectric section of the first sample was solid polyethylene and the dielectric section of the other 8 samples was cellular polyethylene with different densities and structures. The relative density of samples was measured and consequently, the void fraction of samples was calculated based on Equation (2). Samples were numbered based on increasing in void fraction. The results of relative density and void fraction are reported in Table 1.

The morphological properties of the foamed samples (samples 2-9) were derived from the SEM pictures of samples. The SEM pictures of samples are depicted in Figure 2.

The results of cell density were determined using Equation (3) and also the average cell size of samples is given in Table 2.

In the next step, Equation (9) is used to calculate the

Table 1. Results of relative density and void fraction of dielectric samples.

Sample	Relative Density (ρ_{rel})	Void fraction (υ_f)
1	1	0
2	0.919	0.081
3	0.836	0.164
4	0.737	0.263
5	0.580	0.420
6	0.575	0.425
7	0.572	0.428
8	0.565	0.435
9	0.365	0.635

relative permittivity of different samples according to their void fraction. The relative permittivity of solid polyethylene (ε_1) is 2.25 and for air (ε_2) is 1 [27]. Table 3 reports the results of relative permittivity for different samples.

When we put these values in Equation (8) instead of relative permittivity, we can determine the theoretical velocity factor of the samples in this study. In the next step, we used the experimental results obtained from

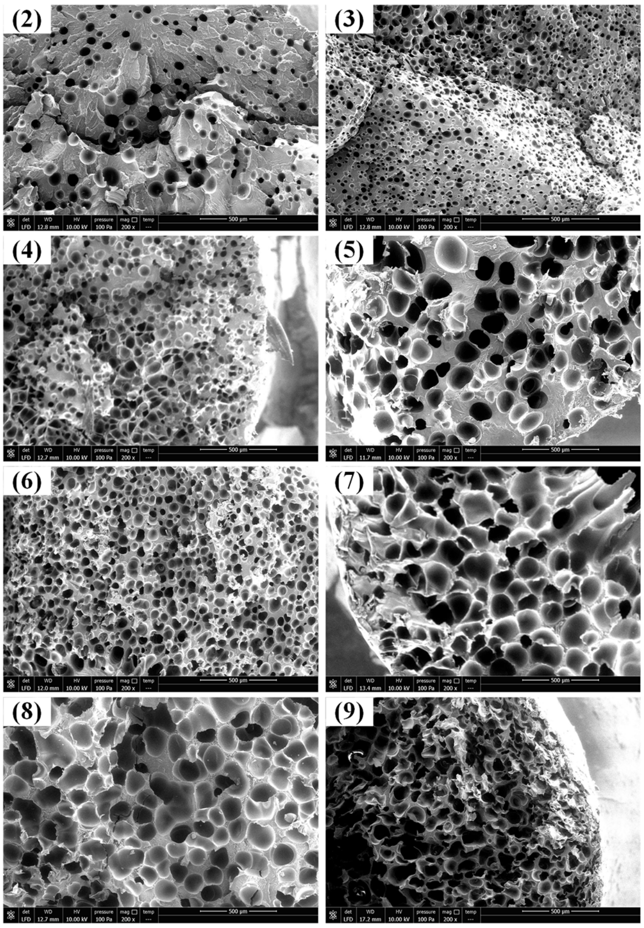

Figure 2. SEM pictures of foamed dielectric samples (2-9) [22].

Table 2. Results of cell density and cell size of dielectric samples.

Sample	Cell density (cell/cm³)	Cell size (µm)
1	0	0
2	6.31×10^5	56.49
3	1.06×10^7	33.26
4	5.18×10^6	46.31
5	3.14×10^5	130.56
6	4.74×10^6	55.23
7	3.87×10^5	130.55
8	5.05×10^5	130.87
9	2.10×10^6	68.35

the VNA device to find the experimental velocity factor. For this purpose, first, we plotted the phase angle of S11 parameter versus frequency for different samples. Figure 3 shows a typical diagram of this type which shows the trend of phase degree change with frequency change.

Out of this diagram, the velocity of propagation in the sample is reachable through Equation (5) and finally, the experimental velocity factor is calculated based on Equation (6). The theoretical and experimental velocity factor output is reported in Table 4.

There is a contrast between the theoretical and experimental results of the velocity factor, and the reason must be explained. As it was explained in the materials and method section, in the theoretical approach, the velocity factor is calculated according to the relative permittivity of the dielectric section of the cable. This theoretical relative permittivity is determined based on Maxwell-Garnet theory which only takes void fraction of the foam into consideration among all other foam properties. The main point here is apart from void fraction; there may be other structural parameters that affect the relative permittivity. The cell

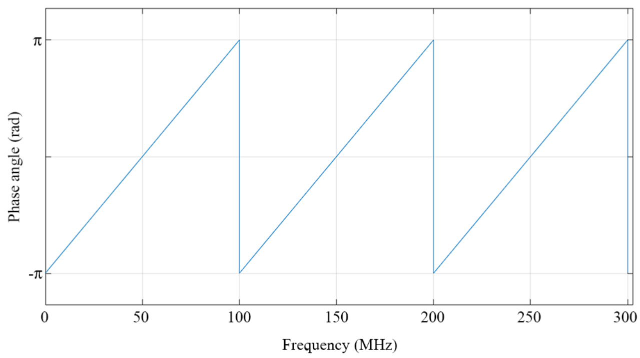

Figure 3. Typical diagram of phase angle versus frequency.

Table 3. Results of theoretical relative permittivity of dielectric samples.

Sample	Relative permittivity
1	2.25
2	2.12
3	2.01
4	1.86
5	1.67
6	1.66
7	1.65
8	1.64
9	1.40

distribution and cell size seem to affect the dielectric properties of the polymeric foam.

The experimental results of this study reveal that the increase of the void fraction of the dielectric section of coaxial cables does not necessarily lead to a higher velocity factor through the cables. For instance, sample 9 has the highest void fraction among samples of this study but does not show a proper improvement in the velocity factor. One of the reasons can be the cell structure of the foam of the dielectric section. Studies have proved that foams with open-celled structures are more prone to moisture ingress, which worsens their dielectric properties and as shown in Figure 3, sample 9 contains a large number of open cells [28].

It is concluded from the results of sample 3 that there are other more effective parameters than the void fraction that affect the relative permittivity and consequently the velocity factor of the cable. Sample 3 shows a high velocity factor while its void fraction is not very high. This highlights the role of cell distribution. Sample 3 has a high cell density, meaning that a greater number of cells are distributed in the unit of volume in the foam. This is equivalent to a higher number of dipoles formed over the cells [29].

In Figure 4 the theoretical and experimental velocity factor through a coaxial cable is plotted versus the void fraction of the foam of its dielectric section.

The trend of this diagram supports the arguments given for Table 4. As it is observable, the theoretical velocity factor increases linearly with the increase of void fraction because the theoretical velocity factor is calculated based on theoretical relative permittivity and as it was discussed above, in the theoretical permittivity only void fraction is taken into account. On the other hand, the experimental velocity factor shows a significant increase compared to the theoretical velocity factor by the increase of foam void fraction. This shows that by foaming the dielectric section, apart from the increase of the void fraction and its effect on the relative permittivity and velocity factor, there must be other mechanisms that boost the increase of velocity factor and this is the main reason for the difference between the experimental and theoretical results. These other mechanisms as discussed above may be the structural properties of foam which affect the electrical dipoles distribution and orientation.

Another key point in this diagram is the decreasing trend of experimental results in void fractions greater than 0.4. This behavior is justifiable because by increasing the void fraction in the foam the probability of interference between gas cells and consequently increasing the open-cell content increases. This fact is also supported by the SEM graphs of samples with higher void fractions depicted in Figure 2.

In general, due to the widespread use of polyolefins in the electrical insulation industry and their challenging foaming process, it is important to research the foaming process and its effective parameters on foam properties. The results of this study indicate that the

Table 4. Results of theoretical and experimental velocity factor together with the foam properties.

Sample No.	Cell size (µm)	Cell density (cell/cm^3)	Void fraction	Velocity factor	
				Theoretical	Experimental
1	0	0	0	66.67	65.20
2	56.49	6.31×10^5	0.081	68.68	74.95
3	33.26	1.06×10^7	0.164	70.53	86.43
4	46.31	5.18×10^6	0.263	73.32	78.58
5	130.56	3.14×10^5	0.420	77.38	89.01
6	55.23	4.74×10^6	0.425	77.61	73.8
7	130.55	3.87×10^5	0.428	77.84	70.56
8	130.87	5.05×10^5	0.435	78.08	76.28
9	68.35	2.10×10^6	0.635	84.51	65.56

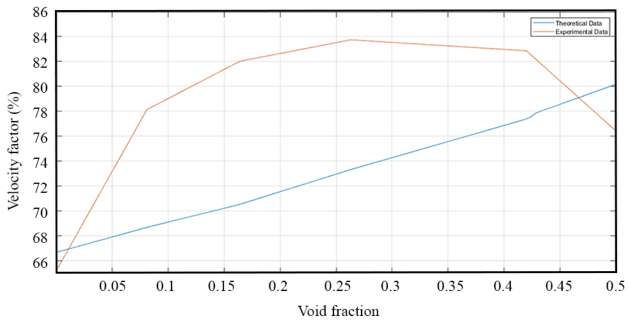

Figure 4. Diagram of velocity factor in the cable versus the void fraction of the foamed dielectric section for both theoretical and experimental results.

foaming process of these dielectric materials should be optimized in a way to achieve proper insulation and signal transmission properties.

CONCLUSION

Coaxial samples with different dielectric section structures are studied considering the effect of dielectric foam structure on velocity factor in the cable. It is concluded that the increase of void fraction leads to an increase in the velocity factor based on the theoretical results. However, the experimental results show that this increase is valid up to a point that the structure of the foam is still closed cell. Thus, open-cell content causes moisture absorption and consequently weak insulation properties. Another major issue observed is the role of cell density of the foam, which seems to have been completely ignored in previous theories of relative permittivity prediction. Some samples are detected with a low void fraction but high cell density, which shows a good improvement in the velocity factor of the cable used in them.

REFERENCES

1. Hanley TL, Burford RP, Fleming RJ, Barber KW (2003) A general review of polymeric insulation for use in HVDC cables. IEEE Electr Insul M 19: 13-24
2. Green CD, Vaughan AS, Stevens GC, Sutton SJ, Geussens T, Fairhurst MJ (2013) Recyclable power cable comprising a blend of slow-crystallized polyethylenes. IEEE Trans DEI 20:1-9
3. Green CD, Vaughan AS, Stevens GC, Pye A, Sutton SJ, Geussens T, Fairhurst MJ (2015) Thermoplastic cable insulation comprising a blend of isotactic polypropylene and a propylene-ethylene. IEEE Trans DEI 22: 639-648
4. Albertini M, Bareggi A,Caimi L, De Rai L, Dumont A, Franchi S, Pozzati G (2015) Development and high temperature qualification of innovative 320 kV DC cable with superiorly stable insulation system. 9th International Conference on Insulated Power Cables, Milano, Italy: A7.3
5. Zhang K, Li L, Lisheng Z, Chen N, Xu M, Xie D, Chen G (2015) The mechanical properties of recyclable cable insulation based on thermo-plastic polyolefin blends. IEEE 11th International Conference on the Properties and Applications of Dielectric Materials, Sydney, Australia: 532-535
6. Dabbak ASZ, Illias HA, Ang BC, Abdul Latiff NA, Makmud MZH (2018) Electrical properties of polyethylene/polypropylene compounds for high-voltage insulation. Energies 11: 1448
7. Li L, Zhang K, Zhong L, Chen N, Xu M, Xie D, Chen G (2015) Dielectric behaviors of recyclable thermo-plastic polyolefin blends for extruded cables. IEEE 11th international conference on the Properties and Applications of Dielectric Materials, Sydney, Australia: 180-183
8. Pleşa I. Noţingher PV, Stancu C, Wiesbrock F, Schlögl S (2019) Polyethylene nanocomposites for power cable insulations. Polymers 11: p.24
9. Lee RE, Hasanzadeh R, Azdast T (2017) A multi-criteria decision analysis on injection moulding of polymeric microcellular nanocomposite foams containing multi-walled carbon nanotubes. Plast Rubber Compos 46: 155-162
10. Daryadel M, Azdast T, Hasanzadeh R, Molani S (2018) Simultaneous decision analysis on the structural and mechanical properties of polymeric microcellular nanocomposites foamed using CO_2. J Appl Polym Sci 135: 46098
11. Azdast T, Lee RE, Hasanzadeh R, Moradian M, Shishavan SM (2019) Investigation of mechanical and morphological properties of acrylonitrile butadiene styrene nanocomposite

foams from analytical hierarchy process point of view. Polymer Bull 76: 2579-2599

12. Azdast T, Hasanzadeh R (2019) A review on principles and fundamentals of fabrication of polymeric foams in regards to increasing cell density/reducing cell size. Modares Mech Eng 19: 211-222
13. Shishavan SM, Azdast T, Hasanzadeh R, Moradian M (2019) Comprehensive investigation of morphological properties of ABS/nanoclay/PMMA polymeric nanocomposite foam. Polym Sci-A 61: 334-344
14. Molani S, Azdast T, Doniavi A, Hasanzadeh R, Moradian M, Mamaghani Shishavan S (2018) A Taguchi analysis on structural properties of polypropylene microcellular nanocomposite foams containing Fe_2O_3 nanoparticles in batch process. Plast Rubber Compos 47: 106-112
15. Standaert A, Rousstia M, Sinaga S, Reynaert P (2017) Permittivity measurements in millimeter range of PTFE foams. IEEE Microw Wirel Co 27: 766-768
16. Knott EF (1993) Dielectric constant of plastic foams. IEEE T Antenn Propag 41: 1167-1171
17. Kim YH, Jeon BJ, Cha SW, Nam GJ, Park CY, Lee GJ (2008) Relationships between processing parameters and the foaming performances of polyethylene for coaxial cable insulation. Polym Plast Technol Eng 47: 1283-1288
18. Jeon BJ, Kim YH, Lee KS, Cha SW, Nam GJ, Park CY, Lee GJ (2008) Parameter design of a coaxial cable insulation manufacturing process using axiomatic design and the Taguchi method. Polym Plast Technol Eng 47: 785-790
19. Chu HJ, Zhu BK, Xu YY (2006) Preparation and dielectric properties of polyimide foams containing crosslinked structures. Polym Adv Technol 17: 366-371
20. Zhao B, Zhao C, Wang C, Park CB (2018) Poly (vinylidene fluoride) foams: A promising low-k dielectric and heat-insulating material. J Mater Chem C 6: 3065-3073
21. Nazri M, Behravesh A, Shahi P (2008) Investigation on microstructure and production of coaxial cable foam insulation using butane gas. ADMT J 2: 37-42
22. Moradian M, Azdast T, Doniavi A (2020) Investigating the effect of foam properties on the attenuation of coaxial cables with foamed polyethylene dielectric. Polym Adv Technol 31: 3328-3340
23. Esmailzadeh M, Danesh Manesh H, Zebarjad SM (2018) Fabrication and characterization of functional graded polyurethane foam (FGPUF). Polym Adv Technol 29: 182-189
24. Williams MK, Weiser ES, Fesmire JE, Grimsley BW, Smith TM, Brenner JR, Nelson GL (2005) Effects of cell structure and density on the properties of high performance polyimide foams. Polym Adv Technol 16: 167-174
25. Ferrero A, Pirola M (2006) Generalized mixed-mode S-parameters. IEEE T Microw Theory 54: 458-463
26. Tereshchenko OV, Buesink FJK, Leferink FBJ (2011) An overview of the techniques for measuring the dielectric properties of materials. XXXth URSI General Assembly and Scientific Symposium: 1-4
27. Geyer RG (1990) Dielectric characterization and reference materials. Technical Note (NIST TN): 1338
28. Hsu YT, Chang-Liao KS, Wang TK, Kuo CT (2006) Monitoring the moisture-related degradation of ethylene propylene rubber cable by electrical and SEM methods. Polym Degrad Stabil 91: 2357-2364
29. Ameli A, Nofar M, Park CB, Pötschke P Rizvi G (2014) Polypropylene/carbon nanotube nano/microcellular structures with high dielectric permittivity, low dielectric loss, and low percolation threshold. Carbon 71: 206-217