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Investigation of the properties of aluminous porcelain samples of a long-rod insulator subjected to high DC voltage

***Abstract**. The objective of this examination was to test the aging resistance of the aluminous porcelain material C 130 type, when exposed to direct current (DC) high voltage. Long-term exposure to high DC voltages can potentially lead to various negative effects, in particular ionic current development in the porcelain material. This process may reduce the mechanical strength and, consequently, cause a failure. This problem has been noticed in the case of glass disc insulators. The samples were examined using the 3-point bending test, ultrasonic and microscopic analysis. No recordable degradation effects were found. Long-term impact of DC high voltage did not reduce the mechanical parameters or change the microstructure of the porcelain material.*

***Streszczenie.** Celem prezentowanych badań było sprawdzenie odporności na starzenie się wysokoglinowego materiału porcelanowego rodzaju C 130, w warunkach oddziaływania wysokiego napięcia prądu stałego (HVDC). Długotrwałe narażenie na wysokie napięcie prądu stałego może potencjalnie prowadzić do różnych negatywnych efektów, w szczególności do przepływu prądu jonowego w tworzywie porcelanowym. Proces taki może poważnie obniżyć wytrzymałość mechaniczną materiału. W konsekwencji mogłoby nastąpić pęknięcie izolatora i dojść do awarii. Problem ten był rejestrowany w przypadku izolatorów szklanych. Próbki poddano pomiarom ultradźwiękowym, badaniu wytrzymałości mechanicznej metodą 3-punktowego zginania oraz analizie mikroskopowej. Nie stwierdzono żadnych możliwych do rejestracji efektów degradacji. Długotrwałe działanie wysokiego napięcia prądu stałego nie spowodowało obniżenia parametrów mechanicznych ani zmian w mikrostrukturze materiału porcelanowego.*
(Badania właściwości próbek porcelany wysokoglinowej izolatora długopniowego poddanych wysokiemu napięciu stałemu)

Keywords: DC high voltage, aluminous porcelain C 130, 3-point bending test, mechanical strength.
Słowa kluczowe: Wysokie napięcie prądu stałego, porcelana wysokoglinowa C 130, trójpunktowe zginanie, wytrzymałość mechaniczna.

Introduction

Aluminous porcelain C 130 type with high mechanical strength has been widely used in the production of reliable electrical insulating elements for years. This material is used to produce HV and LV line insulators, HV post insulators, also medium voltage (MV) line and post insulators as well as traction insulators. It is particularly important to use this type of material to produce various types of hollow insulators, especially those with high parameters and large dimensions. This is not only due to the requirements for the short-term mechanical strength of electrical insulating elements. More important is ensuring the reliability of the power supply, which is determined by durability, i.e. the long-term mechanical strength of the ceramic material. In the case of the above-mentioned products, in addition to high mechanical strength, a long period of failure-free operation is also required. This results in an upward trend in the production of C 130 type material, at the expense of other porcelain materials. However, in the case of low-voltage elements or various types of bushings, it is sufficient to use ordinary, much cheaper quartz porcelain (C 110 type).

Despite strong competition from insulators of other kinds - especially composite ones, C 130 type material has been widely used since the 1980s and enjoys the reputation of being durable and reliable. This happens despite the difficult and complicated production technology [1,2]. It should be emphasized, however, that porcelain materials were designed to work in alternating current electric fields and were not tested for use in direct current overhead power lines. Nevertheless, the possibility of using electrical porcelain for operation in direct current electric fields is currently being taken into account. [3].

Progress in the construction of high-voltage converter systems and the dynamic development of electricity generation systems from the so-called renewable sources, have resulted in an rise in interest in transmitting electricity using high-voltage direct current (HVDC) overhead power lines [4,5]. The high costs of converter stations – from alternating current (AC) to direct current (DC) and vice versa - are offset by a significant reduction in losses of energy transmitted over long distances via HVDC lines, compared to AC systems. Moreover, they are characterized by lower costs of construction of the transmission line [6].

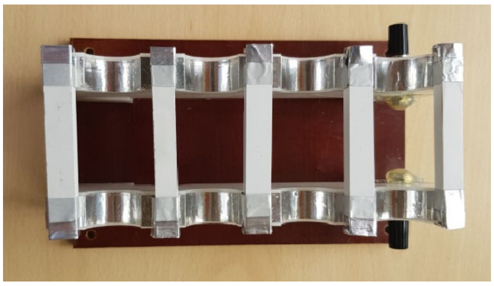
However, the use of HVDC lines for electricity transmission raises some technical problems. The constant electric field generated by an HVDC line can have a serious impact on the integrity of dielectric materials, typically manufactured for AC applications [7]. Compared to systems operating at alternating voltages, electrostatic phenomena may cause increased degradation processes, changes in electrical strength [8,9], and even a multiple increase in the accumulation of surface contaminants [10]. Under such conditions, when leakage current flows through a contaminated surface without crossing the zero of the voltage-current curve, ignition of unextinguished concentrated surface discharges may occur and accelerate degradation of the insulating material. The aging process in the presence of HVDC causes increased accumulation of space charge in areas where the material is more degraded, thus contributing to a stronger distortion of the electric field [11]. This phenomenon may cause an increase in partial discharges. In the presence of direct current, the ignition of concentrated surface discharges is not turned off, as in an alternating current network - where the voltage curve crosses zero [10]. This dangerous effect may cause increased erosion of the insulating material.

There is one more serious threat. If the insulating material is exposed to an electrostatic field for a long time, ion current may flow, ion migration and electrolysis may occur. This may cause a gradual degradation of the mechanical properties of the material [12]. This process can be activated at elevated temperatures. The possible flow of ions between the fittings through the material, and thus the movement of mass, may result in damage to the material structure. Further potential effects include the formation of deposits of reaction products of active atoms, which arise as a result of the neutralization of conductive ions on the electrodes (mainly mobile Na^+ cations). Electrolysis of the insulating material may therefore lead to damage to the insulator and, consequently, even to failure. Such a problem was recorded in the case of glass insulators [13].

Porcelain samples and research methods

The subject of the research was a domestic aluminous material C 130 type from LP 75/31 line insulator from 2022. The insulator rod was cut in several places between the shades, perpendicular to its longitudinal axis. Ten partially cuboidal samples with approximate dimensions of 70 mm x 10 mm x 10 mm were cut from the insulator fragments. The longitudinal axis of the samples was perpendicular to the axis of the insulator rod. The samples were divided into two groups - 5 elements constituted the reference group, while the remaining 5 were exposed to high direct voltage – 2 kV/cm for 6.000 hours. The aging process took place at a constant temperature of 23ºC. Then, samples from both groups - Figure 1 - were subjected to comparative tests, which were aimed to reveal possible degradation effects in samples aged with DC voltage. Ultrasonic measurements, mechanical strength testing - using the three-point bending method, and optical microscopic observations on specially made specimens were used.

a)



b)

Fig.1. Tested samples: a - before starting aging tests; b – after completing the test

Ultrasonic tests were performed on cut, partially cuboidal samples, in a direction parallel to the longitudinal axis of the insulator. The sides of samples with sufficiently good planar parallelism were used for measurements with a measuring path of approximately 10 mm. Acoustic measurements were performed using the echo method, on a system that was prepared for testing ceramic and composite elements of various sizes and having material with different parameters and varying degree of microstructure degradation. The measurement system consisted of a transmitting and receiving module, a digital oscilloscope and a set of pulse – echo UT probes for longitudinal and transverse waves.

Aged and reference samples were subjected to comparative 3-point bending mechanical strength tests - Figure 2. For this purpose, an INSTRON 1343 testing machine was used, which was expanded with drivers and software from MTS (Mathematisch Technische Software-Entwicklung GmbH, Berlin, Germany). Due to the length of the samples, which was approximately 70 mm, spacing of the supports was 55 mm. A high speed of movement of the machine traverse was used, amounting to 1 mm/min. The measuring system recorded the force acting on the sample, which was then converted into the breaking stress MOR, according to the relationship [14]:

$$MOR = \frac{3Fl}{2bh^2} \quad (1)$$

where: MOR – Modulus of Rupture – breaking stress in MPa, F – force acting on the sample in N, l – distance between the supports - equal to 55 mm, b – sample width in mm, h – sample thickness in mm.

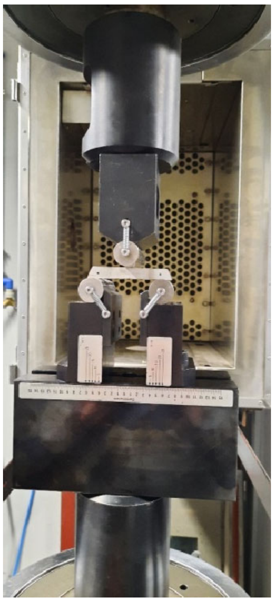


Fig.2. Reference sample denoted 2 in a testing machine, prepared for 3-point bending mechanical strength test

Research on the microstructure of the material, using the optical microscopy (MO) method, required special surface preparation - making of microsections. Fragments of samples, intended for microscopic examination, were gently cut off with a precise saw, with an internal diamond grit with a grain size of 90 µm. The grains in such a saw do not protrude more than 30 µm above the binder. This allowed to reduce significantly the layer of the material damaged by cutting (up to about 100 µm). The grinding process was omitted and the surfaces intended for testing were polished successively with diamond pastes of decreasing granulation – 5 µm, 1 µm and 0,25 µm, as well as finally with silicone colloid with a grain size of 60 nm. Optical studies were performed using a microscope equipped with a computer image analyser. Magnifications ranging from 50 to 500 times were used. Nomarski interference-phase contrast was used to interpret the phase structure of the porcelain and defects in its microstructure.

Tests results

Ultrasonic tests of samples - both reference and aged ones - as it was mentioned - were carried out in a direction parallel to the axis of the insulator. Aluminosilicate ceramic materials, formed from plastic masses using extrusion method (extruded in vacuum venting presses), show a clear effect of unidirectional anisotropy. Its consequences are differences in the results of measurements carried out on different axes. The propagation velocities of ultrasonic waves, measured in the direction consistent with the axis of the long-rod insulator, are generally several hundred meters per second higher than in the perpendicular directions [15].

Precise measurements of the propagation velocities of ultrasonic waves, made with an accuracy of ±10 m/s, showed no differences for reference and aged samples. The classification of the material as C 130 type aluminous porcelain was confirmed, with a moderate scatter of results. It indicated a certain inhomogeneity of the material on a semi-macro and macro scale. For all 6 acoustically tested samples - 3 reference and 3 aged elements, tested at three measurement points, the following values were obtained:

- propagation velocity of longitudinal waves c_L in the range of 6860 ÷ 6950 m/s, average value equal to 6900 m/s.

- propagation velocity of transverse waves c_T in the range of 4040 ÷ 4120 m/s, average value equal to 4080 m/s.

Given the known density of the material ρ = 2,64 g/cm^3, provided by the manufacturer, the value of the Young's modulus of elasticity E of the material of both groups of samples was determined, based on the classical relationships [16]. It was E in the range of 106 ÷ 110 GPa, the average value was 108 ± 1,0 GPa. As mentioned, the obtained values correspond to the longitudinal axis of the insulator material, where in practice it carries operational loads. The acoustic parameters of the material and the value of the elastic modulus, determined on their basis, are typical for the domestic porcelain material C 130 type in various modifications [15]. Ultrasonic tests performed with high precision showed no reduction in the material parameters as a result of high direct voltage (HVDC).

Table 1. Breaking stresses in the 3-point bending test of C 130 porcelain samples. Comparatively, the results given in megapascals (MPa) were collected for reference samples and samples aged with high direct voltage (HVDC).

Designation of the sample	Reference samples	Aged samples
1	100.0	123.4
2	88.3	102.8
3	151.6	131.1
4	136.6	108.4
5	119.1	105.0
Average value	**119.1**	**114.2**
Relative dispersion [%]	53.2	24.8

Tests of the mechanical strength of the material of reference and aged samples showed a significant dispersion of results in both groups. The results of measurements of breaking stresses (Modulus of Rupture) for both groups of specimens are summarized in Table 1. The samples were cut off from fragments of the insulator rod, received from the manufacturer, which was cut in several places between the sheds, perpendicular to its longitudinal axis. It was possible to cut the samples only in such an arrangement that their longitudinal axis was perpendicular to the axis of the insulator rod. A small, precise saw with internal diamond grit and small grain size was used, which significantly reduced the layer of material damaged by cutting. Nevertheless, the surface of the cut samples had defects, and their geometry - including planar parallelism - varied to some extent. This is the reason why the obtained results are characterized by a large scatter and the obtained values can only be treated comparatively. Nevertheless, it can be said with certainty that the long-term aging process with high direct voltage did not reduce the mechanical strength of the porcelain material. Despite the large dispersion of the results, considerably larger for the reference samples, the average values of the breaking stress for both groups of specimens are very similar. Certainly, under the influence of high direct voltage there were no effects that would reduce the mechanical strength of the tested material.

Optical microscopy tests did not reveal any differences in the microstructure of the reference samples and those aged with constant voltage. However, examination of the bodies of various samples indicated differences in the content of the phases that make up the body in individual observation fields. The material was well sintered, but its homogeneity on a semi-macro and even macro scale could raise objections. Clear differences in the phase structure were found in samples taken not only from different fragments, but even from the same one.

This was previously indicated by differences in the recorded propagation velocities of ultrasonic waves. Therefore, the low homogeneity of the material at the micro scale is obvious. In particular, this applies to the precipitates of the mullite phase in the glassy matrix, but also to the corundum and quartz phases. Both the reference and aged samples were characterized by a less homogeneous microstructure, and no differences were observed between them and no degradation effects were found in the material microstructure of the aged samples. Figure 3 shows a typical image of the microstructure of the material - on the example of the reference sample marked 2. Figure 4 shows, at a higher magnification, the microstructure of the aged sample marked 1.

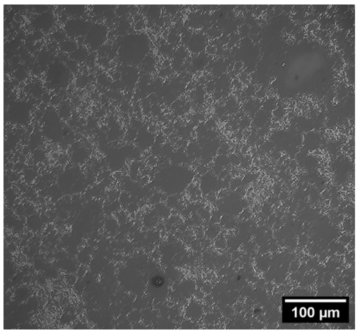


Fig.3. Typical image of the microstructure of the tested material - reference sample marked 2. Numerous small, light corundum grains with an elongated shape are visible against the background of a dark glassy-mullite matrix. In the lower part of the image two small black pores and a round black area left by a chipped off quartz grain can be seen. Inhomogeneity of the material microstructure draws attention

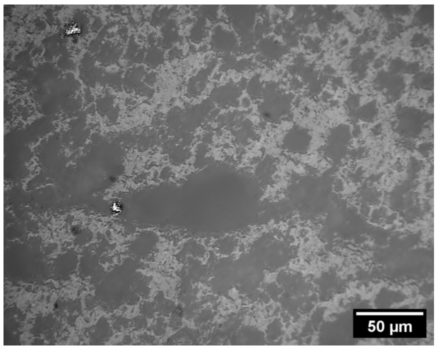


Fig.4. Image of the microstructure of the aged sample marked 1. Low homogeneity of the material structure on the micro scale is visible. Noteworthy are large, dark glassy-mullite precipitates and two characteristic white fragments of cullet

In the case of high-strength aluminous porcelain C 130 type, the basic phase constituting the structural, mechanical reinforcement - in this case dispersive - is fine-grained corundum. This phase was distributed quite heterogeneously in the structure of the tested material on a micro scale. The corundum content, averaged for dozen observation fields, was 15%. However, there were significant differences in individual fields of observation - from 10 to 18%. The small, light grains with an elongated shape had a size ranging from a few to a dozen or so micrometers - on average about 6 μm, with a width of about 2 μm. Corundum grains most often occurred in clusters, and their significant concentration was often observed in the vicinity of mullite precipitates. It should be noted that the corundum grains were well bonded with the remaining phases that make up the material, especially the glassy matrix.

The quartz content in the tested porcelain was difficult to determine. There were significant differences in the amount of this phase in individual fields of observation. The average quartz content can be estimated at about 5%. Quartz relics were most often well melted on their borders, although they frequently contained peripheral and internal cracks. Some of the grains or their fragments were chipped off during polishing. The grains ranged in size from a few to over a hundred micrometres. Smaller grains dominated, with dimensions of a few or a dozen or so micrometres. They were heterogeneously distributed in the matrix. There were found clusters of quartz grains. Figure 5 shows a grouping of large quartz grains with characteristic internal cracks indicating their plate-like morphology.

The mullite phase stood out very poorly from the matrix of the tested material. It formed a uniform alloy with the glassy phase, which created the material matrix. However, the microscopic image showed characteristic gray fields with a rounded, often elongated shape, usually surrounded by groups of corundum grains. The glassy-mullite precipitates had a length ranging from a few to over 100 μm. Most often, their size was several dozen micrometres. The rounded shape and size indicate that the fields of mullite precipitates reflect particles of raw materials (silty minerals). The total content of the glassy-mullite matrix was high and, depending on the field of observation, ranged from less than 75% to over 80%, with an average of 77%. The content of the mullite phase could not be determined precisely, it can only be estimated at over 25% of the surface of the samples. It is worth emphasizing the heterogeneous distribution of the mullite phase in the form of precipitates, clearly visible on the micro scale. Moreover, regardless of the visible precipitates, there were scattered needle-shaped mullite crystals, several micrometers long, in the glassy matrix of the material. They constitute a fibrous reinforcement of the material structure.

Small black pores with a regular, oval shape usually constituted a fraction of a percentage of the surface of the material. Most often, their size was within a single micrometre. However, larger pores were also found on occasion. The spatial distribution of pores was heterogeneous and varied in different fields of observation. Areas with slightly higher pore concentrations were found locally - usually around 0,5%. The dark fields, that were visible in the images of the structure of the tested material, remained from elements of the body that were chipped off during the preparation of the observation surfaces. They usually occupied approximately 3% of the area of microsections, although there were significant differences in different fields of observation. Most of the chipped off elements of structure were particles of cullet, the connection of which with the matrix is generally weak. Especially since they do not melt during firing (sintering). The content of cullet in the composition of the tested mass did not exceed 3%. The size of the dark fields was most often in the range of 5,0 ÷ 10,0 μm and these are the dimensions of the cullet particles. The remaining white particles of cullet in the microstructure are visible in Figure 4.

Summarizing the results of microscopic tests, it should be stated that the tested material belongs to aluminous, high-strength porcelains C 130 type. It has a phase structure typical for this class of materials, but with low homogeneity. The microstructure of the material turned out to be resistant to long-term exposure to high direct voltage. No signs of material degradation were observed.

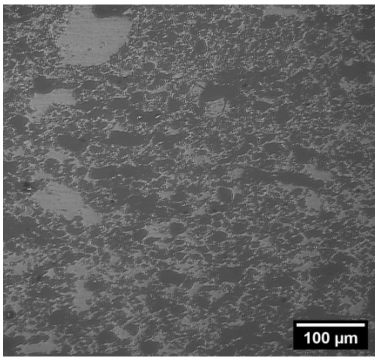


Fig.5. Image of the microstructure of the aged sample marked 4. Attention is drawn to the grouping of large light quartz grains. They contain characteristic internal cracks indicating an unfavourable lamellar morphology

Summary and Conclusions

The tests results confirmed that the insulator material belongs to aluminous, high-strength porcelains C 130 type. It has a phase structure typical for this class of materials, although with low homogeneity. Also, the strength and acoustic parameters of the material, as well as the determined value of the Young's modulus of elasticity, are typical for C 130 type materials that has been studied for years, in various modifications [1,2,15]. The insulator and the porcelain material from which it is made were designed to operate in high voltage alternating current (HVAC) conditions.

The aim of the presented research was to check the resistance of aluminous porcelain material C 130 type to aging - degradation under high voltage direct current (HVDC) conditions. Therefore, a group of 5 samples was exposed to high direct current voltage - 2 kV/cm for 6.000 hours. Long-term exposure of the material to such conditions can potentially lead to various negative effects. First of all, an ionic current may flow - the effect of ion migration and the material electrolysis. The possible flow of ions towards the electrodes through the material, and therefore the movement of mass, may result in damage to the structure of the porcelain and, consequently, cause a gradual degradation of the mechanical properties of the material.

Ultrasonic measurements did not reveal any differences between the material of the aged and reference samples. Also, 3-point bending tests of porcelain samples showed that there were no effects that would reduce the mechanical strength of tested material. Microstructure of the material turned out to be resistant to long-term exposure to high direct voltage. No signs of material degradation were observed. Therefore, the possibility of using aluminous, high-strength porcelain C 130 type of long-rod insulator for operation under high voltage direct current (HVDC) was demonstrated.

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