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Key dielectric properties and performance evaluation of high-density pressboard for electrical purposes

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ABSTRACT
A high-density electrical pressboard plays a significant role in maintaining the safe and stable operation of power equipment. In response to concerns about finding an evaluation method based on the dielectric performance of the pressboard, this study set up a measurement platform to capture data for three key dielectric properties, namely, relative permittivity, volume resistivity, and surface resistivity. Five kinds of pressboards obtained from representative insulating materials manufacturers were chosen as test samples, and the effects of temperature and moisture content of the pressboards on their dielectric properties were quantitatively investigated. The results indicated that (1) with increasing temperature and moisture content of the pressboards, there was an increase in the relative permittivity, with a maximum increase of 55.85%; (2) the higher the temperature and moisture content of the pressboards, the lower the volume and surface resistivity, and the maximum reduction was as much as 98.25%; (3) significant differences exist in the dielectric properties of different batches of pressboards from the same manufacturer; and (4) the results of tests of conventional physical and chemical properties of pressboards could help explain the differences in dielectric properties between different types of pressboards. Finally, based on the variation in dielectric properties for different test conditions, a method for evaluating the performance of pressboards is proposed. Using this method, the dielectric properties of different insulating pressboard products can be compared horizontally, which will provide data support and technical reference for the design of insulation structures and the selection of insulating materials for different applications.

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I. INTRODUCTION
With the rapid development of high voltage direct current (HVDC) transmission projects, the capacity of power grids continues to increase and the operating voltage levels of converter transformers are also continually increasing. The internal insulating structures of converter transformers are of great importance for maintaining the safe and reliable operation of power grids, while their failure is also one of the leading causes of operational faults.1,2

The main insulating structure of a converter transformer is a typical oil–pressboard composite insulation composed of transformer oil and a high-density pressboard for electrical purposes. The latter (referred to simply as “pressboard” in the following) is made of natural vegetable fibers, mineral fibers, synthetic fibers, and other admixtures. The various celluloses are deposited on the papermaking machinery under the action of water or another fluid medium, and then the forging, drying, and polishing procedures are carried out to form the pressboard.3 With the advantages of high tensile strength, low shrinkage, high apparent density, and excellent insulating properties, pressboards have been widely used as an insulating medium in transformers, generators, capacitors, and other power equipment.4,5 In view of the actual
operating conditions of the insulating structures in converter transformers, pressboards are able to withstand the long-term applications of multiple field coupling stresses, for example, uneven temperature fields and the complex electric fields of DC, AC, and impulse voltages. Moreover, during the installation or maintenance processes carried out on transformers, the pressboard can encounter external ingress of moisture, and the aging process of pressboard or transformer oil can produce additional quantities of moisture. Both these conditions would exert significant moisture-dependent effects on the pressboard. Therefore, the key dielectric properties of the pressboard and their variation with external conditions such as temperature and moisture will directly or indirectly affect the operational reliability, safety, and service life of related power equipment.

With a view to elucidate the dielectric properties of pressboards and the conditions that affect them, some researchers have carried out and reported relevant studies. Li et al. investigated the effects of temperature, field strength, and aging on the resistivity of oil and oil-impregnated pressboard. Kierczynski et al. made a comparison of the DC conductivity of the insulating oil and the moisturized electrical pressboard impregnated with insulating oil. In addition, the influence of temperature on the DC conductivity of dry electrical pressboard impregnated with synthetic ester has also been studied. Huang et al. emphasized the effect of water conductivity on the permittivity of the pressboard and built a model of the effective permittivity of insulating presspaper based on the microstructure of the material.

A state of the art literature review indicated that relevant studies do exist. However, taking the complex insulating structures of converter transformers into consideration, certain deficiencies in the research protocols of these studies stand out. Due to the requirements of high capacity and high voltage levels for converter transformers, various complex insulation components are needed to maintain their high-performance insulating properties, such as the surrounding pressboards in the outlet devices or wet-molding angle rings. Generally, in the manufacture or assembly of insulating structures in large quantities, different kinds of insulating materials are used. In addition, there are different manufacturers for the development of different types of converter transformers, which explains the use of different kinds of pressboards. Previous studies have mostly been conducted on a single characteristic of one particular kind of pressboard. Thus, there exists a large void in the research related to the following aspects: (1) the influence of operating conditions on the performance of pressboards, (2) the parallel comparative study of the dielectric performance of different kinds of pressboards, and (3) the stability of performance of these same pressboards. More significantly, without such systematic comparative studies, there will not be any method for evaluating satisfactory performance in selecting insulating pressboards.

In response to the above-mentioned research void, this study chose five different kinds of high-density pressboards for electrical purposes supplied by five well-known manufacturers of converter transformer insulation materials as the test samples. Multiple tests were conducted to determine the effects of temperature and moisture content on the key dielectric properties, such as relative permittivity and volume/surface resistivity. The dielectric properties of different batches of the same kind of pressboard were measured to determine the stability of their performance. The differences in the properties among the different kinds of pressboards are discussed below based on the test results for the physical and chemical properties of the pressboards. On the basis of a large amount of test data, this paper proposes a performance evaluation method for a high-density pressboard for electrical purposes, which is dielectric-property dominant. It is hoped that this method can provide data and technical support for the design of insulating structures and the selection of insulating materials.

II. PERFORMANCE INDICATORS AND TEST PLATFORMS

A. Performance indicators

As the pressboard insulating structures in converter transformers can bear AC, DC, AC/DC combined, and impulse voltages under actual operating conditions, the electric field characteristics of pressboards under different voltages should be taken into account when determining the performance indicators for dielectric properties. Under DC voltage, the electric field strength is proportional to the resistivity of the dielectric medium, while under AC voltage, the field strength is inversely proportional to the relative permittivity of the dielectric medium. Therefore, this study chose the relative permittivity and volume/surface resistivities of pressboards as the performance indicators of the dielectric properties, and the specific characteristics of each indicator are stated in detail as follows.

1. Relative permittivity

The relative permittivity of the pressboard, a material property that affects the Coulomb force between two point charges in the material, indicates how easily the pressboard can become polarized by imposition of an electric field on it, which originates from a number of sources, including electronic, atomic, dipolar, space charge, or ionic. The temperature and moisture content of the pressboard can exert a significant effect on the relative permittivity and can then affect the electric field or charge characteristics of the insulating structures.

2. Volume and surface resistivities

The volume and surface resistivities of the pressboard are a fundamental property that quantifies how strongly the material resists or conducts electric current within the internal volume of the pressboard or on its surface. The internal carrier concentration and the mobility of the medium can play a significant role in determining the conductivity characteristics of the pressboard. During the manufacturing process, it is inevitable that small amounts of impurities will be doped into the material to form carriers. In addition, there may also be small amounts of carriers in various additives that are not involved in the compounding process. The mobility of carriers refers to their directional movement inside the dielectric polymer, the kinetic energy of which is closely related to the temperature and moisture content of the pressboard. For example, when the operating temperature of the insulating structure increases, the microscopic behavior of the molecules is enhanced by their thermal motion. Moreover, the collisions between carriers are also more
energetic, resulting in a shortened relaxation time, which might explain the decrease in the resistivity of the insulating medium. Therefore, the volume and surface resistivities of the pressboard and how they vary with the temperature and moisture content can sensitively reflect the electrical conductivity of the material, which is an important indicator for evaluating the dielectric properties of the board.

B. Test platform

To ensure the reliability and accuracy of the test results, the sample testing, design of the test procedures, and the construction of the measurement platforms for the dielectric property tests followed strictly the standards laid down by the International Electrotechnical Commission, namely, IEC 62631-2-1:2018, IEC 62631-3-1:2016, IEC 62631-3-2:2015, and IEC 62631-3-4:2019.\textsuperscript{19–22}

1. Volume/surface resistivity test platform

The measuring principle and schematic diagram of the volume/surface resistivity test platform are illustrated in Figs. 1 and 2. The volume/surface resistivity test platform comprised a three-electrode system, DC voltage supplier, test cavity, and data acquisition device, as shown in Figs. 1(a) and 1(b). The DC voltage supplier had an output voltage ranging from $-10 \text{kV}$ to $+10 \text{kV}$ and a ripple factor of less than 0.1%. The temperature control unit initiated the heating action via the oil-bathing module, and the temperature controlling and monitoring functions were processed by the intelligent PID control module, ensuring an accuracy of less than 0.1 °C. The three-electrode system consisted of three brass electrodes with a surface roughness $R_a$ of less than 0.5 μm. A Keithley 6517B electrometer was adopted as the current data acquisition device, which had an input impedance of more than 200 TΩ and a current measuring ranging from 1 fA to 20 mA.

2. Relative permittivity test platform

A Haefely Hipotronics 2830/2831 precision solid dielectric analyzer was used to measure the relative permittivity of the pressboard. The instrument had a measuring range of relative permittivity from 1 to 30, with a maximum resolution of 0.001. The heating controller controlled the temperature of the sample in the range from ambient temperature to 200 °C, with a maximum resolution of 0.1 °C and an accuracy of ±0.5 °C.

C. Test samples and test conditions

Depending on operational requirements, manufacturing costs, and other considerations, the complex pressboard insulation in converter transformers can consist of different samples supplied by different insulating material manufacturers. In consequence, five different kinds of 1 mm thick high-density pressboards for electrical purposes from five well-known material manufacturers were chosen as the test samples for our study, which were labeled PB-A, PB-B, PB-C, PB-D, and PB-E. The sample quantity of each kind of pressboard adopted in each test was set as 10, and the average values of the test results are presented in the following discussion.

In the manufacture and assembly of the insulating structures of converter transformers, the moisture content of the insulating
pressboard is required to be less than 1.0%, but since the body is inevitably exposed to the atmosphere during its installation or maintenance, external moisture can, therefore, penetrate into the pressboard. In addition, during the long-term operation of complex electric fields, the aging process of pressboard or transformer oil can also produce a certain amount of moisture, resulting in the moisture content of a partial area in the pressboard reaching a level of more than 7%. Hence, the moisture gradients of the pressboards in our tests were chosen to be 1.0%, 3.0%, 5.0%, and 7.0%.

The normal operating temperature of insulating structures in transformers is between −40 and +40 °C. However, the heat generated by the transformer under the multiple actions of various fields will cause the internal operating temperature to be higher than the ambient temperature but is usually below 95 °C. In this study, taking the operating environment, climatic conditions, altitude, and other conditions of operating a converter transformer into account, the test temperature gradients were chosen to be 20, 40, 60, and 80 °C.

For temperature control of the pressboards being tested, the test platform described in Sec. II B was sufficient to accomplish the precise actions necessary. As for processing pressboards with different moisture contents, a programmable controller to maintain a constant temperature and humidity of the sample was employed, which had a temperature adjustment range of −40 to +150 °C and a humidity adjustment range of 20%–98% RH. With regard to the tests for determining the moisture content of the pressboards, a Metrohm 831 KF Coulometer and a Metrohm 860 KF Thermoprep KF831 were employed, which had a moisture measuring accuracy of 0.1 μg. In summary, the specific samples and test conditions employed in this study are given in Table I.

### III. KEY DIELECTRIC PROPERTIES OF THE PRESSBOARDS

#### A. Effect of temperature

In the tests for the effect of temperature on the dielectric properties of pressboards, temperature conditions of 20, 40, 60, and 80 °C were chosen. The test results for the relative permittivity and the volume/surface resistivity of different pressboards are shown in Fig. 3.

The test results for the dielectric properties of pressboards at different temperatures (20–80 °C) are as follows:

1. As the temperature increased, the relative permittivity of the pressboard also gradually increased. Pressboard B showed the maximum increase of 9.01%, while pressboard E showed the minimum increase of 3.37%. At 20 °C, the relative permittivity of pressboard C was the greatest, with a value of 3.35, while that of pressboard B was the smallest, with a difference of 4.03% compared to that of pressboard A. At 80 °C, pressboard D had the greatest relative permittivity of 3.63, while that of pressboard E was the smallest at 3.37.

2. In contrast to the test results for relative permittivity, the volume/surface resistivity of the pressboards both gradually decreased with the increase in temperature. In terms of volume resistivity, pressboard C showed the greatest reduction of 97.56% and pressboard A showed the smallest reduction of 90.03%. At 20 °C, the volume resistivity of pressboard C was the largest, while that of pressboard D was the smallest, and their difference was 68.11%. At 80 °C, the largest volume resistivity was shown by pressboard A and the smallest by pressboard D. Pressboard C showed the largest volume resistivity of 97.60%, while pressboard D showed the smallest value of 77.16%. At 20 °C, the difference in surface resistivity between pressboard C (largest) and pressboard D (smallest) was 61.52%. At 80 °C, however, the maximum and minimum values were shown by pressboards A and B, respectively, and the difference between them increased to 78.79%.

The temperature dependence of the relative permittivity and volume/surface resistivity of the pressboards (Fig. 4) can be expressed by the following equations:

\[ \varepsilon_{P(T)} = \varepsilon_0 + A_1 \times e^{A_2 \times T}, \]  
\[ \rho_{P(T)} = \rho_0 + B_1 \times e^{B_2 / T}, \]

where \( \varepsilon_{P(T)} \) and \( \rho_{P(T)} \) are the relative permittivity and volume/surface resistivity of the pressboard as a function of temperature, respectively, \( \varepsilon_0 \) and \( \rho_0 \) are parameters related to the inherent characteristics of different pressboards, \( A_1 \), \( A_2 \), \( B_1 \), and \( B_2 \) are relative permittivity parameters correlated with the temperature-dependence of the pressboards, and \( T \) is the temperature.

The effect of temperature on the dielectric properties of the pressboards can be stated as follows:

1. When the temperature of the pressboard is relatively low, the thermal motion of the polar molecules in the pressboard is very weak, resulting in a long relaxation time, and there is not enough time for them to be oriented with the applied alternating electric field. At this state, only electron displacement polarization is observed. When the temperature of the pressboard increases, the thermal motion of the molecules is enhanced and is followed by a reduction in the relaxation time. Hence, the relaxation polarization associated with thermal motion can be readily observed, leading to an increase in the relative permittivity.
During the manufacture and processing of insulation pressboards, it is inevitable that small quantities of impurities are mixed into the materials. As the temperature increases, the activation energy of these impurity ions gradually decreases and the ions began to migrate directionally, resulting in an increase in current and a decrease in volume resistivity. The effect of these charges, either in the actual operating environment of the pressboard or in the resistivity measurement environment, becomes more significant at higher temperatures.
process, is that the metal electrode will inject charge carriers into the pressboard under the action of the electric field. In addition, an increase in temperature can intensify the charge injection, thereby resulting in an increase in current and a decrease in resistivity.

B. Effect of moisture content

In the tests for the effect of moisture content on the dielectric properties of the pressboard, the test moisture gradients were chosen to be 1.0%, 3.0%, 5.0%, and 7.0%. The test results for relative permittivity and volume/surface resistivity of the different pressboards are presented in Fig. 4.

The test results in Fig. 4 indicate the following points:

(1) As for the different temperatures, as the moisture content of the pressboard increases, its relative permittivity also gradually increases. Pressboard E showed the maximum increase of 97.42%, while pressboard B showed the smallest increase of 55.85%. When the moisture content of the pressboard was 1.0%, the relative permittivity of pressboard A was the largest and that of pressboard B was the smallest, with a small difference of 2.98%. For a pressboard moisture content of 7.0%, pressboard E showed the largest relative permittivity of 6.44, while pressboard B showed the smallest value of 5.02, with a difference of 22.05%, larger than that in the case of a 1.0% moisture content.

(2) The effect of moisture content on the volume/surface resistivity indicated that the larger the moisture content of the pressboard, the smaller its volume/surface resistivity. With regard to volume resistivity, pressboard D showed a maximum reduction of 98.25%, while pressboard B showed a minimum value of 88.25%. Whether the moisture content in the pressboard was 1.0% or 7.0%, the volume resistivity of pressboard C was the largest and that of pressboard D was the smallest. With regard to surface resistivity, the maximum reduction with an increase in the moisture content was shown by pressboard C and the minimum reduction was shown by pressboard B. For the pressboard with a 1.0% moisture content, the surface resistivity of pressboard C was the greatest, with a value of 7.22 $\times 10^7$ Ω, while pressboard D showed the smallest value of 5.26 $\times 10^7$ Ω, with a difference of 31.94%. For a pressboard moisture content of 7.0%, pressboard B showed the smallest surface resistivity, with a difference of 22.05%, larger than that in the case of a 1.0% moisture content.

The fitted curves in Fig. 4 can be expressed by the following equations:

$$\varepsilon_r(W) = \varepsilon_0 + A_3 \times W^{\Delta_4},$$  
$$\rho_v(W) = \rho_0 + B_1 \times W^{\Delta_4},$$

where $\varepsilon_r(W)$ and $\rho_v(W)$ are the moisture-dependent relative permittivity and volume/surface resistivity of the pressboard, respectively, $\varepsilon_0$ and $\rho_0$ are constants related to the inherent characteristics of the pressboards, $A_3$, $A_4$, $B_1$, and $B_4$ are parameters associated with the variation in pressboard properties with its moisture content, and $W$ is the moisture content of the pressboard.

The effect of moisture content on the dielectric properties of the pressboard can be explained as follows:

(1) The increase in the moisture content of the pressboard leads to an increase in the number of carriers and strengthens the interactions between molecules in the pressboard. Under the action of an external electric field, the number of carriers with directional motion can increase very rapidly, which would result in a higher polarization speed and a shorter relaxation time of dielectric response, leading ultimately to an increase in the relative permittivity. Moreover, the permittivity of water is much higher than that of the pressboard, which also contributes to the increase in its relative permittivity.

(2) The conductivity of the pressboard is determined mainly by the ionic conductance. When the moisture content of the pressboard increases, the internal “impurity” ion concentration also increases, accelerating the ion migration process and resulting in an increase in current, thereby decreasing the resistivity of the pressboard.

IV. DISCUSSION

A. Stability of dielectric properties of different pressboards

Due to the complex insulating structures of converter transformers, there exist various application sites for pressboards with different shapes and dimensions, and these pressboards may come from different batches produced by the same manufacturer. Therefore, knowing how stable the dielectric properties of different batches of the pressboard from the same manufacturer are is of great importance for maintaining the stable operation of these insulating structures.

To test the stability of the dielectric properties, five different batches of pressboards, each from the same manufacturer, were randomly sampled, and five samples from each batch were taken to test their relative permittivity and surface/volume resistivity. The variance of each test result was taken as an indicator to evaluate the dielectric performance stability of the pressboard. Using the test results for conditions of ambient temperature and low moisture content as an example, the performance stabilities of the dielectric properties of the same kinds of pressboard are shown in Fig. 5 and given in Table II.

The test results in Table II show that (1) with respect to relative permittivity, the fluctuations in the test results for different batches of pressboard D are the most obvious, with a variance of 0.049, while the variance of the test results for pressboards A, C, and E were all at a minimum of 0.001; (2) with respect to the volume resistivity, the maximum variance of the test results was shown by pressboard B, while the minimum was shown by pressboard C, with a difference of 94.8%; (3) with respect to the surface resistivity test results, pressboard C also showed the minimum variance, with a value of 0.003, and pressboard A showed the maximum variance of 0.222. Based on comprehensive analysis and comparison, the stability of the dielectric properties of
pressboards. The specific indicators of these physical and chemical properties are as follows:

1. The apparent density of the insulating pressboard is the mass-to-volume ratio, which characterizes its compactness and is closely related to its resistivity. The larger the apparent density, the better the insulating and dielectric performance.

2. The conductivity of the aqueous extract is the conductance of the water-soluble cellulose component of the pressboard, which characterizes the microscopic content of the metal particles within it and which directly affects the key dielectric properties of relative permittivity and resistivity; the smaller the value, the better the performance.

3. Degree of polymerization: the raw material used to manufacture the insulating pressboard is wood pulp, and its main component is cellulose containing several glucose rings, \([\text{C}_6\text{H}_{10}\text{O}_5]_n\), which is a chainlike polymolecular compound where \(n\) represents the degree of polymerization. The long-term operation of an electric field on the pressboard will lead to changes in the degree of polymerization, leading to variations in impurities and moisture content, which will exert a direct effect on the dielectric properties.

In the above-mentioned tests of physical and chemical properties, the sampling procedures, design of the test procedures, and the construction of the test platform were followed strictly in accordance with IEC 60641-1:2007, IEC 60641-2:2004, and IEC-60450-2004 to ensure the reliability and accuracy of the test results.

The results for the general physical and chemical properties and their variance for different pressboards are given in Table III.

It can be seen from Table III that (1) in terms of apparent density, that of pressboard C is the highest, while that of pressboard D is the lowest, and the difference is 6.61%; (2) with respect to the conductivity of the aqueous extract, the minimum value is shown by pressboard C, while the maximum value is shown by pressboard A, and the difference between them is 6.61%; (3) with respect to the degree of polymerization of the pressboard, the maximum and minimum values belong to pressboards C and D, respectively, with a difference of 4.52%; (4) the variances of the test results for the physical and chemical properties of different pressboards are consistent with those of the dielectric property test in Sec. IV A, that is, the performance stability of pressboard C is the highest.

### Table II. Variance of dielectric property test results for different batches of pressboards (20 °C, 1.0% moisture content).

| Pressboard | Relative permittivity/\(\text{variance}\) | Volume resistivity/\(\text{variance}\) | Surface resistivity/\(\text{variance}\) |
|------------|------------------------------------------|-------------------------------------|-------------------------------------|
| Pressboard A | 0.001/0.002 | 0.205/0.022 | 0.011/0.002 |
| Pressboard B | 0.030/0.016 | 0.618/0.016 | 0.003/0.003 |
| Pressboard C | 0.001/0.003 | 0.032/0.003 | 0.017/0.003 |
| Pressboard D | 0.049/0.017 | 0.523/0.017 | 0.003/0.003 |
| Pressboard E | 0.001/0.002 | 0.041/0.002 | 0.011/0.002 |

### Table III. Physical and chemical properties of different kinds of pressboards and their variance.

| Pressboard | Apparent density (g/cm\(^3\))/\(\text{variance}\) | Conductivity of aqueous extract (mS/m)/\(\text{variance}\) | Degree of polymerization/\(\text{variance}\) |
|------------|-----------------------------------------------|--------------------------------------------------|------------------------------------------|
| Pressboard A | 1.035/2.74 \(\times\) 10\(^{-6}\) | 2.31/3.56 \(\times\) 10\(^{-4}\) | 1631.5/2.65 |
| Pressboard B | 1.073/7.17 \(\times\) 10\(^{-5}\) | 1.85/6.96 \(\times\) 10\(^{-4}\) | 1688.0/18.00 |
| Pressboard C | 1.090/1.69 \(\times\) 10\(^{-6}\) | 1.78/1.85 \(\times\) 10\(^{-4}\) | 1701.4/2.85 |
| Pressboard D | 1.018/1.02 \(\times\) 10\(^{-4}\) | 2.27/4.74 \(\times\) 10\(^{-3}\) | 1624.5/31.25 |
| Pressboard E | 1.072/6.21 \(\times\) 10\(^{-6}\) | 1.85/1.41 \(\times\) 10\(^{-4}\) | 1635.1/7.69 |
best, while that of pressboard D is the worst; (5) by a comprehensive comparison of the results of both the dielectric properties and the physical and chemical properties tests, the differences in the physical and chemical properties of different pressboards could make for a convincing explanation for those of the dielectric properties.

V. METHOD OF PERFORMANCE EVALUATION BASED ON THE KEY DIELECTRIC PROPERTIES OF PRESSBOARDS

According to the results of the above tests on the dielectric properties of different pressboards, the differences in performance of different pressboards are obvious, but each kind of pressboard has its own advantages. In addition, the dielectric properties of different batches of pressboards provided by the same manufacturer also differ. Therefore, when selecting insulating pressboards, their different properties should be taken into account to ensure that they perform to the optimal level. Based on the dielectric properties, a comprehensive method of evaluating the performance of different insulating pressboards is proposed in this paper, the flow chart for which is shown in Fig. 6. Five kinds of pressboards were labeled as the evaluation objects, and the difference in the condition of temperature in Fig. 6, the standard deviation of the test results. As shown in Fig. 6, data processing was first carried out to nondimensionalize all of the dielectric property data of the test pressboards. Second, the variations in the dielectric properties data of five kinds of pressboards under different conditions and moisture conditions were determined to estimate the weight of each indicator. Third, the weight of temperature and moisture was differentiated with respect to the variations of different dielectric properties of pressboards with the temperature and moisture. Finally, the grade of dielectric performance of each pressboard was obtained by the sum of the weighted data, and their ranking based on dielectric properties could then be determined.

A. Composition of the evaluation database

The database of dielectric properties is composed of all of the test data for the five kinds of pressboards, including the data for the relative permittivity and volume/surface resistivity at different temperatures (20, 40, 60, and 80 °C) and moisture contents (1%, 3%, 5%, and 7%). The data matrix for each dielectric property is expressed by the following equation:

\[
[P] = \begin{bmatrix}
X_{11} & \cdots & X_{14} \\
\vdots & \ddots & \vdots \\
X_{51} & \cdots & X_{54}
\end{bmatrix}
\]  

where \([P]\) is the matrix of all test results, \(X_{ij}\) represents the original test result of pressboard \(i\) at a specific temperature and moisture condition, \(i = 1, 2, \ldots, 5\) and \(j = 1, 2, \ldots, 4\) correspond the temperatures and moisture contents, respectively.

B. Data processing

This study adopted three different key dielectric properties of pressboards as the performance indicators, namely, relative permittivity, volume resistivity, and surface resistivity, but these different indicators have different units. In order to perform data processing uniformly, it was necessary to perform dimensionless processing on all of the test data. Taking as an example the relative permittivity of the pressboard at 20 °C and with a 1.0% moisture content, namely, the \(x_{11}\) in Eq. (5), data processing could be performed using the following equation:

\[
x_{11}^* = \frac{x_{11}}{\sqrt{\sum_{i=1}^{n} (x_{1i})^2}},
\]

where \(x_{11}\) represents the original test result of the relative permittivity of pressboard A at 20 °C and with a 1.0% moisture content, \(x_{11}^*\) represents the test results at different temperatures, \(Y_{ni}\) represents the test result for different moisture contents, and \(n\) is the number of samples (1–5 corresponds to pressboards A–E, respectively), \(i\) represents the four temperature conditions (1–4 corresponds to 20, 40, 60, and 80 °C, respectively), and \(j\) represents the four moisture content conditions (1–4 corresponds to 1.0%, 3.0%, 5.0%, and 7.0%, respectively).

C. Determination of the weighting of each indicator under different conditions

Since there are two condition variables, namely, the temperature and moisture content of the pressboard, for each dielectric property indicator, stepwise processing is required when determining their weighting, as shown in the flow chart in Fig. 7. Taking as an example the indicator of relative permittivity and the condition of temperature in Fig. 6, the standard deviation of the relative permittivity of the five kinds of pressboards at 20 °C was...
found to be 0.006, and then those at temperatures of 40, 60, and 80 °C were obtained as 0.007, 0.010, and 0.012, respectively. Thereafter, all of the standard deviations were obtained via the normalizing process to capture the different weightings of relative permittivity under different temperature conditions, which were 0.185, 0.188, 0.276, and 0.352, corresponding to 20, 40, 60, and 80 °C, respectively. Similarly, the weightings of all other indicators under different conditions were obtained. As an example, the weighting matrix of relative permittivity under different conditions is expressed by the following equation:

$$[\omega_\text{1}] \text{ or } [\omega_\text{2}] = \begin{bmatrix} \omega_{11} \\ \omega_{12} \\ \omega_{13} \\ \omega_{14} \end{bmatrix} \quad (7)$$

where $[\omega_\text{1}]$ or $[\omega_\text{2}]$ is the column matrix for weighting of relative permittivity related to different conditions of temperature and moisture content, $i$ represents the four different temperature conditions (1–4 corresponds to 20, 40, 60, and 80 °C, respectively), and $j$ represents the four moisture content conditions (1–4 corresponds to 1.0%, 3.0%, 5.0%, and 7.0%, respectively).

**D. Performance grades**

For a certain indicator of dielectric properties, the processed data sample matrix is left-multiplied by its corresponding weighting column matrix, and the performance grade corresponding to each kind of pressboard is then obtained, as shown by the following equation:

$$\begin{bmatrix} X_{xy} \end{bmatrix} \begin{bmatrix} \omega_{xy} \end{bmatrix} = S'_{5 \times 1},$$

$$\begin{bmatrix} Y_{xy} \end{bmatrix} \begin{bmatrix} \omega_{xy} \end{bmatrix} = S''_{5 \times 1}.$$  

In Eq. (8), $X_{xy}$ and $Y_{xy}$ represent the dimensionless dielectric properties of the pressboards under different temperatures and moisture conditions, $\omega_{xy}$ and $\omega_{xy}$ represent the temperature and moisture content weightings for the dielectric properties, and $S'_{5 \times 1}$ and $S''_{5 \times 1}$ represent the performance grades of pressboards at different temperatures and with different moisture contents, respectively. Adding $S'_{5 \times 1}$ and $S''_{5 \times 1}$, the performance grades of pressboards based on the tested dielectric property can be obtained, namely, the $S''_{5 \times 1}$ in the following equation:

$$S''_{5 \times 1} = S'_{5 \times 1} + S''_{5 \times 1}.$$  

In the same way, the data for the other dielectric properties can be processed to work out the performance grades of different pressboards based on the tested dielectric properties under different conditions of temperature and moisture content.

**E. Application of the evaluation method**

Utilizing the large amount of test result data in this study combined with the pressboard performance evaluation method proposed above, we have attempted to rank the dielectric performance of the five kinds of pressboards chosen for this study. The specific processes are enumerated as follows.

1. **Data processing and weight determination**

Adopting the data processing and weight determination method proposed in Secs. V B and V C, the weightings of each dielectric property under different conditions of temperature and moisture content for each of the pressboards are given in Table IV.

2. **Performance grades**

The processed dielectric property data matrix is multiplied by the weighting column matrix of each indicator to obtain the dielectric property grade and its performance rankings for different kinds of pressboards, as follows:

1. The performance grades of the five kinds of pressboards (PB-A to PB-E) related to relative permittivity were 0.8741, 0.8483, 0.9246, 0.8883, and 0.9291, respectively, while for the volume resistivity, they were 0.8179, 0.8454, 1.2814, 0.4093, and 0.7455, respectively, while for the surface resistivity, they were 0.7441, 0.7814, 1.2809, 0.7023, and 0.5222, respectively.

2. Adding the grades of the five kinds of pressboards with different dielectric properties to their comprehensive performance grades associated with the dielectric properties gives values of 2.4361, 2.4751, 3.4869, 1.999, and 2.1968. In summary, on the basis of the dielectric properties under different conditions of temperature and moisture content, the five chosen kinds of high-density pressboards for electrical purposes have a comprehensive ranking of C > B > A > E > D.

**TABLE IV.** Weightings for the dielectric properties of pressboards under different conditions of temperature and moisture content.

| Temperature (°C) | Moisture content (%) |
|------------------|----------------------|
|                  | 20       | 40       | 60       | 80       | 1.0      | 3.0      | 5.0      | 7.0      |
| Relative permittivity | 0.185   | 0.188   | 0.276   | 0.352   | 0.038   | 0.160   | 0.322   | 0.479   |
| Volume resistivity   | 0.186   | 0.156   | 0.277   | 0.380   | 0.507   | 0.295   | 0.124   | 0.074   |
| Surface resistivity  | 0.228   | 0.210   | 0.247   | 0.315   | 0.465   | 0.261   | 0.189   | 0.085   |
VI. CONCLUSIONS

This paper systematically tests the key dielectric properties of five kinds of high-density electrical pressboards provided by five well-known insulating material manufacturers, and the influencing rules and mechanism of external conditions such as temperature and moisture on different dielectric properties of the pressboard were revealed. According to the large quantity of test results, this paper proposes a pressboard performance evaluation method based on dielectric properties and evaluates the dielectric properties of different pressboards based on the measured results. The main research achievements are concluded as follows:

1. Considering the manufacturing process and operating conditions of a high-density pressboard for electrical purposes, the key dielectric properties such as relative permittivity and volume/surface resistivity are selected as the performance indicators for key dielectric properties. The temperature and moisture content of the pressboard were adopted as the main influencing conditions, and their effects on key dielectric properties of five different kinds of pressboards were completely tested to build a full database.

2. Following the instructions of the corresponding international standards, the test platforms and test procedures were technically built and proposed in this paper, ensuring the reliability and effectiveness of test results. For the volume and surface resistivity tests, the self-developed platform has a current measuring accuracy of 1 fA and a temperature control of 0.1 °C. In terms of relative permittivity test, the accuracy of measuring and temperature controlling of the test device can reach 0.001 pF and 0.1 °C.

3. With the increase in both temperature and moisture content of the pressboard, the relative permittivity of the pressboard also increased with a maximum growth rate of 55.85%, yet the different kinds of pressboards could witness various effects exerted by different conditions, and the maximum deviation could reach 22.05%. On the contrary, the volume/surface resistivity of pressboards gradually decreased as the temperature and moisture content of the pressboard mounted up, and the maximum drop is up to 98.25%. There are huge differences in the performance stability of different batches of the same kind of pressboard, which is closely related to the manufacturing technique. The test results of conventional physical and chemical properties of different kinds of pressboards can make the explanation and analysis for the difference of dielectric properties of different kinds of pressboards.

4. Based on the large quantity of test results, the varying rules and mechanism for the different dielectric properties of insulating pressboards with the temperature and moisture content were revealed, and correspondingly, the relative weightings of different influencing conditions were obtained. Finally, a performance evaluation method based on dielectric properties for high-density pressboards for electrical purposes was proposed, aiming to provide data support and technical reference for the insulation design of electrical equipment and the selection of insulation materials.

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