European Journal of
Engineering and Applied Sciences

ISSN: 2651-3412 (Print) & 2667-8454 (Online)
Journal homepage: http://dergipark.gov.tr/EJEAS
Published by Çorlu Faculty of Engineering, Tekirdağ Namık Kemal University

European J. Eng. App. Sci. 9(1), 49-54, 2026

Research Article

Polymeric Insulators With Enhanced Performance: A Study On Polyester Resin Additives

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Received 15.05.2026 *Accepted: 22.06.2026* *DOI: 10.55581/ejeas. 1951545*

Abstract: Power system reliability and sustainability are significantly influenced by the performance of insulation materials. Polymeric insulators, particularly polyester resin, offer promising alternatives to traditional ceramic and glass insulators. This study investigates the potential of enhancing the electrical and hydrophobic properties of polyester resin through the incorporation of various additives. Five different additive materials (boron oxide, boric acid, borax pentahydrate, silicon carbide, and alumina) were added to polyester resin at three distinct concentrations The resulting composite materials were subjected to two rigorous tests: the inclined plane test (IEC 587) to evaluate electrical durability and the hydrophobicity test to assess water resistance. The study revealed that the addition of 2% boric acid yielded the most significant improvement in electrical durability compared to pure polyester resin. However, the hydrophobicity tests indicated a decrease in contact angle for all doped samples, suggesting a potential trade-off between electrical and hydrophobic properties. A key innovation of this research lies in the utilization of large-sized, unique additive materials. These findings contribute to the development of advanced polymeric insulators with enhanced performance, thereby promoting the reliability and sustainability of power systems.

Keywords: *Insulator, sustainability, inclined plane test, hydrophobicity test, polyester resin.*

Geliştirilmiş Performansa Sahip Polimerik İzolatörler: Polyester Reçine Katkı Maddeleri Üzerine Bir Çalışma

Öz. Güç sistemlerinin güvenilirliği ve sürdürülebilirliği, izolatör malzemelerinin performansından önemli ölçüde etkilenmektedir. Polimerik izolatörler, özellikle polyester reçine, geleneksel seramik ve cam izolatörlere umut verici alternatifler sunmaktadır. Bu çalışma, çeşitli katkı maddelerinin polyester reçineye eklenmesiyle elektriksel ve hidrofobik özelliklerin geliştirilme potansiyelini araştırmaktadır. Beş farklı katkı malzemesi (bor oksit, borik asit, boraks pentahidrat, silisyum karbür ve alümina), polyester reçineye üç farklı oranda eklenmiştir. Elde edilen kompozit malzemeler iki kapsamlı teste tabi tutulmuştur: elektriksel dayanımı değerlendirmek için eğik düzlem testi (IEC 587) ve suya dayanımı değerlendirmek için hidrofobiklik testi uygulanmıştır. Çalışma sonuçları, %2 oranında borik asit ilavesinin saf polyester reçineye kıyasla elektriksel dayanımda en belirgin iyileşmeyi sağladığını göstermiştir. Ancak hidrofobiklik testleri, katkı eklenen tüm numunelerde temas açısının azaldığını ortaya koymuş ve bu durum elektriksel özellikler ile hidrofobik özellikler arasında olası bir ödünleşim olduğunu göstermiştir. Bu araştırmanın temel yeniliği, büyük boyutlu ve özgün katkı

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malzemelerinin kullanılmasıdır. Elde edilen bulgular, gelişmiş performansa sahip ileri düzey polimerik izolatörlerin geliştirilmesine katkı sağlayarak güç sistemlerinin güvenilirliği ve sürdürülebilirliğini desteklemektedir.

Anahtar Kelimeler: *İzolatör, sürdürülebilirlik, eğik düzlem testi, hidrofobiklik testi, polyester reçine.*

1. Introduction

When the history of electrical insulating materials that are widely used today is examined, it can be seen that it dates back to the 19th century, when Michael Faraday first noticed the electrical insulation feature of gutta-percha [1]. In this study, polyester resin which is proposed as a base material is in the polymeric insulating material category. Since the early 1960s, the use of insulators made of polymer composite materials has become widespread [2]. The polyester resin samples used in the study are added with three different ratios and five types of additive materials. Boron oxide, boric acid, borax pentahydrate, silicon carbide and alumina are preferred as novel additives with the percentages of (2%, 1% and 0.5%). In the selection of additive materials, attention is paid to the fact that the materials have widespread use, their technical qualities, low cost and that there is no harm in using them as additives to polyester resin [3-7].

After a successful production process, two test setups are employed for the tests. These tests are the inclined plane test and hydrophobicity test. The inclined plane test is established according to the IEC 60587 standard [8-9]. Since aging is an inevitable fact in polymeric materials, this situation has been examined in detail for the samples by the inclined plane test [10]. In the inclined plane test, the samples are compared with pure polyester samples with the additive ratios in terms of their electrical durability. It has been shown that especially in boron-doped samples, the added doping rate does not always have a significant linear increase or decrease.

In terms of electrical durability, the most durable material is polyester samples with 2% boric acid additive. In the hydrophobicity test, which is the second test of the study, the contact angles of the produced samples are examined and their water resistance is evaluated according to the results obtained. Water resistance is one of the most important features in determining the surface properties of polymeric insulating materials [11-13]. In this study, the half angle method is applied in the hydrophobicity test. In the results, numerical values of the inclined plane test and hydrophobicity test on the surface are obtained. In both test setups, measurements are repeated and their averages are taken to ensure that the tests are reliable and the results are accurate. Increasing insulator material operation lifetime decreases disposal material and hence increase sustainability of the power systems.

2. Material and Method

2.1. Test Materials

The additive materials used in this study are Alumina (Aluminum Oxide), Silicon Carbide, Boric Acid, Boron Oxide and Borax Pentahydrate, respectively. The alumina used in the study has a white hexagonal crystal structure [14]. The chemical formula of silicon carbide is SiC and it is a non-oxide ceramic-based compound [15]. The chemical formula of boric acid, which is another additive material, is defined as H_3BO_3 [16]. The next material is boron oxide and its chemical formula is defined as B_2O_3 [16]. Finally, the next preferred additive material is borax pentahydrate, also known as disodium tetra borate. Its chemical formula is $Na_2B_4O_7.5H_2O$ [16].

Since the same mold silicone is used for production in both test setups for the study, the production steps are common for sample production. In this study, general purpose glass fiber reinforced polyester resin is preferred. Since the additive and non-additive production steps are the same, they are based on the additive polyester resin production. All the samples are subjected to the same production process. In this study, the amount of polyester is selected as 50 g, considering the volume of the mold silicone and the density of the polyester resin. 50 g of general purpose glass fiber reinforced polyester resin is added into a container and added according to the percentage of the determined additive material and mixed slowly until a homogeneous appearance is achieved [17].

This stage is very sensitive because air bubbles that may occur in the insulation are the defects that the electrical industry avoids. In the second stage, cobalt (Co) equal to 0.2% of the polyester weight is poured onto the mixture [17]. Since the cobalt and methyl ethyl ketone peroxide (MEKP) used in the study are liquid materials, a 5cc syringe is preferred for the doping process. The function of cobalt here is to both be an accelerator and give color to polyester. The coloring function can be observed more clearly after the drying process. After mixing the cobalt homogeneously, MEKP is added at the rate of one percent of the weight of the polyester, and after mixing carefully again, the solution is poured into the mold silicone.

The MEKP used in production, is used to harden the polyester. The residence time in the mold silicone is 24 hours for the polyester type used in this study. During this period, the curing process continues. The samples are dried in the oven to increase the strength of the produced polyester resin material sample by chemically cross-linking it. The samples in this study are kept in the oven at 80°C for 5 hours without interruption. Figure 1 shows the silicone mold and the test sample used in both test setups. This mold silicone complies with the dimensions in the IEC 60587 standard [9].

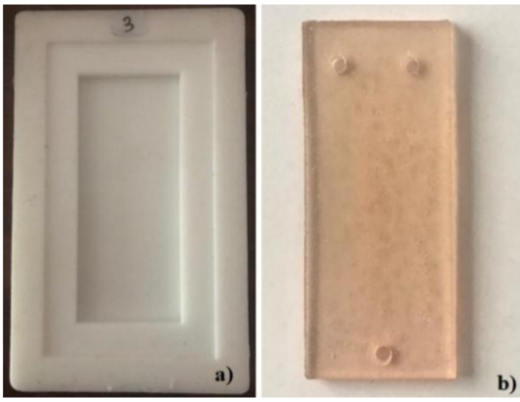

Figure 1. *a) sample silicone mold and b) test sample are used for production in the study.*

2.2. Inclined Plane Test Setup

All polyester resin samples are tested under laboratory conditions in the test setup in accordance with the IEC 60587 test standard [8-9]. In the first step, the 4kV AC output voltage specified in the standard is ensured with a high voltage probe. The value of this output voltage is adjusted via the test transformer and variac (autotransformer) in the experiment setup. Then, the 36 ml/s liquid flow rate value specified in the IEC 587 standard is set on the infusion pump. In all subsequent steps, all materials in the test setup are tested in accordance with the IEC 60587 standard and the degradation times of the samples are examined. In order to obtain reliable results, each series in these tests are produced in certain numbers [8]. The inclined plane test setup must provide an angle of 45° for the test sample [8]. Ammonium chloride (NH_4Cl) and Triton-X 100 are used as electrolyte solutions for the pure water in the percentages specified according to the standard [9]. The conductivity level of this solution is measured by using a liquid conductivity meter just before starting the experiment, and a value of approximately 0.2615 S/m is noted. Whatman type filter paper is used as filter paper in the experiment by cutting it to the desired dimensions. The high voltage and ground electrodes used in the inclined plane test have the dimensions specified in the standard and are also made of steel as specified in the standard [9]. The inclined plane test setup is given in Figure 2.

Figure 2. *Inclined Plane Test Setup.*

2.3. Hydrophobicity Test

In this part of the study, hydrophobicity tests are applied to samples with 2% additive rate and pure polyester samples, since the most durable additive rate is obtained in 2% additive rate in all additive materials as a result of the inclined plane test. Hydrophobicity testing has an important role in determining the surface properties of polymeric insulating materials [11-13]. Contact angles are measured to evaluate the wettability properties (hydrophobicity and hydrophilicity) of the prepared samples. Contact angle measurements are made by using the MATLAB program [18]. In this program, the half angle method is used in contact angle measurement. Droplet shape and contact angle values are obtained by flowing 20 µL of pure water onto the surface of the tested samples. During the measurements, the temperature of the environment where the test is performed is recorded as 24°C±1°C and the humidity value of the environment is noted as RH 35±3%. The same process is applied to all samples, and in order to obtain accurate results, the processes are repeated at least 5 times and their averages are taken. Figure 3 gives an example of the contact angle measurement of an alumina polyester sample with a 2% additive ratio.

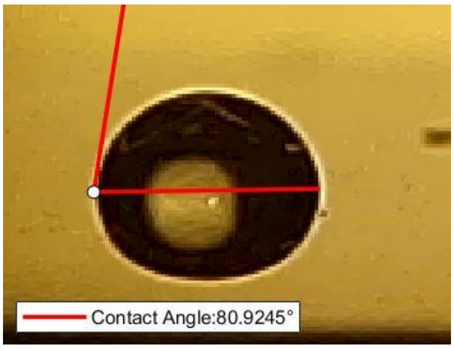

Figure 3. *Contact angle measurement of the alumina sample with 2% additive ratio.*

3. Results

Inclined plane test results and hydrophobicity test results of the test samples are discussed in this section. Since there is no size information for the boron additives provided, a digital microscope is used to specify particle size of the additive. Considering the criterion that the measurements are reliable and accurate, the measurements are repeated for each material type and their averages are taken. Particle radius values of borax pentahydrate, boric acid and boron oxide particles are given in Figure 4.

(a) *(b)* *(c)*

Figure 4. *Particle size measurement with a digital microscope (a) An image of borax pentahydrate (b) An image of boric acid (c) An image of boron oxide.*

While measuring with a digital microscope, boron compounds; it has been observed that the particle structure of borax pentahydrate is the most uniform, while the particle structure of boron oxide is the most irregular. In the measurements, it is determined that the average radius value of boric acid is 0.26 mm, the average radius value of boron oxide is 0.86 mm and the average radius value of borax pentahydrate is 0.70 mm. According to these values, it is observed that the boron compound in the largest size is boron oxide.

3.1. Inclined Plane Test Setup Results

In order to compare the effect of the additive material added to the electrical lifetime value on the polyester resin, firstly the average test times of pure (without additive) polyester samples are examined and then the samples with additives are tested. Degradation times of the samples indicate the lifetime of the material. In this study, the average degradation time of pure polyester resin samples is 18 minutes and 36 seconds. Numerical results about the doped samples subjected to inclined plane test is given in Table 1.

Table 1 Average degradation time depending on additive type and additive rate.

	Average degradain time		
Additive Material	**2% Additive Rate**	**1% Additive Rate**	**0.5% Additive Rate**
Silicon Carbide (SiC)	30 min 46 sec	13 min 47 sec	10 min 48 sec
Alumina (Al_2O_3)	35 min 43 sec	14 min 19 sec	10 min 3 sec
Boric Acid (H_3BO_3)	68 min 15 sec	25 min 50 sec	14 min 22 sec
Boron Oxide (B_2O_3)	58 min 11 sec	13 min 51 sec	40 min 41 sec
Borax Pentahydrate ($Na_2B_4O_7.5H_2O$)	18 min 34 sec	35 min 49 sec	26 min 48 sec

The results of silicon carbide samples are in accordance with the studies in the literature [19-20]. As a result of the tests, except for borax pentahydrate, it is observed that the most durable additive rate is provided at 2%. Additionally, when Table 1 is examined, it is clear that the most durable material is boric acid polyester prepared with 2% additive rate. Additionally, carbonized surface tracking formation is observed while testing the samples [21]. Figure 5 shows a pure polyester sample with carbonized surface tracking.

Figure 5. *Pure polyester resin sample with carbonized surface tracking.*

The corresponding sample images, of each series, tested on the inclined plane setup are given below. Samples with 2% additive polyester resin with carbonized surface tracking are given in Figure 6. Additive materials, from left to right; are listed as alumina, borax pentahydrate, boron oxide, boric acid and silicon carbide.

Figure 6. *Inclined plane sample series with 2% additive ratio.*

3.2. Hydrophobicity Test Results

The terms hydrophocity and hydrophilic refer to the concept of wettability in samples. A contact angle of less than 90° indicates a hydrophilic surface, and a contact angle greater than 90° indicates that the surface is hydrophobic [11]. The average of the contact angle values obtained from the samples as a result of the hydrophobicity test is given in Table 2.

Table 2 Average contact angle values of test samples.

Sample	**Average Contact Angle Values**
Polyester with 2% boron oxide additive	76
Polyester with 2% borax pentahydrate additive	78
Polyester with 2% boric acid additive	80
Polyester with 2% alumina additive	80
Polyester with 2% % silicon carbide additive	80
Pure polyester	89,5

When Table 2 is examined, the additive type with the lowest contact angle value at 2% additive rate is boron oxide. It was observed that the contact angle values of the samples with 2% additive ratio are smaller than the pure polyester sample. In other words, samples with 2% additive content are more hydrophilic than pure polyester samples.

4. Conclusion

In order to increase sustainability and waste management in power systems polymeric insulator lifetimes are critical. In this study, inclined plane test and hydrophobicity test are applied to determine the electrical strength and hence operation lifetime of the samples proposed. The surface conditions of the samples are examined by the hydrophobicity test. In order to obtain healthy and accurate results in each test setup, the tests are repeated and averaged. The inclined plane test is first applied to pure polyester samples, and it is observed that their average degradation time is between 15 and 25 minutes (average 18 minutes and 36 seconds). In the tests, the highest degradation time values are observed in 2% additive rate and the most durable material type is the polyester sample with 2% additive boric acid. The particle size, purity percentage, density and production conditions of the additive material played an active role in this situation.

It has also been observed that when the particle size exceeds a certain threshold, the increase in the additive ratio does not result in a proportional increase in the endurance time. In addition, it is highly important that the material used has a purity level close to 100%.

The density of the additive material is another critical parameter, and additive materials with densities compatible with the polyester matrix should be preferred to ensure optimal material performance.

Otherwise, the presence of foreign atoms may also become one of the parameters affecting the durability. Manufacturing conditions constitute another important parameter, and the same production process should be applied with great care and precision for each sample.

There are various studies in the literature about insulation materials with additives. The most important novelty of this study in contrast to previous studies is that boron compounds with very large particle sizes are used as additive materials. As a result of the inclined plane test, it is observed that there is no significant change depending on the additive ratio in additive materials with large particle sizes (700 µm, 860 µm diameter). It is noted that the contact angle values obtained as a result of the hydrophobicity test decreased the contact angle value regardless of the type of additive. The anode-cathode condition of the sample surface, the conductivity of the liquid solutions used in the tests, the particle size of the additive, the percentage purity of the additive and the environmental conditions are the main reasons of this situation.

These parameters may alter the surface characteristics, leading to variations in the measured contact angle values. In particular, high conductivity, large particle size, low purity, and high humidity conditions may contribute to a reduction in hydrophobicity.

In this study, it clear that alumina and silicon carbide-added samples showed similar durability in the inclined plane test (even though the additive ratio varied) and gave the same contact angle values in the hydrophobicity test. The most durable sample in the inclined plane test is boric acid added polyester with 2% additive rate, while in the hydrophobicity test this sample exhibit highest contact angle after the pure polyester sample. In the hydrophobicity tests, it is observed that there is a decrease in the contact angle value compared to pure polyester samples, regardless of the type of additive. Additionally, it is seen that when the particle size exceeded 0.26 mm diameter, there is an inverse proportion between the contact angle and the particle size.

Author Contributions

Data curation - Seren Çelik (SÇ), Cengiz Polat Uzunoğlu (CPU); Formal analysis - SÇ, CPU, Mukden Uğur (MU); Investigation - SÇ, CPU, Mustafa Karhan (MK), Şafak Gökhan Özkan (ŞGÖ), MU; Methodology - SÇ, CPU, MU; Experimental work - SÇ, CPU, MK; Data collection - SÇ, CPU, MK ; Data processing - SÇ, CPU, MK; Literature review - SÇ, CPU; Supervision - MU; Project administration - MU; Resources - ŞGÖ, MU; Writing – Original Draft - SÇ; Writing – Review and Editing - SÇ, CPU, MK, ŞGÖ, MU. All authors have read and approved the published version of the manuscript.

Conflict of Interest Statement

The authors have declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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