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THE EFFECT OF BAKELITE BINDERS ON MAGNETIC PROPERTIES AND HARDNESS VALUES OF MQP-TYPE BONDED NdFeB MAGNETS

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Abstract

Permanent magnets are important in modern society as components in various devices used by many industries and consumers, especially in generators and electric motors. Bonded magnet technology allows combining powdered magnetic materials with polymers as a binder to produce magnetic components that can be applied to certain applications, such as SynRM (synchronous reluctance) motors. Bonded magnets are easy to form without sacrificing their magnetic properties, which are too large, and also reduce costs, making them more effective and efficient. This paper reports the results of a study on the manufacture of bonded magnets NdFeB using bakelite binder on MQP-type NdFeB magnets with a bakelite variation of 0.5 - 2 wt.%. The characterization included testing magnetic properties with Permagraph, morphology with SEM (scanning electron microscope), and hardness values with micro Vickers hardness tester. The results of this study obtained remanence values in the range 5.53 - 6.44 kG and hardness values in the range 341.8 - 507.9 HV for NdFeB bonded magnets. According to SEM observations, the bakelite polymer matrix has successfully bound NdFeB grains, and no porosity is visible.

***Keywords:** Magnet, bonded, NdFeB, bakelite*

1. INTRODUCTION

The need for minerals is increasing and diversifying with the rapid development of civilization and technology. The latest trend in the development of environmentally friendly energy and industry is using minerals as a raw material for energy sources (electric batteries), energy conversion (solar, cell, wind turbines, etc.), the defense industry, electric vehicles, other electronics industries (industry 4.0) which require several types of minerals such as rare earth metals, lithium, cobalt, nickel, manganese, tin, graphite, quartzite, and others [1].

Rare earth metals are one of the strategic minerals. They are included in the critical minerals which consist of a collection of elements such as scandium (Sc), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and yttrium (Y). These elements play a vital role in developing of technology-based advanced industries [1].

The use of these rare earth metals triggers the development of new materials. New materials using REEs provide significant technological developments in materials science. The result of this material is widely used in industry to improve the quality of products, such as magnets[1].

Rare earth metal permanent magnets have much higher magnetic properties than the previous types of permanent magnets, where the (BH)max of this type of magnet reaches 30-35 MGOe or 240 – 280 kJ.m-3. As a permanent magnet with a high energy density as indicated by the (BH)max value, this type of permanent magnet becomes a permanent magnet capable of

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meeting the demands of today's technological products. These namely products prioritize space miniaturization [2].

Magnets have become an essential part of everyday life, and many applications can be applied to devices such as electric motors, loudspeakers, microwaves, telecommunications, and others [3]. Many other magnet applications are found in a miniature component in a mobile phone that relies on tiny NdFeB magnets for vibrational operation. These magnets are also often used in computer hard disk drives, where they contribute to the device by ensuring read/write positions [4]. From Figure 1, it can be seen that NdFeB magnets are widely applied to motors and generators with a percentage of 34% [5].

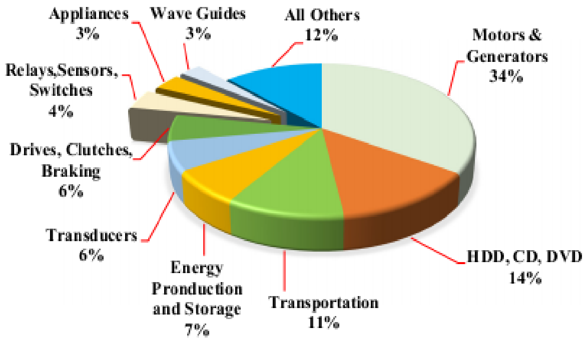


Figure 1. Proportion of Application of NdFeB Magnets [5]

The SynRM motor, or the Synchronous reluctance motor, is a 3-phase electric motor without permanent magnets and with a magnetically anisotropic rotor structure [6]. This type of motor is very popular as an electric or hybrid vehicle because of its easy and strong construction [7]. In the process, NdFeB magnets can be manufactured through powder metallurgy techniques known as bonded magnets [8]. The bonded magnet method mixes magnetic powder with polymer as a binder to produce a magnetic component [9]. The advantage of this bonded magnet is that it is easy to form without sacrificing its magnetic properties, which are too large, and reduces costs, making it more effective and efficient [10]-[11].

This study aims to improve the magnetic properties and hardness values of bonded NdFeB magnets using a bakelite binder. Through this research, it was possible to determine the effect of the bakelite binder on the magnetic properties and hardness values of the MQP-type bonded NdFeB magnets.

2. Materials And Methods

This research begins with preparing the tools and materials needed in the research process. The materials used are MQP-type NdFeB magnetic powder and bakelite polymer. In the early stages, the mass percentage estimates of the bakelite polymer to manufacture bonded NdFeB magnets was carried out. The bakelite and NdFeB powders were weighed according to previous calculations, with a total mass of 3 g per sample on the weighing paper using a spatula. After weighing, the sample is put into a plastic clip and then labeled so that the sample is not mixed up. In addition, mixing is carried out through a manual grinding process so that samples with coarse (large) grain sizes become finer (small). The weighed bakelite and NdFeB powder were mixed until homogeneous for 30 minutes using a mortar and pestle. Homogeneous samples were put into a die with a size of 12 mm and compacted using a hydraulic press. The sample was pressed with a compressive force of 10 MPa for 1 minute. The sample that comes out will be in the form of a pellet. The heating process (baking) was continued in the oven at a temperature of 250 °C for 30 minutes so that a bonded NdFeB magnet was formed.

Its physical properties (density), magnetic properties, microstructure (scanning electron microscope (SEM) - energy dispersive spectroscopy (EDS)), and hardness (micro Vickers) were then characterized. Density testing was carried out by weighing NdFeB magnets using digital scales and then measuring their dimensions using a caliper gauge so that the data obtained could be calculated using the density formula in Eq. (1).

$$\rho = \frac{m}{\pi d t^2} \quad (1)$$

In this study, Magnet-physics Dr. Steingroever GMBH Permagraf C is a tool used to determine the magnetic properties of bonded NdFeB magnets. A sample of known density is placed in the coil so that the magnet can be read by a computer. An SEM-EDS examination was conducted to determine the NdFeB composite magnet's morphology and elemental composition. In this test, the sample was irradiated with an electron beam at a voltage of 3 kV with image magnification of 500x and 2000x. This micro Vickers test was conducted to determine the hardness of the NdFeB composite magnet. Vicker hardness tester is a tool used to measure hardness values. The load given in this study was 25 gf with a dwell time of 10 seconds.

3. RESULT AND DISCUSSION

This measurement data for bonded NdFeB magnets can be seen in Table 1.

Table 1. Dimension measurement result data

Sample (%Bakelite)	Weight (g)	d(mm)	t(mm)
0.5	2.862	12	5.18
1	2.968	12	5.44
1.5	3.042	12	5.59
2	2.968	12	5.50

In this study, bonded NdFeB magnets were in the form of pellets. Figure 2 shows that the density value per sample decreased from 4.89-4.77 g/cm^3 with increasing bakelite content.

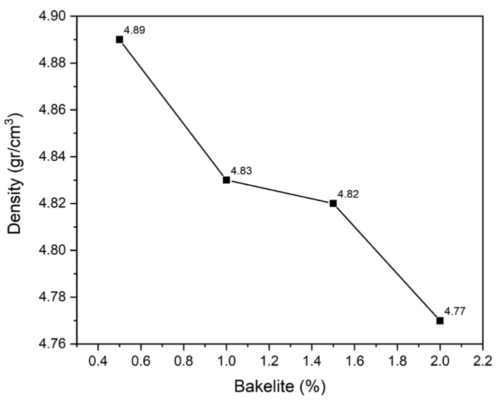


Figure 2. Graph of the relation between density and bakelite

The decrease in density indicates a reduction in sample density due to the influence of the bakelite polymer mixture on the bonded NdFeB magnet. The density of bakelite, which is 1.3 g/cm^3, is less than the density of the NdFeB magnet, which is 7.61% [12]. The highest density value is owned by a sample with 0.5% bakelite, and the smallest density value is owned by a sample with 2% bakelite. The difference between the density values obtained by the research and the theory is quite large, which can affect the magnetic properties of the bonded NdFeB magnets.

After calculating the density, permagraph testing was carried out to determine the magnetic properties of the bonded NdFeB magnets. The results obtained from this permagraph are in the form of a hysteresis curve in Fig. 3, which can provide information on the value of remanence (Br), coercivity (Hc), and maximum product energy $(BH)_{max}$. Magnetic properties data can be seen in Table 2. From Figure 3, the hysteresis curve of the bonded NdFeB magnets, it can be seen that the material is a hard magnet; this is indicated by the loop shape of the hysteresis curve, which widens considerably. The hysteresis curve shows that the wider the hysteresis curve, the higher the Coercivity is the strength of the magnetic field required to reduce the magnetization or magnetic induction to 0 from the saturation magnetization state [13]. From Figure 5, the coercivity value tends to increase with increasing bakelite. From the results of this study for a bakelite content of 1.5-2%, the coercivity value is not much different from the reference magnet of 6.032-6.06 Oe. The specification for MQP type NdFeB magnetic powder has a coercivity value of 6.5-7.5 kOe [14]. bakelite composition. The most expansive curve is found in samples with 2% bakelite. Samples with 0.5% bakelite have a smaller curve shape than other bakelite variations.

Table 2. Magnetic properties data

Sample (%Bakelite)	Br(kG)	Hc(kOe)	$(BH)_{max}$ (MGoe)
0.5	6.44	4.983	3.84
1	6.20	5.976	6.54
1.5	5.57	6.050	5.57
2	5.53	6.032	5.84

Based on the curve results, magnetic properties such as remanence Br, coercivity Hic, and energy product $(BH)_{max}$ for each sample are presented in Table 2.

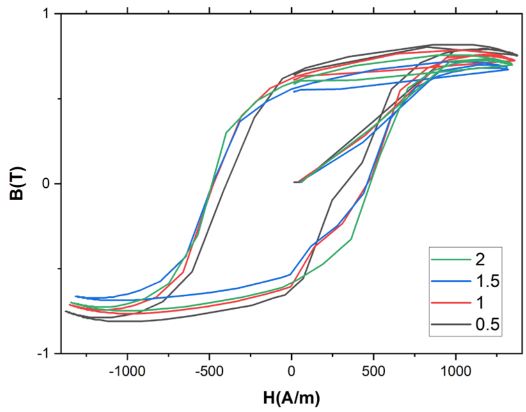


Figure 3. Hysteresis curve of the bonded NdFeB magnets with a bakelite variation of 0.5, 1, 1.5 and 2

The results show that the remanence value decreases, and the coercivity and BH_{max} values increase with each addition of bakelite composition. The bakelite composition significantly affects the Br, Hc, and $(BH)_{max}$ values.

Remanence is the residual magnetic field (B) during magnetization when the H magnetic field is removed [13]. The remanence value decreases as more bakelite is added. This is because bakelite is a non-magnetic material, so the remanence decreases as the amount of bakelite increase. From Figure 4, samples with 0.5% bakelite have the highest remanence, and samples with 2% bakelite have the lowest remanence.
Samples with 0.5% bakelite have stronger magnetic properties than samples with greater bakelite variation. The decrease in magnetic properties is due to the increase in bakelite, a polymer.

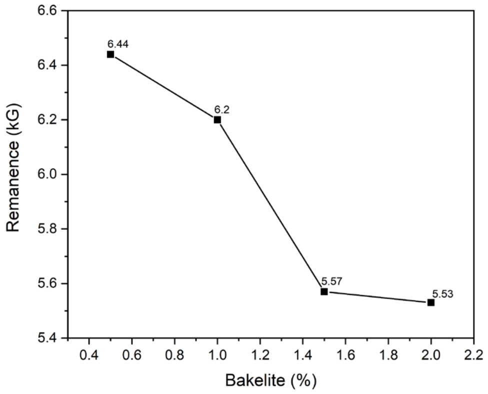


Figure 4. Graph of the remanence relation with bakelite

The greater the coercivity value of a magnet, the stronger the magnetic properties.

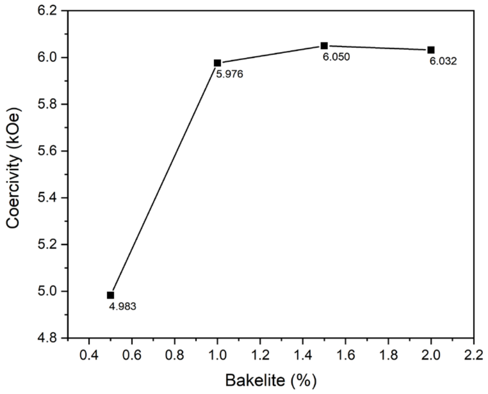


Figure 5. Graph of the coercivity of bakelite

Figure 6 shows that the $(BH)_{max}$ values increase with increasing bakelite content. It's simply that from 0.5% to 1% bakelite samples, there was a significant increase with a difference in value of 2.7 MGOe.

Several factors that can affect the magnetic properties of bonded magnets are grain size, compaction pressure, and temperature [15]. According to research by A. Ritawanti et al., the larger the grain size, the stronger the magnetic properties.

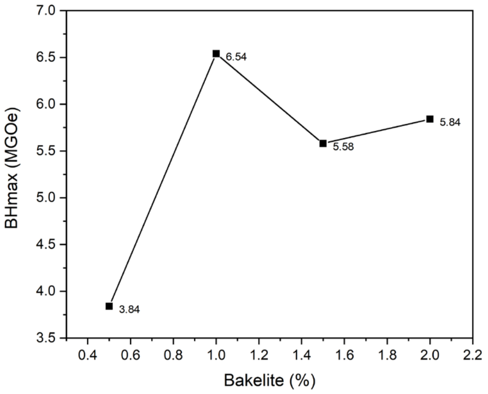
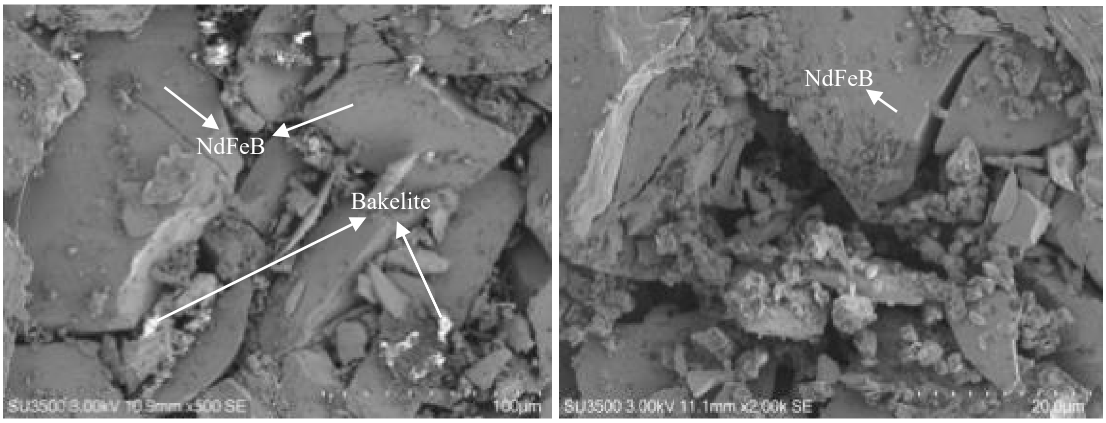


Figure 6. Graph of the relation between BH_{max} and bakelite

The formation of porosity due to grain size can affect the density value; if it does not approach the theoretical density value, then the magnetic properties will not be appropriate [16]. If the temperature applied exceeds the curie temperature, the magnetic properties will be weakened [17]. In physics and materials science, the Curie temperature is the temperature at which a particular material loses its permanent magnetic properties [21]. In this study, the NdFeB bonded magnet is a ferromagnetic material that will lose its magnetic properties when it is above the curie temperature, and NdFeB bonded magnets are ferromagnetic materials that feature good loop hysteresis curves because when an external magnetic area is applied to a ferromagnet, the atomic dipoles align themselves with it. Even when the field is removed, part of the alignment will be retained: the material has become magnetized [17]. SEM-EDS (scanning electron microscope-energy dispersive spectroscopy) testing was carried out to determine the surface morphology and composition of the elements in bonded NdFeB magnets. In the SEM test, magnification was carried out two times, namely 500x magnification and 2000x magnification. The NdFeB powder in the SEM results is marked in gray, while the bakelite is marked in white.

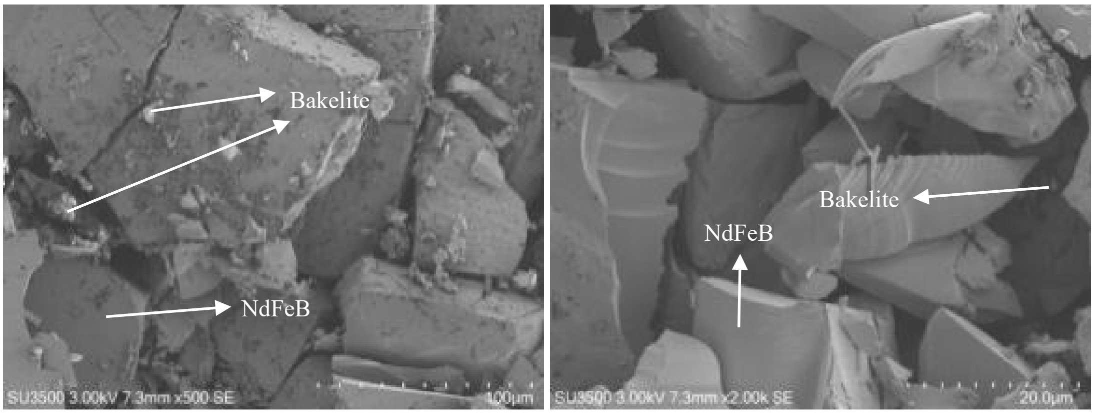
SEM results from Fig. 7(a) 0.5% bakelite sample with 500x magnification, it can be seen in the figure that the NdFeB powder has non-uniform grain sizes; this could be due to the process of mixing the NdFeB powder and bakelite manually with a mortar and pestle where the pressure is applied at the time of grinding is different and also no sieving is done. The grain size of these samples ranged from 45-100 μm as measured directly by SEM. In the results of this image, it is clear that there are gaps between the grains; this can be caused by non-uniform grain sizes and the lack of compacting pressure used so that the sample still has a lot of porosity [18]. In addition, the increase in bakelite affects the presence of porosity [18]. Bakelite is located between the grain gaps, and the distribution of bakelite is not evenly distributed. SEM results with 2000x magnification did not show any bakelite distribution; this could be due to the small percentage of bakelite. After magnification, the presence of bakelite is not visible, as in Fig. 7(b).



(a) (b)

Figure 7. (a) Morphology of NdFeB + bakelite 0.5%, (b) magnification area of (a)

The results of a 1% bakelite with 500x magnification demonstrate that the grain size is not homogeneous, as illustrated in Fig. 8(a). Bakelite distribution is not limited to grain gaps, and bakelite begins to appear above the surface.



(a) (b)

Figure 8. (a) Morphology of NdFeB + 1% bakelite, (b) magnification area of (a)

In Figure 9, the presence of bakelite is not visible; a lens magnification is needed to confirm the presence of bakelite. The presence of bakelite had bonded some of the grains together, and there was a difference in grain size after magnification.

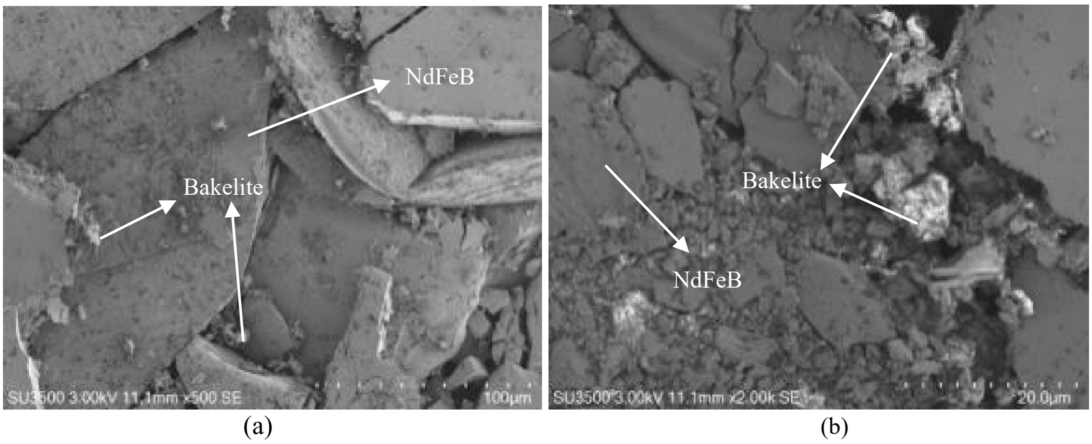


Figure 9. (a) Morphology of NdFeB + bakelite 1.5%, (b) magnification area of (a)

Figure 10 shows the SEM results for the 2% bakelite sample. The image clearly shows the presence of bakelite compared to the other sample results. In Figure 10, it is very clear that evenly distributed bakelite can provide very good bonding properties [19].

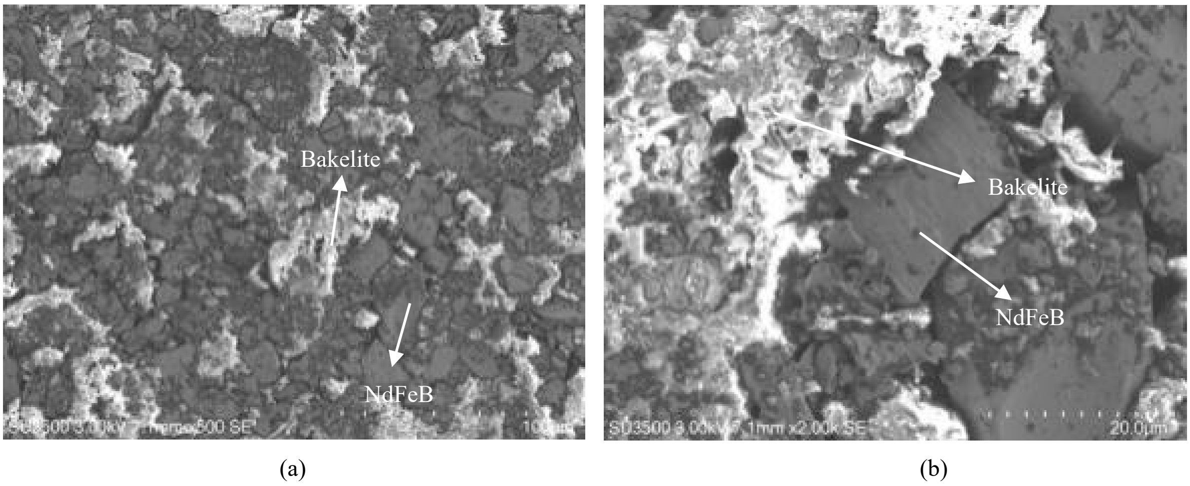


Figure 10. (a) Morphology of NdFeB + bakelite 2%, (b) magnification area of (a)

During the heating process, the bakelite melts. This melted bakelite coats the surface and adhered one grain to another. The presence of bakelite is not only between grains but above the grain surface. This can happen because there is an indication that the bakelite is burning. So it can be concluded that the more bakelite, the smaller the porosity is formed because the bakelite fills the gaps between the grains, which then envelops the surface of the bonded NdFeB magnets.

Table 3 shows the result of EDS testing of 4 samples. EDS detected 9 elements. The atomic percentages of the elements Nd, Pr, and Fe tend to decrease with increasing bakelite. The EDS results showed the presence of oxygen (O) in the sample, indicating that the bonded NdFeB magnets were well oxidized [20]. From the above data, as bakelite increases, the number of carbon elements from the four samples increases from 5.53%, 7.31%, 17.22% to 44.86%. This is because bakelite is a polymer, which a cross-linked carbon chain pattern, so there is a contribution that can alter these magnetic metals.

Table 3. Elemental composition of EDS results

Element	Composition (wt.%)/% Bakelite			
	0.5	**1**	**1.5**	**2**
Nd	0.33	0.72	0.01	2.05
Pr	16.50	15.47	9.43	-
Fe	61.12	61.09	55.31	22.68
B	5.09	4.60	7.20	5.96
C	5.53	7.31	17.22	44.86
Co	5.96	5.16	-	-
O	3.92	4	10.84	20.21
F	5.53	1.66	-	-
Ca	-	-	-	4.14

The micro Vickers results can be seen in Table 4. From Table 4, each sample was tested at three points. So that the hardness value obtained is the result of the average, the hardness value of the bonded NdFeB magnets can be seen in Table 4.

Table 4. Micro Vickers test result

Sample (% Bakelite)	Hardness Value (HV)			
	I	II	III	Average
0.5	329.1	368.6	327.7	341.8
1	473.1	456.8	443.9	457.93
1.5	512.1	514.8	487.7	504.86
2	477.4	515.4	530.9	507.9

In this study, the sample with 2% bakelite had the highest hardness value. This is because bakelite, in its molecular structure, has excellent strength, so it can form cross-linked solid networks to increase strength during the heating process [19]. As evidenced by Figure 10(g), the results of SEM data on this sample show that the bakelite polymer is evenly distributed, which can provide excellent bonding and better mechanical properties to bind NdFeB magnets [19]. Therefore, the bakelite polymer provides good hardness properties to these bonded NdFeB magnets.

Figure 11 shows that with increasing bakelite, the hardness value of the bonded NdFeB magnets will be higher.

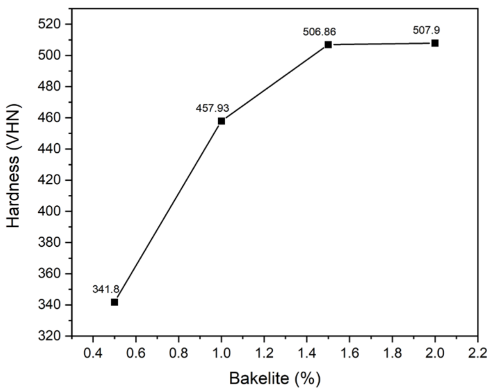


Figure 11. The effect of bakelit level on the hardness value of NdFeB

4. CONCLUSION

Conclusions from the results of the study on the effect of bakelite on the magnetic properties and hardness values of MQP-type bonded NdFeB magnets:

Bonded NdFeB magnets can be made by mixing NdFeB magnetic powder with bakelite polymer, compacting it, and then heating it. In this study, the 1% bakelite sample was optimal regarding magnetic properties, while the 2% bakelite sample was optimal regarding hardness properties. This is because the addition of bakelite is very influential. The sample with 0.5% bakelite has a high remanence value of 6.44 kG, so it can be said that this sample has a higher magnetic strength compared to the other samples. Because a significant percentage of bakelite succeeded in binding the NdFeB granules, the hardness value of 507.9 HV was higher in the NdFeB with 2% bakelite than in the others.

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