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Synthesis of Silica-Based Glass from Quartz Sand and P_2O_5-BaO-Na_2O Compounds Using the Melt-Quenching Technique

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ABSTRACT

This study reports the development of phosphate-based glass materials incorporating quartz sand sourced from Huta Ginjang, North Sumatra, Indonesia, with a specific focus on their potential application as host matrices for rare earth ions in optical amplification systems. Phosphate glasses are recognized for their excellent transparency and chemical stability, making them promising candidates for various optical applications. Quartz sand was collected and subjected to a cleaning process to eliminate impurities, such as dust and organic matter, which may negatively impact the quality of the resulting glass. The purified sand was subsequently ground using a ball mill for 4 h to achieve the desired particle size distribution. The ground quartz was then combined with phosphorus pentoxide (P_2O_5), barium oxide (BaO), and sodium oxide (Na_2O) in the following molar composition: x mol% quartz sand + (60 − x) mol% P_2O_5 + 10 mol% BaO + 30 mol% Na_2O, where x = 0, 2.5, 5, 10, 15, and 20 mol%. The glass batches were melted at 1200 °C for 3 h using the melt-quenching technique. The synthesized glass samples demonstrated good homogeneity and high optical transparency. The physical characteristics of the resulting materials indicate their suitability for use as host matrices in optical devices. Further analysis is required to assess the incorporation efficiency and spectroscopic properties of rare earth dopants within this glass system.

Keywords: *quartz sand; phosphate oxide; glass medium; Huta Ginjang*

ABSTRAK

Penelitian ini bertujuan untuk mengembangkan material gelas berbasis fosfat dan pasir kuarsa yang berasal dari Huta Ginjang, dengan fokus pada aplikasinya sebagai host matrix untuk ion tanah jarang sebagai penguat optik. Gelas fosfat memiliki potensi untuk digunakan dalam berbagai aplikasi optik karena sifat transparansi dan stabilitasnya yang tinggi.Proses penelitian dimulai dengan eksplorasi dan pengumpulan pasir kuarsa dari lokasi Huta Ginjang, yang terletak di Sumatera Utara, Indonesia. Pasir kuarsa yang diperoleh dibersihkan untuk menghilangkan kontaminan, seperti debu dan kotoran, yang dapat mempengaruhi kualitas gelas yang dihasilkan. Setelah pembersihan, pasir kuarsa dihaluskan menggunakan teknik ball-mill selama 4 jam untuk mencapai ukuran partikel yang diinginkan. Selanjutnya, pasir kuarsa yang telah dihaluskan dicampurkan dengan senyawa kimia lainnya, seperti Fosfat oksida (P2O5), Barium oksida (BaO), dan Natrium oksida (Na2O). Komposisi senyawa ditentukan melalui formula kimia (x) Pasir kuarsa + (60 - x) P2O5 + 10BaO + 30Na2O (dimana x = 0; 2,5; 5; 10; 15; 20 mol%). Proses peleburan dilakukan pada suhu 1200°C selama 3 jam menggunakan teknik melt-quenching.Hasil penelitian menunjukkan bahwa medium gelas yang dihasilkan memiliki homogenitas dan transparansi yang baik, dengan karakteristik fisik yang sesuai untuk aplikasi optik.

Kata kunci: pasir kuarsa; oksida fosfat; media kaca; Huta Ginjang

1. INTRODUCTION

Research on glass materials has garnered increasing attention due to their wide range of applications, particularly in optics and telecommunications. Quartz sand serves as a primary raw material in glass production, and its quality is significantly influenced by its purity and the presence of other mineral components. In this study, we focus on utilizing quartz sand from Huta Ginjang, which is expected to exhibit characteristics suitable for glass fabrication.

Phosphate glass and quartz sand are essential components in glass synthesis. Quartz sand contains more than 97% silicon dioxide (SiO_2) and offers notable advantages such as resistance to chemical corrosion and thermal stress (Unasir et al., 2015; Syafrizal et al., 2022). Therefore, the objective of this study is to investigate the effect of quartz sand concentration from Huta Ginjang on the physical and structural properties of phosphate-based glass. The melt-quenching method was employed due to its effectiveness in achieving material homogeneity and high thermal resistance, despite the challenges associated with high-temperature glass synthesis (Rajagukguk et al., 2022).

According to Hutahaean et al. (2025), quartz sand represents a rich source of silica and can be effectively used as a precursor in phosphate glass production. The incorporation of quartz sand into phosphate glass compositions can significantly influence the material's physical properties, microstructure, and optical characteristics. Previous studies have shown that utilizing quartz sand from Huta Ginjang yields amorphous structures with potential applications as optical amplifiers. Characterization techniques such as X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) have demonstrated changes in absorption bands and network structures with increasing quartz content. The ball milling technique was employed to refine the quartz sand prior to melting, thereby enhancing the homogeneity and reactivity of the batch materials. Subsequently, the melt-quenching method was used as the primary synthesis technique, wherein the homogeneously mixed batch was melted at high temperature and rapidly cooled to form an amorphous structure (Hutahaean et al., 2025; Carta et al., 2007; Li et al., 2020; Xu et al., 2019).

The development of phosphate- and quartz-based glass materials through a combination of ball milling and melt-quenching is expected to yield materials with optimal physical and structural properties suitable for optical applications (Hutahaean et al., 2025; Carta et al., 2007; El-Bardai et al., 2024). Experimental studies in this area are essential to understand the influence of composition and synthesis methods on the properties of the resulting glass. This paper presents a detailed examination of the experimental procedures involved in the synthesis of phosphate–quartz glass using the following base composition: Quartz Sand + $(60 - x)P_2O_5 + 10BaO + 30Na_2O$ (mol%), where x = 0, 2.5, 5, 10, 15, 20 mol%.

2. METHOD

2.1. Quartz Sand Preparation and Glass Synthesis

The synthesis of silica oxide (SiO_2) based on quartz sand began with the collection of natural sand from Huta Ginjang village, followed by the selection of glass-like grains. The quartz sand was soaked and washed with detergent for 12 hours to remove surface impurities. It was then rinsed with distilled water and soaked for an additional 4 hours, followed by drying. The dried sand grains were ground using a ball mill for 4 hours to produce fine quartz powder.

The resulting quartz powder was mixed with other glass-forming and modifying compounds according to the following molar composition: x mol% quartz sand (QS) + (60 − x) mol% P_2O_5 + 10 mol% BaO + 30 mol% Na_2O, where x = 0, 2.5, 5, 10, 15, 20 mol%. The mass of each compound in the formulation was calculated based on its molar mass to ensure accurate batch preparation. The final stage of the process involved melting the prepared batch and forming glass samples via the melt-quenching method, which was conducted at 1200 °C for 3 hours to achieve transparent and homogeneous glass.

Table 1. Composition of synthesized phosphate–quartz glass samples

Samples	Glass compositions (mol.%)
PBN	60 P2O5 - 10 BaO - 30 Na2O - 0,0 QS
PBNQS1	57,5 P2O5 - 10 BaO- = 30 Na2O - 2,5 QS
PBNQS2	55 P2O5 - 10 BaO- - 30 Na2O- 5 QS
PBNQS3	50 P_2O_5 - - 10 BaO- 30 Na2O- 10 QS
PBNQS4	45 P_2O_5 - - 10 BaO- 30 Na2O- 15 QS
PBNQS5	40 P_2O_5- - 10 BaO- 30 Na_2O - - 20 QS

2.2. Ball Milling Technique

Ball milling is a mechanical process used to crush, grind, or reduce the size of materials into fine particles. According to Wei et al. (2023), the ball milling process enhances the conversion of quartz sand into powder form, which is essential for glass synthesis. This technique is widely adopted to improve particle uniformity and increase material reactivity. Additionally, Rad et al. (2019) noted that ball milling can also induce structural changes, such as reduced crystallinity, thereby affecting the material's functional properties. In this study, quartz sand was milled for 4 hours, and the milling parameters were carefully optimized to achieve the desired fineness and reactivity.

2.3. Melt-Quenching Technique

The melt-quenching process involves the melting of homogenized chemical precursors at elevated temperatures. Each compound was weighed using a digital balance according to its specified molar percentage (0.0, 2.5, 5, 10, 15, and 20 mol%) with purities exceeding 99%, for a total batch mass of 15 grams. The components were then manually mixed using a spatula in an alumina crucible. To minimize moisture, the crucible was stored in a silica gel-filled container for 24 hours in a vacuum environment.

The homogeneously mixed batch was subsequently heated in a furnace at 1200 °C for approximately 3 hours. Upon achieving a homogeneous melt, the mixture was poured into a stainless-steel mold to form rectangular samples. The glass samples were then annealed at 500 °C for 3 hours, followed by slow cooling to room temperature to relieve internal stresses and ensure structural integrity (Rajagukguk et al., 2016).

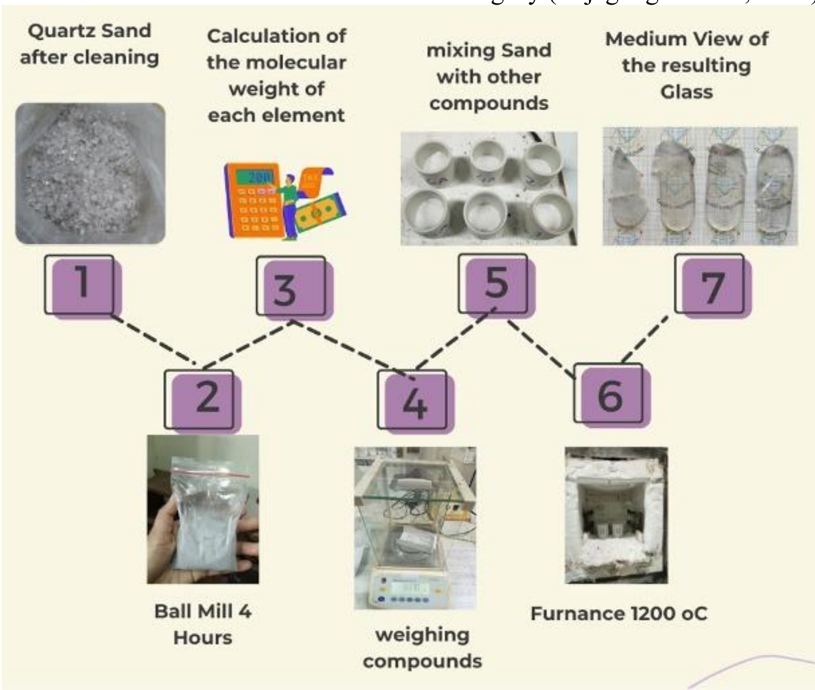

Figure 1. Flowchart of phosphate–quartz glass synthesis process.

3. RESULT AND DISCUSSION

This study presents the compositional calculations for each compound used in the preparation of phosphate- and quartz sand-based glasses. The glass composition follows the formula $xQS + (60–x)P_2O_5 + 10BaO + 30Na_2O$ (mol%), where x = 0; 2.5; 5; 10; 15; and 20, with a total material weight of 15 grams per sample. In addition, this study categorizes the constituent compounds of phosphate-based glass to determine the relative atomic mass of each element. The detailed molecular weights are shown in Table 2.

Table 2. Atomic Weights of the Glass System Constituents Used in This Study

Elements	Simbol	Atomic Weight (g/mol)
Phosphorus	P	30,974
Oxygen	O	15,999
Barium	Ba	137,327
Sodium	Na	22,9898
Silicon	Si	28,0855

The atomic weights listed in Table 2 were used to calculate the molecular weight of each glass-forming compound. These values were derived from the periodic table. The molecular weight of each component was obtained by multiplying the molar fraction of each element by its molecular weight, then summing all results to determine the total molecular weight of the glass composition (El-Alaily et al., 2018). The four main compounds used in this glass system are Diphosphorus Pentoxide (P_2O_5), Barium Oxide (BaO), Sodium Oxide (Na_2O), and Silicon Dioxide (SiO_2). The calculations and results for the molecular weights of the compounds are shown in Table 3.

Table 3. Molecular Weights of Glass-Forming Compounds

Compound	Symbol	Molecular Weight (g/mol)
Diphosphorus Pentoxide	P_2O_5	(30.974 × 2) + (15.999 × 5) = 141.943
Barium Oxide	BaO	137.327 + 15.999 = 153.326
Sodium Oxide	Na_2O	(22.9898 × 2) + 15.999 = 61.9786
Silicon Dioxide	SiO_2	28.0855 + (15.999 × 2) = 60.083

After determining the relative molecular masses, the four compounds were combined according to the chemical formulas for each of the six samples. These samples differ based on increasing quartz sand (QS) content, offset by a decrease in diphosphorus pentoxide (P_2O_5), to analyze the effect of added silica on the structure and properties of the resulting glass (Kaur et al., 2024; Ragagukguk et al., 2019; Khan et al., 2025). The calculation of each compound's mass for the first sample (PBN), which contains no quartz sand (0 mol% QS), is presented in Table 4.

Table 4. Mass of Each Compound Required for the First Sample ($60P_2O_5 + 10BaO + 30Na_2O$ (PBN))

Compound	**Composit ion (mol%)**	**Molecular Weight (%) (g/mol)**	**Mass of Component (g)**
P_2O_5	60.0	85.1658	10.7268
BaO	10.0	15.3329	1.9312
Na_2O	30.0	18.5935	2.3419
QS	0.0	0.0000	0.0000
Total	100.0	119.0922	15.000

As shown in Table 4, the first sample was prepared without quartz sand (QS), indicating a QS content of 0 mol%. This configuration was selected to assess the structural and physical differences between glass samples without and with the addition of QS. Using the same procedure as in Table 4, the required compound masses for a composition with 2.5 mol% QS were calculated based on the formula: $2.5QS + 57.5P_2O_5 + 10BaO + 30Na_2O$ (PBNQS1), as presented in Table 5.

Table 5. Mass of Each Compound Required for Glass Sample 2 ($2.5QS + 57.5P_2O_5 + 10BaO + 30Na_2O$ (PBNQS1))

Compound	**Composition (mol%)**	**Molecular Weight (g/mol)**	**Mass of Component (g)**
P_2O_5	57.5	81.61723	10.4596
BaO	10	15.3329	1.96988
Na_2O	30	18.5935	2.38286
QS	2.5	1.50207	0.19249
Total	100	117.0458	15

In Table 5, 2.5 mol% quartz sand was added to the glass composition, reducing the P_2O_5 content to 57.5 mol%. This gradual substitution of phosphate oxide (P_2O_5) was aimed at studying its effect on the glass structure. A similar procedure was applied for a 5 mol% QS composition, as shown in Table 6. With the addition of QS, the phosphate oxide content was further reduced to 55 mol%, using the formula $5QS + 55P_2O_5 + 10BaO + 30Na_2O$ (PBNQS2).

Table 6. Mass of Each Compound Required for Sample 3 ($5QS + 55P_2O_5 + 10BaO + 30Na_2O$ (PBNQS2))

Compound	Composit ion (mol%)	Molecular Weight (%) (g/mol)	Mass of Component (g)
P_2O_5	60.0	85.1658	10.7268
BaO	10.0	15.3329	1.9312
Na_2O	30.0	18.5935	2.3419
QS	0.0	0.0000	0.0000
Total	100.0	119.0922	15.000

Table 6 confirms that increasing the QS content leads to a proportional decrease in phosphate oxide content, maintaining the total molar composition at 100 mol%. In the fourth sample (PBNQS3), QS content was increased to 10 mol%, which further decreased the P_2O_5 content to 50 mol%, as detailed in Table 7. The corresponding formula is $10QS + 50P_2O_5 + 10BaO + 30Na_2O$ (PBNQS3).

Table 7. Mass of Each Compound Required for Sample 4 ($10QS + 50P_2O_5 + 10BaO + 30Na_2O$ (PBNQS3))

Compound	Composition (mol%)	Molecular Weight (g/mol)	Mass of Component (g)
P_2O_5	50	70.9715	9.598848
BaO	10	15.3329	2.073764
Na_2O	30	18.5935	2.514769
QS	10	6.0083	0.812619
Total	100	110.9063	15 gr

Table 7 shows that increasing the QS content to 10 mol% leads to a further reduction in P_2O_5 to 50 mol%. This adjustment aims to gradually reduce the phosphate content, which is expected to enhance the stability and mechanical properties of the glass.

Table 8. Mass of Each Compound Required for Sample 5 ($15QS + 45P_2O_5 + 10BaO + 30Na_2O$ (PBNQS4))

Compound	Composition (mol%)	Molecular Weight (g/mol)	Mass of Component (g)
P_2O_5	45	63.8743	8.9700
BaO	10	15.3329	2.1532
Na_2O	30	18.59358	2.6111
QS	15	9.01245	1.2656
Total	100	106.8133	15 gr

As illustrated in Table 8, a 15 mol% QS addition further reduces the P_2O_5 content to 45 mol%. Following the same approach, the sixth sample (PBNQS5) incorporated 20 mol% QS, resulting in a P_2O_5 reduction to 40 mol%, as detailed in Table 9. The formula used is $20QS + 40P_2O_5 + 10BaO + 30Na_2O$ (PBNQS5).

Table 9. Mass of Each Compound Required for Sample 6 ($20QS + 40P_2O_5 + 10BaO + 30Na_2O$ (PBNQS5))

Compound	Composition (mol%)	Molecular Weight (g/mol)	Mass of Component (g)
P_2O_5	40	56.7772	8.2910
BaO	10	15.3329	2.2390
Na_2O	30	18.59358	2.7152
QS	20	12.0016	1.7547
Total	100	102.7203	15 gr

Table 9 shows that in sample PBNQS5, the QS content was increased to 20 mol%, accompanied by a decrease in phosphate oxide to 40 mol%. The QS content across the six samples increased incrementally from 0 to 20 mol%, while the P_2O_5 content decreased from 60 to 40 mol%. The reduction of P_2O_5 is a crucial step in the glass-forming process, which involves mixing the compounds and subjecting them to high temperatures to achieve a homogeneous and transparent glass medium (Meejitpaisan, P. et al., 2024).

Table 10. Comparison of Mass of Glass Sample Components

Compound	Mass compound in each sample (g)					
	PBN	PBNQS1	PBNQS2	PBNQS3	PBNQS4	PBNQS5
Quartz Sand (QS)	0.0000	0.1924	0.3918	0.8126	1.2656	1.7547
P_2O_5	10.7268	10.4596	10.1829	9.5988	8.9700	8.2910
BaO	1.9312	1.9698	1.9999	2.0737	2.1532	2.2390
Na_2O	2.3419	2.3828	2.4252	2.5147	2.6111	2.7151
Total (g)	15	15	15	15	15	15

Table 10 compares the mass of each component across all six glass samples: PBN, PBNQS1, PBNQS2, PBNQS3, PBNQS4, and PBNQS5, each weighing 15 grams. After calculating the required powder mass for each compound, the mixtures were thoroughly blended in an alumina crucible to ensure uniform distribution. Subsequently, the mixtures were melted in a high-temperature electric furnace at 1200°C for 4 hours and poured into stainless steel molds, as illustrated in Figure 2.

Figure 2. Pouring and casting process of molten glass into a stainless steel mold.

Figure 2 shows the process of pouring the molten glass into a stainless steel mold during the fabrication of phosphate-based glass samples.

Figure 3 illustrates the appearance of the cast glass samples with compositions of xQS + (60–x)P_2O_5 + 10BaO + 30Na_2O (mol%), where x = 0, 2.5, 5, 10, 15, and 20. The total mass of the compound mixture for each sample was fixed at 15 grams, based on the optimal composition range reported in previous studies (Alzahrani, J. S., 2025). Six phosphate glass samples were prepared with the following chemical formulations:

- **Sample 1 (PBN):** 60P_2O_5 + 10BaO + 30Na_2O
- **Sample 2 (PBNQS1):** 2.5QS + 57.5P_2O_5 + 10BaO + 30Na_2O
- **Sample 3 (PBNQS2):** 5QS + 55P_2O_5 + 10BaO + 30Na_2O
- **Sample 4 (PBNQS3):** 10QS + 50P_2O_5 + 10BaO + 30Na_2O
- **Sample 5 (PBNQS4):** 15QS + 45P_2O_5 + 10BaO + 30Na_2O
- **Sample 6 (PBNQS5):** 20QS + 40P_2O_5 + 10BaO + 30Na_2O

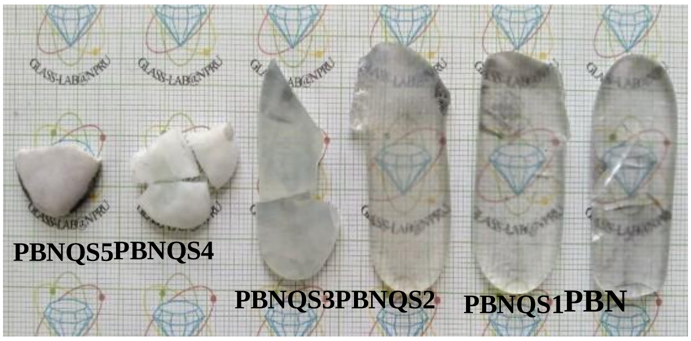

Figure 3. Glass sample appearance prior to cutting and polishing.

From Figure 3, it is observed that samples **PBN**, **PBNQS1**, and **PBNQS2** exhibit higher transparency compared to the others. Specifically, samples **PBNQS1** and **PBNQS2** contain quartz sand (QS) at 2.5 mol% and 5 mol%, respectively. This indicates that the optimal quartz sand content for phosphate glass samples lies in the range of 2.5–5 mol%.

In contrast, **PBNQS4** and **PBNQS5** samples exhibit significant physical degradation, as indicated by their opacity and fractured structure. This deterioration is attributed to the high content of quartz sand, which contributes to increased turbidity and reduced thermal stability. The decrease in phosphate content (P_2O_5) plays a critical role in this behavior, as phosphate compounds are known for their excellent transparency, low melting points, and good thermal stability—all of which enhance the quality and performance of the glass material (Jiménez, J., & Thomas, M., 2024).

4. CONCLUSION AND RECOMMENDATION

This experimental study successfully developed a phosphate-quartz sand-based glass medium as a candidate host matrix. Glass materials were synthesized using raw materials from Huta Ginjang through ball milling and melt-quenching methods. The results indicate that the addition of quartz sand to phosphate glass compositions influences both the physical and structural properties of the resulting glasses. The quartz sand was refined using ball milling for 4 hours to enhance homogeneity. The melting process at 1200°C for 3 hours yielded glass with good transparency and uniformity, suitable for optical applications. The compositional variation of quartz sand from 0 to 20 mol% was shown to impact properties such as density, transparency, and structural integrity.

Future research should explore further compositional variations of phosphate-based glass by incorporating additional compounds to improve optical and mechanical properties. Investigations into the influence of melting temperature and duration may also yield deeper insights into the synthesis process. Finally, studies focusing on the application of phosphate glass in optics and telecommunications are strongly encouraged.

5. ACKNOWLEDGE

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