



Prospect of Heat Insulating Ceramic Fibre on Energy-Saving and Environmental Protection from Carbon Emission in Bangladesh

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Abstract: Rising energy costs, concerns regarding future energy security, and increasingly stringent environmental regulations on greenhouse gas emissions have intensified the need for energy-efficient technologies and sustainable industrial practices. Thermal insulation is one of the most effective approaches for reducing energy consumption and improving energy efficiency in high-temperature industrial processes. The development of environmentally friendly insulation materials from locally available resources offers a promising alternative to conventional insulation products. This study investigates the potential of producing bio-soluble ceramic fibre insulation materials using indigenous clay deposits and dolomite available in Bangladesh. Clay serves as the primary source of silica and alumina, while dolomite contributes calcium and magnesium oxides that enhance the bio-solubility of the resulting fibres. The developed materials are expected to provide excellent thermal and acoustic insulation, fire resistance, and chemical stability under harsh operating conditions. The implementation of efficient furnace insulation systems can substantially reduce fuel consumption, improve process efficiency, and contribute to environmental sustainability. The availability of suitable clay resources in Bangladesh provides an opportunity for the local production of ceramic fibre-based insulation products, reducing dependence on imported materials. To assess the suitability of these raw materials, comprehensive characterization techniques including X-ray fluorescence (XRF), X-ray diffraction (XRD), differential scanning calorimetry–thermogravimetric analysis (DSC–TG), and particle-size analysis were employed. These methods provide detailed information on the chemical composition, mineralogical phases, and thermal behaviour of the clay deposits. The findings demonstrate the potential of locally sourced clay materials for the development of sustainable ceramic fibre insulation products capable of supporting energy conservation and industrial development in Bangladesh.

Keywords: Heat Insulation, Ceramic Fibre, Energy Saving, Carbon Emission, Environment.

INTRODUCTION

Ceramic fibre is an advanced inorganic fibrous material primarily composed of alumina (Al_2O_3), silica (SiO_2), and other metal oxides. These fibres are widely used as high-temperature insulation materials because of their excellent thermal properties, lightweight structure, and

resistance to harsh operating environments. Kaolin clay is one of the most important natural sources of alumina and silica and serves as a key raw material to produce ceramic fibres and other refractory products [1]. Clay minerals are predominantly composed of silica, alumina, and chemically bound water, together with minor quantities of iron oxides, alkali metals, and alkaline earth elements [2]. The crystal structure of clay minerals consists of two fundamental building units: octahedral sheets and tetrahedral sheets. The octahedral sheets contain aluminum, iron, or magnesium ions coordinated with oxygen and hydroxyl groups, whereas the tetrahedral sheets are formed by interconnected silica tetrahedra arranged in a repeating hexagonal network. The combination of these structural units determines the physical, chemical, and thermal characteristics of clay materials [3].

The growing demand for energy-efficient industrial processes has increased interest in the development of advanced thermal insulation materials. Ceramic fibers produced from kaolin-rich clay offer several advantages over conventional refractory materials, including lower thermal conductivity, reduced heat storage, and improved thermal shock resistance [4]. Owing to their porous fibrous structure, ceramic fibers effectively minimize heat transfer and significantly reduce energy losses in industrial furnaces and high-temperature processing equipment. Consequently, they contribute to improved fuel efficiency and lower operating costs [5]. Based on their composition and service temperature, ceramic fibres can generally be classified into two categories: vitreous alumina–silica fibers and crystalline alumina fibers. Vitreous alumina–silica fibers are typically used at temperatures below 1250°C, whereas crystalline alumina fibers are suitable for applications exceeding 1250°C due to their superior thermal stability and refractoriness [6]. These materials exhibit a unique combination of desirable properties, including low density, high-temperature resistance, low thermal conductivity, low specific heat capacity, and excellent resistance to thermal shock [7].

In addition to their thermal insulation performance, ceramic fibers possess outstanding chemical durability. They exhibit resistance to attack by acids, oils, water, and various corrosive environments. Furthermore, ceramic fibers demonstrate excellent resistance to erosion by molten non-ferrous metals such as aluminum and zinc, making them highly suitable for metallurgical and industrial furnace applications [8]. The increasing consumption of fossil fuels has resulted in a significant rise in greenhouse gas emissions, contributing to global warming and climate change. These environmental challenges have encouraged industries to adopt energy-saving technologies and sustainable manufacturing practices. Since ceramic fibers possess substantially lower bulk density and heat-storage capacity than conventional refractory materials, they can effectively reduce thermal energy losses and improve overall energy efficiency in industrial systems [9]. The implementation of high-performance insulation materials therefore represents an important strategy for reducing fuel consumption and mitigating carbon emissions.

Recent developments in insulation technology have led to the introduction of bio-soluble ceramic fibers, commonly known as “super wool.” Unlike conventional refractory ceramic fibers, which primarily consist of alumina and silica, bio-soluble fibers are mainly composed of silica, calcium oxide (CaO), and magnesium oxide (MgO) [10]. These fibers exhibit excellent thermal insulation characteristics while offering enhanced bio-solubility and reduced environmental and health concerns. As a result, bio-soluble ceramic fibers are increasingly being considered as sustainable alternatives for high-temperature insulation applications. Bangladesh possesses significant deposits of kaolin-rich clay and other mineral resources that can potentially be utilized to produce ceramic fiber insulation materials. The development of

locally sourced ceramic fibers would not only reduce dependence on imported refractory products but also support energy conservation, industrial growth, and environmental sustainability. Therefore, detailed characterization of indigenous clay resources using techniques such as X-ray fluorescence (XRF), X-ray diffraction (XRD), and differential scanning calorimetry–thermogravimetric analysis (DSC–TG) is essential for evaluating their suitability for ceramic fiber manufacturing and high-temperature insulation applications [11, 13].

MATERIALS AND METHOD

In the present study, locally available clay was selected as the primary raw material for the development of ceramic fiber insulation products. Two clay deposits, namely Durgapur clay from Netrokona District and Habiganj clay from Habiganj District, Bangladesh, were investigated due to their high industrial relevance and favorable mineralogical characteristics [11–13, 23–25]. These white clay deposits are currently utilized in various industries, including ceramics, paper, and rubber manufacturing [11,12]. Bangladesh possesses significant clay reserves distributed across several sedimentary regions, particularly in the Netrokona and Habiganj areas [23–25]. The clay deposits are mainly found in alluvial and riverine environments, where long-term sedimentation processes have contributed to the accumulation of fine-grained mineral resources [13,23]. The clay generally exhibits a light gray to bluish-white appearance with occasional pale-yellow coloration. Physically, the material is soft to moderately hard, massive in structure, and displays a slightly smooth or soapy texture [12,13].

Representative clay samples were collected from the selected deposits and subjected to beneficiation prior to characterization and processing. Beneficiation is an essential step for improving raw material quality by reducing undesirable impurities such as free silica, iron oxides, titanium-bearing minerals, and other contaminants that may adversely affect ceramic fiber performance [12,14]. The purification process enhances the chemical uniformity and thermal properties of the clay, making it more suitable for high-temperature insulation applications [5,10,20]. The primary objective of this study was to evaluate the suitability of Bangladeshi clay deposits for ceramic fiber production through detailed investigation of their chemical composition, mineralogical characteristics, and thermal behavior [5,10,15,16,22]. The effectiveness of the beneficiation process was assessed by comparing the properties of raw and treated clay samples using advanced characterization techniques. These analyses provide valuable information for selecting appropriate clay resources and optimizing raw material formulations for the manufacture of energy-efficient ceramic fiber insulation materials [1,5,20].

Bio-soluble ceramic fiber composition

The present study focuses on the development of bio-soluble ceramic fibre insulation materials using locally available kaolin-rich clay and dolomite as the principal raw materials. The ceramic fibres were designed for high-temperature thermal insulation applications and were intended to be produced through a conventional blowing process [5,6]. Kaolin clay was selected as the primary source of silica (SiO_2) and alumina (Al_2O_3), which are essential constituents for the formation of aluminosilicate-based ceramic fibres [10,11,15,22]. The silica content was carefully optimized to improve fibre-forming characteristics and enhance bio-solubility. As a network-forming oxide, SiO_2 contributes to the structural framework of the glassy phase while simultaneously reducing melt viscosity, thereby facilitating fibre production during the blowing process [4,5]. Alumina (Al_2O_3), present at approximately 20 wt.% in the selected clay deposits, functions as an intermediate oxide that significantly enhances the

refractory properties and thermal stability of the ceramic fibres [10,14,22]. The incorporation of alumina improves resistance to high-temperature degradation; however, increasing the Al_2O_3 concentration also results in higher melt viscosity [4,5]. Therefore, the alumina content must be carefully controlled to achieve a balance between thermal performance and processability [5,20].

At elevated temperatures, alumina reacts with silica to form stable aluminosilicate phases that provide excellent thermal resistance and mechanical integrity [5,15,20]. Although these phases contribute to the durability of conventional ceramic fibres, excessive aluminosilicate formation may reduce the dissolution rate of the fibres under physiological conditions [7]. Consequently, the chemical composition was optimized to achieve the desired combination of thermal insulation performance, fibre stability, and bio-solubility [7,20]. Dolomite was incorporated as a source of calcium oxide (CaO) and magnesium oxide (MgO), which act as network-modifying oxides and play a crucial role in enhancing fibre bio-solubility [7]. The addition of these oxides promotes the dissolution of the fibre structure under biological conditions while maintaining the thermal and mechanical properties required for industrial insulation applications [7,20]. Through appropriate compositional control, a bio-soluble ceramic fibre system suitable for temperatures up to approximately 1250°C was developed using indigenous mineral resources available in Bangladesh [5,7,10,22].

For the development of bio-soluble ceramic fibres, the alumina (Al_2O_3) content was maintained below 25 wt.% of the total raw material composition. This limitation is necessary because excessive alumina promotes the formation of highly stable aluminosilicate phases, which can reduce the dissolution rate of the fibres under physiological conditions while increasing refractory characteristics and melt viscosity [5,7,14]. Maintaining a controlled alumina concentration ensures an appropriate balance between thermal stability and bio-solubility [5,7]. Dolomite [$\text{CaMg}(\text{CO}_3)_2$] was incorporated as a key additive due to its ability to provide calcium oxide (CaO) and magnesium oxide (MgO) after calcination. These oxides function as network modifiers within the ceramic fibre structure and play a significant role in enhancing fibre bio-solubility [7]. Calcium oxide contributes to the disruption of the silicate network, thereby increasing the dissolution behaviour of the fibres [7].

Table 1: Effect of different oxide in ceramic fibre composition.

Element	Melting Temp.	Effect on Ceramic Fibre
Al_2O_3	2030°C	Increase viscosity of ceramic fibre melt and insulating properties
SiO_2	1710°C	Decrease viscosity of ceramic fibre melt as a network former
Fe_2O_3	1565°C	Create blackish colour as a impurities of ceramic fibre
TiO_2	1840°C	Create yellowish colour as a impurities of ceramic fibre
MgO	2800°C	Increase bio-solubility and control fibre dimension
CaO	2570°C	Increase bio-solubility and control fibre dimension
B_2O_3	450°C to 510°C	Increase bio-solubility of ceramic fibre
P_2O_5	560°C to 570°C	Increase bio-solubility of ceramic fibre

To maintain the desired thermal and structural properties, the CaO content was restricted to less than 25 wt.% of the overall composition. Magnesium oxide also acts as a network-modifying oxide and influences the morphology of the fibres during fabrication. MgO affects fibre diameter, fibre length, and melt flow characteristics. The MgO concentration was maintained below 8 wt.% to prevent excessive increases in melt viscosity, which could adversely affect fibre formation during the blowing process [4,5]. The thermal performance

and structural stability of the ceramic fibres were optimized by maintaining a CaO-to-MgO ratio of approximately 3:1 by weight. This composition provided a favourable balance between heat resistance, bio-solubility, and fibre-forming capability [7,20]. The presence of these alkaline-earth oxides also contributes to improved thermal shock resistance and high-temperature durability [5,6].

In addition to CaO and MgO, phosphorus pentoxide (P_2O_5) and boron oxide (B_2O_3) were introduced as supplementary network-forming oxides. Like silica, these oxides participate in the glass network structure while enhancing the dissolution behaviour of the fibres in biological fluids [7]. Phosphorite mineral ($Ca_3(PO_4)_2$) and boric acid were used as the primary sources of P_2O_5 and B_2O_3 , respectively. The incorporation of these compounds further improves the bio-solubility of the ceramic fibres without significantly compromising their thermal insulation performance [7]. The optimized bio-soluble ceramic fibre composition was designed to withstand service temperatures up to approximately 1250°C while maintaining excellent thermal insulation characteristics [5,6,20]. Since the principal raw materials were derived from locally available clay deposits and naturally occurring minerals, the proposed ceramic fibre system offers a cost-effective and sustainable alternative to imported insulation products [1,3,10,20,22]. The influence of individual oxide components on ceramic fibre processing and performance is summarized in Table 1.

Ceramic fiber production

Ceramic fibres are typically manufactured by melting a mixture of alumina (Al_2O_3) and silica (SiO_2) in nearly equal proportions, or alternatively by melting kaolin clay. In some formulations, additional oxides such as zirconium dioxide (ZrO_2), boron oxide (B_2O_3), titanium oxide (TiO_2), and chromium oxide (Cr_2O_3) are incorporated to tailor the properties of the final fibre product [5,6]. Among these, chemical composition plays a critical role in determining the maximum service temperature of the fibres. Like other man-made vitreous fibres, properties such as fibre length, diameter, and bulk density—which are influenced by both manufacturing conditions and composition—significantly affect key performance characteristics, including thermal conductivity [4,5]. Although the fundamental composition of refractory ceramic fibres has remained largely unchanged since their initial development, gradual modifications such as increased alumina content and the incorporation of additives including CaO and MgO have enabled the production of fibres capable of withstanding higher operating temperatures while improving bio-solubility and thermal stability [5–7]. Refractory ceramic fibres were originally developed for high-temperature industrial and aerospace applications, and their commercial use expanded considerably with the growing demand for energy-efficient thermal insulation systems [1,5,6,20]. These materials are now widely employed in furnaces, kilns, petrochemical plants, power generation systems, and other high-temperature industrial processes due to their low thermal conductivity, lightweight structure, and excellent resistance to thermal shock [5,6,20].

Blowing method

Ceramic fibers are produced by melting a mixture of alumina (Al_2O_3) and silica (SiO_2) in approximately equal proportions at temperatures exceeding 1800°C , or alternatively by melting kaolin clay and other aluminosilicate raw materials containing selected additives [5,6,10]. The resulting molten material is converted into fibers by directing a high-velocity air or gas stream onto the melt as it flows through an orifice at the base of the furnace, a process commonly referred to as the blowing technique [5,6]. The produced fibers are subsequently collected either as bulk fiber or further processed into blankets through a mechanical needling process.

Although ceramic fibers are marketed in different product forms, all manufacturing routes begin with the production of either bulk fiber or blanket material, which constitute the primary forms of refractory ceramic fiber products [5,6]. The processing stage typically starts from bulk or blanket fiber. Bulk material may be used directly in certain high-temperature insulation applications; however, it is more commonly employed as a feedstock for secondary processing.

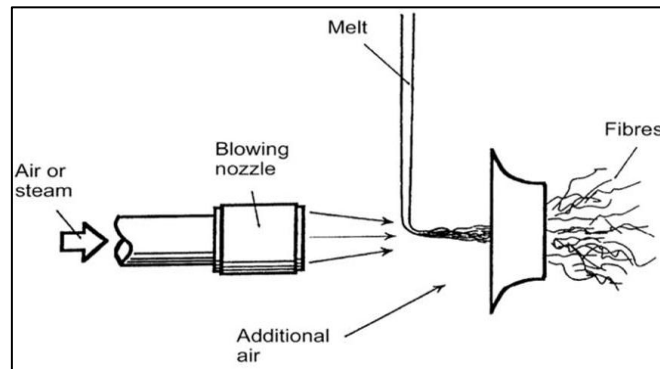


Figure 1: Blowing process for manufacturing ceramic fibers.

Depending on the intended application, the fibers can be transformed into papers, boards, felts, textiles, modules, and vacuum-formed products, or incorporated into liquid and solid matrices to produce advanced thermal insulation systems [5,6,20]. Owing to their low thermal conductivity, lightweight structure, thermal shock resistance, and excellent high-temperature stability, ceramic fiber products have become widely used in furnaces, kilns, petrochemical plants, power generation facilities, and other industrial thermal-processing systems [4–6,20].

RESULT AND DISCUSSION

In this study, the identification and quantification of natural and beneficiated clays for ceramic fibre composition were carried out using X-ray fluorescence (XRF), X-ray diffraction (XRD), and differential scanning calorimetry–thermogravimetric analysis (DSC–TG). XRF analysis was employed to determine the detailed chemical composition of the raw materials [14]. Based on the obtained chemical composition of the selected clays, necessary oxide adjustments were made to achieve the desired ceramic fibre formulation when modification was required [5,10,22]. XRD analysis was used to investigate the mineralogical and structural characteristics of the clay samples [15]. Chemical compositions of Durgapur and Hobiganj clays, collected from different locations within the Netrokona and Hobiganj districts, were determined using an X-ray fluorescence spectrometer, and the samples were subjected to a series of characterization tests [10,22–25]. The crystalline phases present in Durgapur and Hobiganj clays were identified using a PANalytical X-ray diffractometer, with phase analysis performed using HighScore Plus software (version 3) [15,23–25]. In addition, the thermal behaviour and weight-loss characteristics of the clay samples were examined using DSC–TG analysis to evaluate dehydration, dehydroxylation, and phase transformation phenomena occurring during heating [16]. The combined results of XRF, XRD, and DSC–TG analyses provided comprehensive information regarding the chemical composition, mineralogical structure, and thermal stability of the clay materials, thereby enabling the assessment of their suitability as raw materials for ceramic fibre insulation applications [5,10,15,16,22].

X-ray fluorescence characterization

X-ray fluorescence (XRF) is the emission of characteristic secondary (fluorescent) X-rays from a material that has been excited by high-energy X-rays or gamma rays. The emitted fluorescent

radiation possesses energies that are characteristic of the constituent elements present in the sample, enabling both qualitative and quantitative elemental analysis. Due to its accuracy, rapid analysis capability, and non-destructive nature, XRF is widely used for determining the chemical composition of clays, aluminosilicate minerals, and other ceramic raw materials [14,22,23].



Figure 2: Images of (a) Hobbi-08 and (b) Bijoy-07 Clay.

Table 2 indicates that the clay composition also contains minor amounts of CaO, MgO, Na₂O, and K₂O, which act as fluxing agents during high-temperature processing and influence the sintering behavior of ceramic materials [13,14]. However, the presence of iron- and titanium-bearing oxides is generally undesirable because these impurities can adversely affect the color, refractoriness, and overall suitability of clay materials for advanced ceramic and insulation applications [11,12,22]. Conventionally, iron-bearing impurities are reduced through physical beneficiation techniques such as screening, washing, magnetic separation, and classification. Nevertheless, hydrometallurgical methods, particularly acid leaching, have been reported to be more effective for the removal of iron and titanium contaminants and for improving the purity of clay intended for high-value industrial applications [12,23–25]. The reduction of these impurities enhances the chemical quality of the raw material and improves its suitability for ceramic fibre production and other refractory applications [10,22,23].

Table 2: Chemical composition of clay raw materials.

Component ID	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	TiO ₂ %	CaO %	MgO %	K ₂ O %	Na ₂ O %	P ₂ O ₅ %	ZrO ₂ %	Cr ₂ O ₃ %
BIJOY-07	66.32	26.67	2.01	2.47	0.15	0.38	1.56	-	0.06	0.23	0.05
HOBI-08	77.44	16.02	1.77	1.04	0.08	0.68	2.56	0.22	0.05	0.04	0.04

XRD characterization

Figure 3 presents the XRD patterns of the clay samples, where the upper diffractogram corresponds to the Hobbi-08 sample and the lower one represents the raw Bijoy-07 clay. The results indicate that quartz (SiO₂) exhibits the highest peak intensity in both samples, suggesting that silica is the dominant mineral constituent [15,23–25]. The Hobbi-08 sample shows comparatively higher quartz peak intensity, indicating a greater silica content, whereas the Bijoy-07 sample exhibits relatively lower quartz intensity.

In contrast, the Bijoy-07 clay is comparatively richer in alumina-bearing phases than the Hobbi-08 natural clay, which is consistent with the chemical composition obtained from XRF analysis [10,14,15,22]. X-ray diffraction analysis is widely used to identify crystalline mineral phases in clay materials and to evaluate the relative abundance of quartz, kaolinite, feldspar, and other aluminosilicate minerals present in ceramic raw materials [12,15].

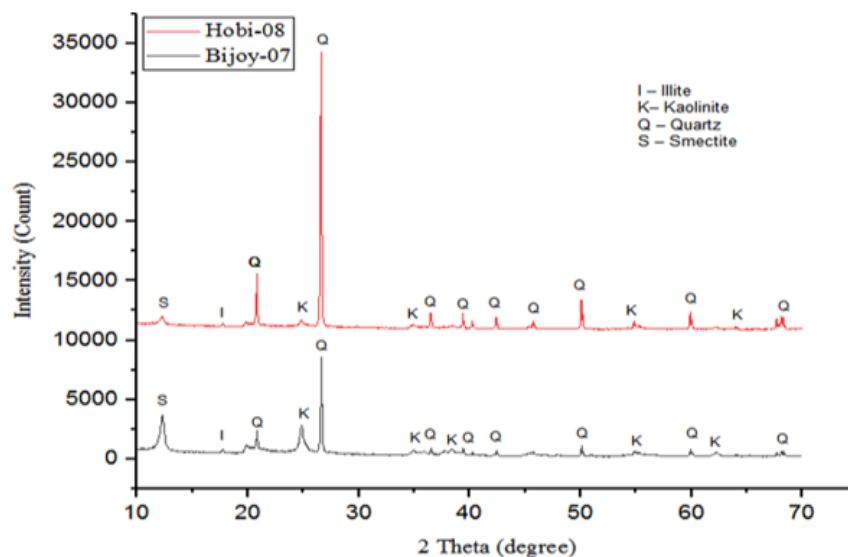


Figure 3: XRD Analysis of Bijoy-07 and Hobbi-08 Clay.

The observed differences in mineralogical composition between the two clay samples are important for assessing their suitability as raw materials for ceramic fibre production, since the silica-to-alumina ratio significantly influences melting behavior, fibre-forming characteristics, and high-temperature performance [5,10,20,22].

DSC-TG Characterization

DSC–TG analysis is a combined thermal technique that records both heat flow and mass variation of a material as a function of temperature or time under a controlled atmosphere. The integration of these two measurements provides complementary insights, allowing detailed evaluation of thermal events such as exothermic and endothermic reactions, including processes like carbon oxidation and dehydroxylation [12].

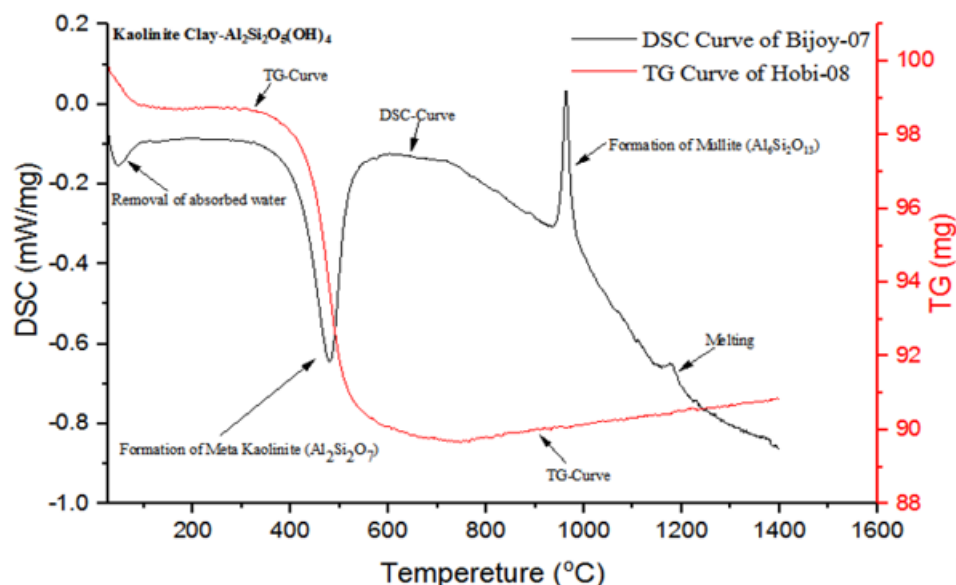


Figure 4: DSC and TG analysis curve of Bijoy-07 clay.

The DSC curves presented in the figures illustrate the energy changes associated with endothermic and exothermic reactions occurring within the clay samples during heating. In clay minerals, endothermic reactions are primarily attributed to the removal of physically

adsorbed surface water and interlayer water at relatively low temperatures, typically around 100°C [16]. As the temperature increases, dehydration and dehydroxylation processes occur, resulting in significant structural changes within the clay minerals [16]. For kaolinite-rich clays, the transformation to the amorphous metakaolinite phase generally takes place within the temperature range of 450–650°C, with a characteristic endothermic peak often observed near 456°C [15,16]. The α - β quartz phase transformation is typically detected at approximately 573°C and is accompanied by a reversible structural change in quartz [15,16].

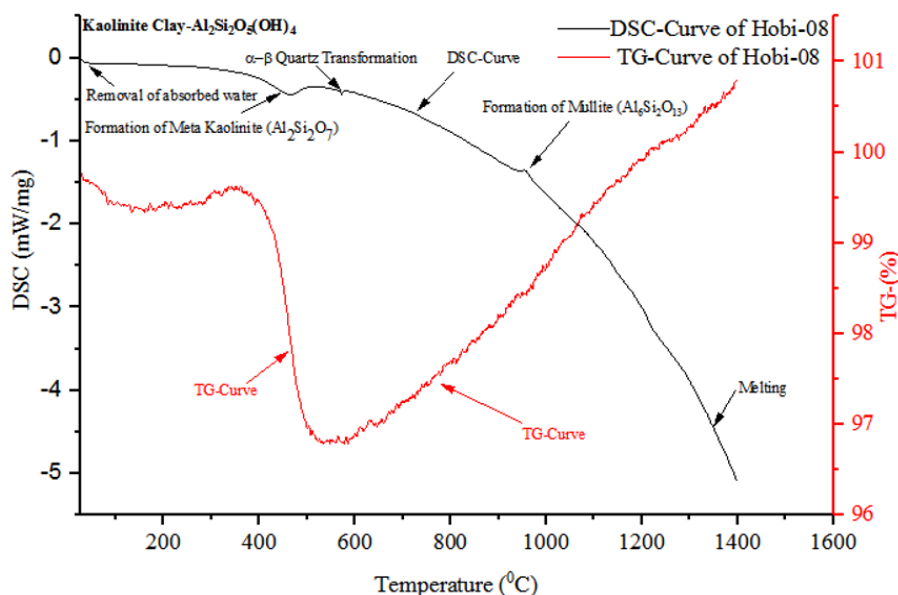


Figure 5: DSC and TG analysis curve of Hobi-08 clay.

Exothermic reactions observed at higher temperatures are generally associated with recrystallization processes and the formation of new aluminosilicate phases, such as spinel-type structures and mullite precursors [16]. These reactions may occur concurrently with or subsequent to dehydroxylation and partial melting phenomena. The thermal transformations identified through DSC–TG analysis provide important information regarding the thermal stability, phase evolution, and suitability of the clay materials for high-temperature ceramic fibre production and insulation applications [5,10,16,22].

CONCLUSION

The adoption of environmentally friendly materials is widely recognized as an effective approach to achieving sustainability in material development. The selection of sustainable materials can be assessed using several key criteria, including: (1) the local availability of raw resources, (2) embodied energy of the materials, (3) the proportion of recycled or waste-derived content, (4) the use of rapidly renewable resources, (5) contribution to energy efficiency, (6) recyclability, (7) durability, and (8) overall environmental impact. Based on XRD, chemical, and DSC analyses of Hobi-08 and Bijoy-07 clay samples, it was observed that both clays are primarily composed of silica and alumina, with minor amounts of iron, calcium, potassium, and magnesium oxides. Mineralogical evaluation revealed that kaolinite, quartz, and illite are the dominant phases present in both samples. The overall properties indicate that Hobi-08 and Bijoy-07 clays have strong potential as important raw materials in the ceramic fibre industry in Bangladesh to produce various ceramic fibre-based products. Their utilization could also reduce dependence on imported ceramic insulating materials. Among the two samples, the washed Bijoy-07 clay exhibits superior quality and performance characteristics.

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