Suitability of Thulamela Clays for Use in The Ceramic Industry: A Case Study in Thulamela Municipality, Limpopo Province, South Africa

By

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Declaration

I, **Ralushai Murendeni,** at this moment declare that this dissertation for the Master of Environmental Sciences in Geography submitted to the University of Venda in the Department of Geography and Environmental Sciences, Faculty of Science, Engineering and Agriculture has not been submitted for any other degree at this or any other university. I further declare that this dissertation is my own in design and execution, and all the reference materials and cited work of others have been fully acknowledged.

15/07/2025

Student's signature Date

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Dedication

This study is dedicated to my late father, Ralushai Thembatshira Leonard, who always loved, believed, encouraged, and gave wise advice regarding the value of education. I hope you, Dad, have eternal peace and rest in peace. I also dedicate this study to my family: my son, siblings and mother, Ralushai Denga Delnah; they all supported and believed in me and pushed me to pursue my education to the fullest. They are undoubtedly highly honoured to view this dissertation.

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Abstract

This study investigated the suitability of Thulamela Municipality clay samples for ceramic applications by examining their physical, chemical, and mineralogical properties. A comprehensive analysis was conducted using various tests, including particle size analysis, Atterberg limits, X-ray fluorescence (XRF), and X-ray diffraction (XRD). The study evaluated the clays' strength, cracking, water absorption, and linear shrinkage during and after firing at different temperatures (300°C, 700°C, 800°C, 900°C, and 1150°C), aiming to assess their potential for ceramic use.

The study analysed the physical and chemical properties of clays from various locations. Sieve analysis revealed well-distributed particle sizes, while hydrometer analysis showed varying clay and sand content. Atterberg limit tests indicated high plasticity, and XRF analysis identified aluminium oxide (Al_2O_3), silicon dioxide (SiO_2), and iron oxide (Fe_2O_3) as dominant chemical elements. XRD analysis detected quartz, kaolinite, and hematite as primary minerals, with variations between samples.

The study identified Ha-Matsika, Lwamondo, Muledane, and Dzingahe clays as having optimal ceramic properties, suitable for high-end applications like refractory ceramics and sanitary ware. These clays exhibited moderate to low water absorption rates and stable linear shrinkage behaviour. In contrast, clays from Ngwenani, Madadani, Tshilungoma, and Tshino are better suited for less demanding ceramic products. The study's findings have significant implications for the ceramic industry, highlighting the potential of local clay resources for producing high-quality ceramics.

The study recommends further research to improve the properties of certain clays (Ngwenani, Madadani, Tshilungoma, and Tshino). Utilising local clay resources can enable the ceramic industry to adopt sustainable practices, produce high-quality products, and promote environmentally friendly manufacturing.

Keywords: *Ceramic Properties, Clay Characterisation, Clay Suitability, Mineralogical Analysis, Ceramic Applications.*

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Chapter One: Introduction

1.1 Introduction

Chapter one outlined the research study, providing an overview of the background, problem statement, objectives, and rationale. The study aims to investigate the suitability of clay from Thulamela Municipality for various ceramic applications. The chapter also described the study area, covering its climate, topography, drainage, soil, vegetation, population, and economic activities. Additionally, the chapter outlined the research questions guiding the study. Key terms used in the study are also defined to provide clarity and context.

1.2 Background to the Study

Clay is a fine, loose, dusty substance that originates from the ground with particles smaller than 4 µm (Arkame *et al.*, 2023). The raw clay is utilised for a range of applications such as construction and building, environmental applications, industrial applications and is essential and appreciated worldwide (Brown and Sobsey, 2010; Shubbar *et al.*, 2019) (Brindha *et al.*, 2021; La Noce *et al.*, 2021). The usage of raw clay is constantly increasing and wide-ranging because it has applications in various sectors, such as mining, agricultural production, civil and building engineering environment and the ceramics industry (Kome *et al.*, 2019; Otunola and Ololade, 2020; Firoozi *et al.*, 2021; Ayalew, 2022) (Ewis *et al.*, 2022). According to Mefire *et al.* (2018) raw clay has been used in various ceramics as a critical element in most ceramic bodies. It is used to make cement, fibreglass, roof granules, paint, brick, tile, sewer pipe, refractories, kiln furniture, sanitary ware, pottery, and dinnerware *(Del Rio et al., 2022).*

For centuries, clay has been synonymous with pottery, its versatility shaping cultures worldwide (Kiradoo, 2021). From ancient eastern civilisations to modern-day, the ceramic industry's technological advancements have spread radically, influencing various cultures and regions (Esmyol, 2020). Before the widespread use of refrigerators and piped water, ceramic pots were a staple in households, serving multiple purposes such as meal preparations, water storage, and cooling (Antonites, 2020). Beyond their practical applications, clay, the primary material for ceramics, played a significant role in cultural and artistic expression (Esege, 2022). It was utilised to craft musical instruments, create

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decorative and symbolic artefacts, and develop traditional art forms and sculptures in southern Africa (Kumbani, 2020).

Ceramic works are vital in fostering a sense of belonging and pride among creators and admirers as a tangible connection to cultural heritage (de Lapérouse, 2020). By preserving and promoting cultural identity, ceramics honour traditional techniques, celebrate community history, and provide a lasting link to ancestral roots. Beyond their aesthetic value, the development of ceramic products has significant social implications, offering local artists opportunities to establish sustainable livelihoods and contribute meaningfully to their community's growth (Aniyikaiye *et al.*, 2021). This convergence of cultural preservation and economic empowerment not only strengthens community bonds but also promotes cross-cultural understanding and appreciation (Aniyikaiye *et al.*, 2021).

According to Aniyikaiye *et al.* (2021) South Africa heavily relies on clay for traditional pottery and brickmaking, particularly in rural areas. As a developing country with limited industrialisation and economic activity, many residents face financial constraints due to low incomes. However, small-scale ceramic businesses have emerged as vital employment and economic growth sources in these communities (Aniyikaiye *et al.*, 2021). These enterprises preserve traditional craftsmanship and provide essential income opportunities, contributing to the region's economic development.

According to Mefire *et al.* (2018), clay's exceptional properties, both in its raw state and after firing, make it an ideal material for ceramics. Its unique combination of mineralogy, porosity, mechanical strength, plasticity, and particle size distribution enables clay to be moulded and transformed into various forms, exhibiting versatility and adaptability. These characteristics allow clay to be shaped, dried, and fired into durable, long-lasting products. Different types of soil are used to make various clay products, such as pottery, bricks, tiles, bathroom fixtures, heat-resistant materials, sculptures, and household items (Engels and Piribauer, 2022).

Clay selection varies depending on desired properties, with some chosen for texture, colour, or flexibility, while others are valued for durability, making them suitable for outdoor applications *(*La Noce *et al., 2021)*. The characteristics of ceramics, such as their colour,

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shape, size, and texture, affect how they are used and what they are needed for (Fuertes *et al.*, 2022). The type of rock that soil comes from affects its makeup and structure, which determines its properties *(*Da Silva *et al., 2022)*. However, local temperature and precipitation variations cause soil diversity, resulting in distinct soil types with unique qualities (Certini and Scalenghe, 2023). For example, the Thulamela Municipality boasts diverse soil types, ideal for pottery and brick production (Akintola *et al.*, 2020; Akintola *et al.*, 2024). Various locations yield distinct soil types with varying qualities, making each region's ceramic products unique.

The Thulamela Municipality's rural landscape is characterised by expansive alluvial plains featuring an abundance of clay soils in numerous valleys (Akintola, 2018). The community has long utilised these local clay deposits for traditional pottery and the production of ceramic bricks for building purposes (Monatshebe, 2017). The potential of Thulamela's clay for brick making, as well as the establishment of product quality standards and guidelines for informal small-scale brick manufacturing enterprises, has been extensively researched in various studies conducted with the municipality (Matsiketa, 2018).

A previous study conducted by Matsiketa (2018) investigated the brick-making process in Dididi Village, highlighting the presence of significant clay deposits suitable for industrial use, as well as the utilisation of geophonic clay raw materials for both industrial and local applications in Vhembe District, as further explored by (Dacosta *et al.*, 2013). Matsiketa (2018) found that the traditional, labour-intensive method of making bricks in Dididi village often results in bricks of lower quality. Furthermore, the lack of scientific testing material selection resulted in the use of substandard materials, ultimately affecting the final product. Material choices were based solely on knowledge and experience rather than scientific testing.

According to Manjate *et al.* (2020), the absence of thorough research and scientific testing can lead to numerous production issues, including final product deformation and breakage. Additionally, the absence of a scientific basis for ceramic production may hinder innovation and discourage entrepreneurs from creating new ceramic products, such as tiles. This study seeks to fill a critical knowledge gap by assessing the potential of clay from Thulamela Municipality for diverse ceramic uses. The results will substantially

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deepen our insight into clay characteristics and applications, ultimately boosting the raw materials sector, stimulating economic growth, and promoting innovation in the ceramic industry.

1.3 Problem Statement

The Thulamela Municipality is rich in clay deposits, which are currently utilised by local communities to produce fired bricks (Akintola, 2018). People in the area have been making clay bricks and pottery without any oversight, which means the quality is uncertain. Locals rely on these bricks to build homes and use pottery for various purposes including cooking, storage, and ceremonial or cultural practices. Since there is a high demand for clay bricks, the makers depend on selling them to earn a living, creating jobs for themselves in the process.

According to Dacosta *et al.* (2013), the main reasons for the growing demand for clay materials in the Thulamela Municipality are the rising need for building and construction materials, driven by urbanisation and infrastructure development. Evaluating and understanding the properties of clay used for brickmaking is crucial, as traditional methods cannot keep up with the demand for bricks (Dacosta *et al.*, 2013). At the same time, other researchers are investigating various factors that impact clay brick production, such as how the mineral composition affects the brick's compressive strength (Matsiketa, 2018; Monatshebe *et al.*, 2019). In the Thulamela Municipality, some are evaluating the geotechnical qualities of clayey materials for premium burnt bricks (Akintola, 2018). In the Thulamela Municipality, researchers are studying the geotechnical properties of clay materials to produce high-quality burnt bricks.

Most preceding studies concentrated on traditional brick-making, clay deposit evaluations, and masonry product management in South Africa's Limpopo Province (Akintola, 2018; Aniyikaiye *et al.*, 2021; Akintola *et al.*, 2024). In contrast, this research investigates multiple brick production sites within Thulamela Municipality using diverse clay types with potential applications beyond brick making. Specific geographical locations may exhibit unique properties conducive to diverse ceramic applications, including but not limited to bricks, pottery, tiles, and other ceramic items. A comprehensive investigation into the suitability of clay for diverse ceramic applications could catalyse the

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growth of the ceramic manufacturing industry in Thulamela Municipality, extending beyond its current focus on brick production. This research aims to determine the potential of clay in the Municipality for making diverse types of ceramics.

1.4 Rationale of the Study

South Africa's brick industry plays a significant role in boosting the country's economy, with traditional methods still contributing largely to the nation's clay brick output (Aniyikaiye *et al.*, 2021). The small-scale ceramic industry in Thulamela Municipality provides a crucial livelihood for unemployed and unskilled community members, serving as a vital source of income to meet their essential needs (Mabogo, 2021). However, the industry's growth potential remains untapped mainly, hindered by a lack of understanding regarding the properties and capabilities of local clay deposits.

This research aimed to fill a critical knowledge gap by examining the potential of local clay deposits for producing a range of ceramic products. This research aims to provide critical insights into their potential uses in ceramic manufacturing by analysing these clays' physical, chemical, and mineral properties. The results of this study will not only improve the skills of local clay brick makers but also encourage ceramic business owners to expand their product lines, tap into new markets, and ultimately boost the economic growth and development of Thulamela Municipality.

1.5 Research Aim and Objectives

This research aimed to examine the suitability of clay properties for various ceramics in Thulamela Municipality.

1.5.1 Specific Objectives

The specific objectives for this research were to:

- Characterise the physical properties of clay soils found in Thulamela Municipality.
- Determine the chemical and mineral composition of clay soils found in Thulamela Municipality.
- Characterise the chemical and mineral composition of clay soils found in Thulamela Municipality

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1.6 Research Questions

This research sought to answer the following questions:

- What are the physical properties of clay soils found in Thulamela Municipality?
- What is the chemical and mineral composition of clay soils found in Thulamela Municipality?
- How do the chemical and mineral compositions of clay soils vary across various locations within Thulamela Municipality?

1.7 Limitations of the Study

One major constraint of this study is its geographical scope, which is limited to specific locations, thereby restricting the generalizability of the findings to other regions. Moreover, the study's methodology is constrained by the lack of long-term testing, which is crucial for assessing the durability and performance of ceramics over an extended period. This limitation creates a knowledge gap regarding the potential of these clays for long-term applications.

1.8 Study Area

The study area is in the Thulamela Local Municipality, in the Limpopo Province of South Africa (Figure 1.1). Precisely, it is positioned at 22°45'24.22" S latitude and 30°35'53.36" E longitude, within the Vhembe District. Historically, the Vhembe District encompasses the former Gazankulu and Venda homelands (Nemukula, 2019). The Vhembe District consists of four local municipalities: Thulamela, Musina, Mutale, and Makhado (Ahunamure, 2016). This study focused on eight villages along the riverbanks in the Thulamela municipality: Dzingahe, Ha-Matsika, Lwamondo, Madadani, Muledane, Ngwenani, Tshilungoma, and Tshino. These villages are known for their clay brick production. Geographically, Thulamela municipality is bordered by Mutale municipality to the northeast and Makhado municipality to the southwest (Gooch, 2010).

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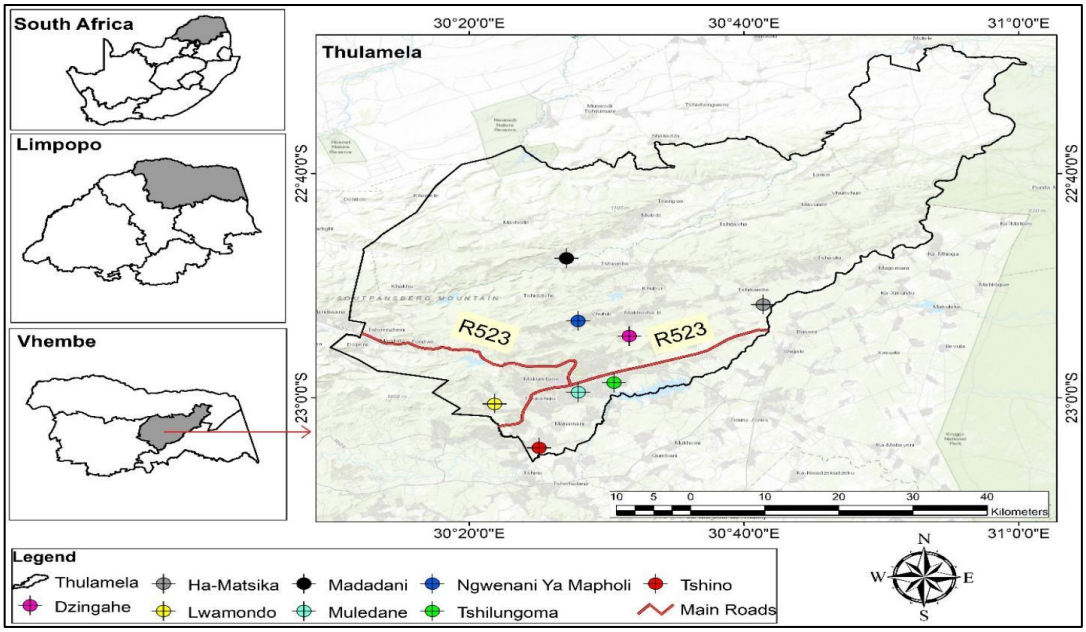

Figure 1. 1: Thulamela Municipality Showing Sampling Areas

1.8.1 Climate

Thulamela Municipality has a subtropical climate, with annual precipitation ranging from 300 to 1000mm (Ahunamure, 2016). Rainfall is mostly from October to March. Notably, mountainous areas experience substantial rainfall, averaging approximately 1329mm per year (Mzezewa *et al.*, 2010). According to Shikwambana *et al.* (2021), the region exhibits a significant east-west precipitation gradient, with yearly evaporation rates of 1400mm in the west and 1900 mm in the east. Temperature fluctuations are pronounced, with the average summertime temperature ranging from 17°C to 37°C, while wintertime temperatures range from 5°C to 20°C (Shikwambana *et al.*, 2021). Exceptionally hot temperatures, reaching up to 45°C, can occur in some areas during summer (Shikwambana *et al.*, 2021). Furthermore, the region's humidity levels vary significantly, averaging 38% in winter and 80% in summer, as observed by (Kabanda and Munyati, 2010).

1.8.2 Topography and Drainage

The Soutpansberg group, a volcano-sedimentary succession, comprises seven distinct formations: Tshifhefhe, Sibasa, Fundudzi, Wylliespoort, Nzhelele, Stayt, and Mabaligwe. The volcanic sequence reaches a maximum thickness of around 3000 meters, comprising

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predominantly volcanic rocks, with lesser amounts of pyroclastic rocks and subaerial basalts (Oyebanjo, 2020). The basalts are characterised by their massive, amygdaloidal, and exemplary nature. In the Thulamela Municipality, the geology is classified as a volcanic succession (Akintola, 2018). In addition to volcanic rocks, local sedimentary deposits are also found, consisting of quartzite, shale, and minor conglomerate, with a maximum thickness of approximately 400 meters (Nemalamangwa, 2020). These sedimentary layers add diversity to the region's predominantly volcanic landscape.

The Thulamela Municipality is characterised by prominent mountains and varied elevations. Geologically, the area is composed of Precambrian granite, specifically the Golden Plate Gneiss (Nethengwe, 2007). The Thulamela Municipality's landscape is formed from high-grade metamorphic rock, which resists erosion. Fault lines have shaped the hills and scarps and allowed dolerite dykes to intrude. However, erosion has been the main force behind the area's current landscape (Mucina and Rutherford, 2006). A network of perennial rivers, including the Mutale, Mutshundudi, Mutangwi, Tshinanne, and Luvuvhu, drain the Thulamela Municipality, ultimately flowing into the Limpopo River, which forms the international border with Zimbabwe (Ahunamure, 2016). Two vital dams, Phiphidi and Nandoni, are located within Thulamela Municipality, providing a reliable source of clean water for households and supporting local farming, thereby meeting the community's water requirements.

1.8.3 Soil and Vegetation

The Thulamela Municipality has different soil types, such as clay, sand, and a mix of both. Most of the soil comes from rocks and is not very good for growing plants because it lacks nutrients and is acidic (Mucina and Rutherford, 2006). The types found there are not common; rather, they are scattered throughout the Vhembe District (Mulugisi, 2015). In the Vhembe District, fertile red loam is the most common type of soil that often suffers from too much water runoff (Nethengwe, 2007). Strong winds and heavy rains quickly erode the fertile red loam soil because it contains a lot of clay which holds water for a long time.

According to Fatima and Siddiqui (2017), the red colour of this clay soil comes from its high iron content. While it has a good amount of potash, it lacks other important nutrients

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like humus, phosphorus, magnesium, nitrogen, and lime. Its pH level can range from neutral to acidic (Osman and Osman, 2013; Ghosh, 2019). This type of soil is created when old, hard rocks like acid granites, gneisses, quartzite, and felspathic rocks break down over time (Dwevedi *et al.*, 2017). Red soil is made up of free quartz sand and is high in silica and alumina (Rakhila *et al.*, 2018). It is mainly loamy, with a mix of minerals from sand to clay, and is rich in potassium. This type of soil is often used to make earthenware products like bricks, wall tiles, and pottery (Anbarasu and Sathyamoorthy, 2020).

1.8.4 Population and Economic Activities

Thulamela Municipality is a big part of the Vhembe District. In fact, about 47.7% of the people living in the district call Thulamela home. The total number of people living in Thulamela is around 618,462 (Frith, 2011). Women make up 54.9% of the population, while men make up 45.1% (Uhunamure *et al.*, 2016). The population of Thulamela Municipality is slowly increasing at a rate of 0.62% each year (Uhunamure *et al.*, 2016). The area is quite spacious, with 110 people living per square kilometre. In total, the municipality covers an area of 5,835 square kilometres. The official unemployment rate is set at 43.10% (Uhunamure *et al.*, 2016). The municipality comprises 228 villages with 156,594 households, nearly all of which are Venda (Uhunamure *et al.*, 2016). Thulamela Municipality is classified as a "Category B" local municipality. This is because it has a small number of towns and a traditional village system where land is owned communally. The municipality's population is mostly rural, with about 90% of people living in tribal or rural areas. There are also some scattered groups of homes, mainly in areas that were formerly homelands (Gumbo *et al.*, 2016).

The homes in Thulamela Municipality are mostly made of cement walls, with roofs made of corrugated iron, clay, or thatch. However, many settlements lack proper infrastructure, jobs, and access to necessities. This is partly because land and resources are not shared fairly. As a result, many households struggle to make ends meet and rely on government support, pensions, and money sent by family members who have moved to cities to find work (Uhunamure *et al.*, 2016). Most people engage in subsistence farming, commercial agriculture, and informal trading to make a living in Thulamela Municipality. When it

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comes to land use, the area is mainly divided into three purposes: mining, agriculture, and settlement (Mathako, 2019).

1.9 Definition of Terms

Ceramics are goods (like earthenware, porcelain, or bricks) primarily created by firing non-metallic minerals (like clay) at a high temperature (Hamood and Khatib, 2016).

The ceramic industry refers to a broad range of goods manufactured from clay and related materials heated to high temperatures (Fatima and Siddiqui, 2017).

Clay is an earthy substance used to make brick, tile, and pottery. It is plastic when wet but hardens when fired. It is primarily made up of fine particles of hydrous aluminium silicates and other minerals (Valášková, 2015).

Clay or shale raw materials are dried and fired to create a sintered porous structure, which is how clay bricks are made (Stevenson, 2010).

Clay minerals include kaolinite, illite, and montmorillonite, which comprise most clays. They are a class of hydrous aluminium silicate minerals (Wimpenny, 2016).

Clayware is earthenware separated from tile, brick, porcelain, and stoneware (Valášková, 2015).

Kaolinite is a soft, earthy, typically white mineral created when aluminium silicate minerals weather chemically. It is a dioctahedral phyllosilicate clay (Kumari and Mohan, 2021).

Mica is one of the silicate minerals. It has the most notable physical properties and can break into fragile, elastic plates from individual mica crystals (Thompson and Ukrainczyk, 2002).

Pottery, consisting of clay objects heated to a solid state, is among the most ancient and popular decorative arts (Fatima and Siddiqui, 2017).

Raw materials are substances or materials that are used in the initial stages of the manufacturing or production of goods (Early, 2012).

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Traditional ceramics describe ceramic items made from raw clay or mixtures of raw clay and granulated or powdered non-plastic minerals (Montana, 2017).

Sieve analysis is an analytical technique for determining the particle size distribution of a granular material's macroscopic granular sizes (Liu *et al.*, 2019).

Smectites are a class of clay minerals that collectively display the common property of hydrational swelling when exposed to water. They have a three-layer crystalline structure consisting of one alumina layer and two silica layers (Maltsev *et al.*, 2021).

1.10 Chapter Summary

This chapter provided an overview of the study's context and framework. It begins with examining the study's background and then clearly articulates the problem statement and the research rationale. The chapter then outlined the study's aim, specific objectives, and limitations, including the research questions and the geographic scope of the investigation. Additionally, the chapter describes the study area in detail, encompassing its climate, topography, drainage patterns, soil composition and vegetation. Finally, the chapter provides an overview of the study area's demographic characteristics and economic activities, laying the groundwork for the subsequent chapters.

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Chapter Two: Literature Review

2.1 Introduction

Chapter two provides an in-depth examination of the interplay between climatic conditions and soil formation, leveraging the Koppen Climate Classification system to illustrate the significant impact of climate on soil development. This chapter is divided into several key sections. First, it explores the physical characteristics of clay soils across different regions, analysing how climatic factors such as temperature, precipitation, and weather patterns influence their composition and structure. Next, it investigates the mineral and chemical properties of clay soils in various climatic zones, shedding light on the complex interactions between climate, geology, and soil chemistry. The discussion then shifts to the practical applications of clay in ceramic industries worldwide, highlighting regional variations in clay utilisation and the implications for ceramic production. Finally, a comprehensive literature review synthesises existing research on clay characterisation methods and suitability assessment for ceramic use, providing a foundational understanding for further investigation.

2.2 Relationship between Climatic Conditions and Soil Formation

Climatic regions play a pivotal role in shaping the soil formation processes around the world (Certini and Scalenghe, 2023). Understanding the relationship between climate and soil formation is essential for comprehending the diverse soil types found across different regions and predicting climate change's effects on soil ecosystems (Okur, 2023). The diverse climatic conditions, including temperature, precipitation, and evaporation rates, significantly influence the development and characteristics of soils (Omotoso *et al.*, 2023). The Koppen climate classification system provides a valuable framework for understanding this relationship, categorising the world's climates into five primary zones (Figure 2.1). These zones delineated by distinct temperature and precipitation patterns profoundly impact soil characteristics, resulting in unique soil properties across different regions.

For instance, tropical regions (Af, Aw, and Am) with high temperatures and precipitation experience rapid soil weathering, leaching, and erosion, resulting in soils rich in iron and

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aluminium, such as Oxisols and Ultisols (Driese *et al.*, 2021). In contrast, temperate regions (Cfa, Cfb, and Csa) with moderate temperatures and precipitation support balanced soil formation, minimal leaching, and well-developed soil profiles, giving rise to soils like Alfisols and Inceptisols (Hakim, 2023). Arid regions (BWh, BWk, and BSh), characterised by low precipitation and high evaporation, exhibit slow soil formation, salinisation and soils with high salt content, such as Aridisols (Rani and Paul, 2023). The boreal regions (Dfa, Dfb, and Dfc) experience low temperatures and precipitation, leading to slow soil formation, limited microbial activity, and soils rich in organic matter, like Gelisols and Histosols (Artaxo *et al.*, 2022). Lastly, the polar regions (EF and ET) have extremely low temperatures and minimal precipitation, resulting in limited soil formation and permafrost (Bui *et al.*, 2020).

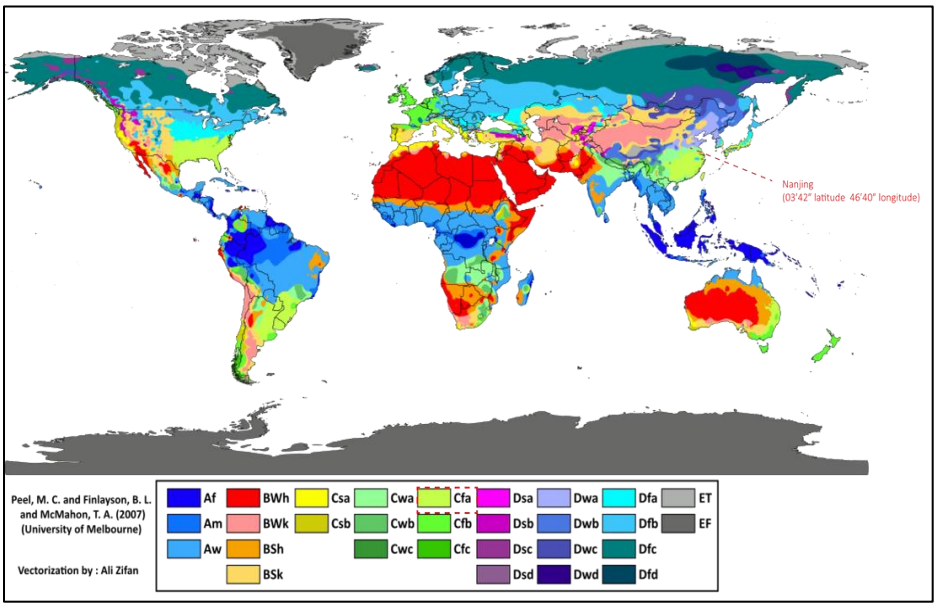

Figure 2. 1: Koppen-Geiger Climate Classification Map (Peel *et al*., 2007)

2.3 Physical Characteristics of Clay Soils Across Different Regions

Clay soils exhibit distinct physical characteristics shaped by regional climates (Sandler, 2013). According to Debuyser and Tessier (2004) European temperate climates give rise to moderately plastic and water-retentive clays, typically characterised by illite and vermiculite minerals and exhibiting slightly acidic to neutral pH values (5.5-7.0). Asia's tropical to temperate climate produces highly plastic and water-retentive clays, rich in kaolinite and montmorillonite, with acidic to neutral pH (4.5-7.0) (Zhou *et al.*, 2019;

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Ohtsubo *et al.*, 2002). The Americas display similar characteristics, with tropical to temperate climates resulting in highly plastic clays, particularly in South America's kaolinite-rich regions. In contrast, North America's clay soils tend to be more illiterite-dominant (Melo *et al.*, 2001; Barre *et al.*, 2007). Regional variations exist, such as Europe's Mediterranean alkaline clays, Asia's Southeast Asian iron-rich clays, and the Americas' diverse clay mineralogy.

Africa's diverse climate zones shape the physical characteristics of its clay soils. Clay soils exhibit high plasticity and water-holding capacity in tropical and subtropical regions, often containing kaolinite and montmorillonite minerals, with acidic to neutral pH (4.5-7.0) (Akinyemi *et al.*, 2014). Clay soils are less plastic and more alkaline in semi-arid and arid regions. South Africa's clay soils reflect this diversity, with the Limpopo Province's Thulamela region displaying unique characteristics. Thulamela's clay soils are typically highly plastic, mixing kaolinite, montmorillonite, and illite minerals, with pH levels ranging from slightly acidic to neutral (5.5-7.0) (Raphalalani, 2017; Oyebanjo, 2020). The region's subtropical climate, with high rainfall and temperatures, contributes to the development of these clay soils (Akintola, 2018; Mulenga and Sengani, 2020).

2.4 Mineral and Chemical Characteristics of Clay Soils Across Different Regions

Clay minerals possess distinct characteristics that make them suitable for various applications. Key factors influencing their utility include particle size, surface chemistry, particle shape, and surface area. Additionally, specific physical and chemical properties play a crucial role in determining their suitability for use. These properties encompass viscosity, colour, plasticity, dry and fired strength, absorption and adsorption capacities, abrasion resistance, and other specialised attributes. Understanding these characteristics is essential for optimising clay mineral applications in diverse fields.

In tropical regions, such as the northern part of Cameroon and South Africa's Limpopo Province, the mineralogical composition of clay soils is characterised by a diverse range of minerals. Quartz, feldspar, plagioclase, kaolinite, illite, and smectite are commonly found, with kaolinite dominating the composition (Kagonbe *et al.*, 2021; Oyebanjo *et al.*, 2021). Limpopo Province's location north of the Tropic of Capricorn classifies it as a tropical zone, where kaolinite is the primary clay component, often accompanied by other

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weatherable minerals. The prevalence of kaolin minerals in tropical and subtropical regions is attributed to the weathering of aluminium-rich rocks or arkosic rocks, resulting in primary or secondary origins, respectively (Ekosse, 2005). Notably, the Hutton soil form, renowned for its striking red hue, is widespread in South Africa, likely due to high rainfall and leaching (Oyebanjo *et al.*, 2021). The mineral composition of these soils makes them suitable for producing earthenware products, such as fire bricks, which are ideal for brick production.

Kaolin deposits, primarily composed of kaolinite, quartz, and siderite, have been identified in various locations, including India's northeastern region (Saikia *et al.*, 2003). Similarly, research in Morocco's Amezmiz region revealed dominant mineral phases of quartz, illite, and vermiculite, accompanied by minor kaolinite, calcite, and smectite phases (Lahcen *et al.*, 2014). In Tunisia, illite and kaolinite are the predominant clay phases, with quartz, dolomite, and hematite present as accessory minerals. The combination of kaolinite and illite is extensively utilised in the ceramic industry (Baccour et al., 2009). The temperate region's moderate climate and precipitation facilitate the chemical weathering of silicate-rich rocks, resulting in the formation of iron oxides and hydroxides responsible for the soil's distinct red colour (Hong *et al.*, 2023). This process, coupled with the region's ancient rocks, leads to the inheritance of illite and kaolinite minerals from parent rocks. Notably, Southeast Tunisia boasts extensive Triassic sedimentary clay deposits rich in illite and kaolinite, which are exploited by the local ceramic industry for red brick production (Baccour *et al.*, 2009).

Climate change is expected to significantly impact South Africa, bringing increased warming and drying to the semi-arid region, along with more frequent and intense extreme weather events such as heatwaves, flooding, and drought (Scholes and Engelbrecht, 2021). The country's soil composition plays a crucial role in understanding these impacts. Research by (Oyebanjo *et al.*, 2021) revealed that kaolinite is the dominant clay mineral in South African soils, particularly in those developed from basalt, accompanied by other minerals like quartz, plagioclase, and microcline (Bordeepong *et al.*, 2012).

Notably, clay fractions from granite and arkosic sandstone exhibit higher percentages of weatherable minerals, contributing to increased levels of CaO, MgO, K_2O, and Na_2O

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compared to those from basalt (Oyebanjo *et al.*, 2021). The Hutton soil form, characterised by its distinctive red colour, is the most prevalent in South Africa, corresponding to Rhodic Eutrustox or Rhodic Ferralsol classifications (Mzezewa *et al.*, 2010; Oyebanjo *et al.*, 2021). These soils typically have low cation exchange capacity (Fey, 2010).

Asia's clay soils exhibit diverse mineral characteristics due to the continent's varied geological, climatic, and weathering conditions. In Thailand, research by Bordeepong *et al.* (2012). revealed that clay soils comprise primarily kaolinite, halloysite, and illite, accompanied by non-clay minerals like quartz, microcline, gibbsite, and anatase. Chemical analysis highlighted Al_2O_3 and SiO_2 as crucial components influencing refractoriness and strength. Notably, Songkhla's brick clays demonstrated medium quality, suitability for ceramic products requiring moderate modulus of rupture, and firing below 1300 °C due to high firing shrinkage (Bordeepong *et al.*, 2012). The ceramic industry relies heavily on two key clay types: kaolin and ball clay. Kaolin, an incredibly versatile industrial mineral, boasts a wide range of applications. Its primary mineral, kaolinite ($Al_2Si_2O_5(OH)_4$), consists of alternating gibbsite and silica layers, forming a distinctive plate-like structure (Chandrasekhar and Ramaswamy, 2007). This unique composition makes kaolin an essential component in ceramic production.

2.5 Global Applications of Clay in Ceramic Industries

In India, aside from the historical evidence of pottery discovered in excavations at Mohenjo-Daro and other sites, the modern whiteware industry drew heavily from European influences, particularly British manufacturers, in the late 19th and early 20th centuries (Manoharan *et al.*, 2012). This led to precursors to modern whiteware, closely following Western techniques and materials. Conversely, traditional earthenware and terracotta production emerged independently in various regions, driven by local craftsmanship and cultural heritage. India's construction sector heavily relies on clay-based bricks, with the country's clay deposits broadly classified into Alluvial, Black, Red, and Laterite (Manoharan *et al.*, 2012). Alluvial clay dominates the landscape, covering vast areas. The semi-arid tropical climate of South India creates an ideal environment for various clay deposits, including sedimentary, alluvial, red, and residual (Sharma and

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Rajamani, 2000). Tamilnadu's rich reserves of alluvial and red clays are particularly valuable, serving as the primary source of raw materials for the local ceramic industry's production of red bricks and roofing tiles (Manoharan *et al.*, 2012).

Southern Europe's ceramic brick and tile sector has traditionally relied on local clays (Moreno and Alonso, 2016). However, certain regions within the European ceramic tile industry increasingly depend on imports from outside the European Union, as Dondi *et al.* (2021) highlighted. This escalating reliance on external raw materials impedes the industry's transition to a circular economy, hindered by technological limitations and fluctuating market demands for ceramic tiles. The ceramic industry can be characterised into two primary segments: traditional ceramics, encompassing wall and floor tiles, tableware, sanitaryware, brick, and heavy clay; and advanced ceramics, comprising electrical, electronic, technical, bio ceramic, and ceramic coating applications. Significantly, traditional ceramics comprise the majority of Europe's ceramic production, as reported by Agrafiotis and Tsoutsos (2001).

According to Arkame *et al.* (2024) Morocco possesses vast and varied clay reserves, yet a significant portion remains unexploited or limited to traditional cement, pottery, and ceramics applications. Nevertheless, the country's ceramic industry has evolved, producing a wide range of products, including floor and wall tiles, stoneware, bricks, and porcelain. Morocco's exceptional craftsmanship has earned recognition throughout North Africa and Europe, particularly in pottery and ceramics (Arkame *et al.*, 2024). The country's unique geology boasts an impressive array of clay minerals, catering to diverse uses (Arkame *et al.*, 2024). This remarkable geological diversity makes Morocco an essential location for studying clay minerals and their varied applications, underscoring its potential for further development.

Morocco's clay landscape is characterised by an abundance of phyllosilicates, particularly smectic clays, predominantly found in the Rif region (Hmeid *et al.*, 2022; Tayea *et al.*, 2023). In contrast, illicit clays are mainly confined to Safi, where they are utilised in traditional handicrafts and semi-industrial applications (Moujoud *et al.*, 2023). The Fez Meknes region serves as a vital source of marl clays, which are highly prized for artisanal creations (Halim *et al.*, 2022; Mohammed *et al.*, 2022). Although kaolinitic clay deposits

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are scarce in Morocco, limited concentrations can be associated with acidic magmatic rocks in the Oulmes region. Furthermore, significant halloysite clay reserves are concentrated in the volcanic terrain of Nador-Melilla, situated in the northeastern part of the Rif (Haddar *et al.*, 2018). Additionally, the High Atlas region is home to notable deposits of talc clay (Amrani and Sadik, 2016).

In Cameroon, the potential of clay materials for earthenware production is gaining momentum. The industrial utilisation of clays is on the rise, particularly in brickworks and tile mills, driven by the discovery of (Kagonbe *et al.*, 2021). Cameroon's vast alluvial plains offer an abundance of clay resources. Research on clays from Sekande and Gashiga revealed an abundance of valuable minerals, including smectites, illite, kaolinite, quartz, feldspar, and mica (Kagonbe *et al.*, 2021). A comprehensive evaluation of these clays, considering their mineralogical, physicochemical, and ceramic properties, confirms their suitability for producing high-quality earthenware products, such as fired bricks. Furthermore, a study on the Lembo clay deposit in Mount Bana, Cameroon, highlights its diverse kaolinitic clay compositions, presenting opportunities for extensive applications in ceramics (Pialy *et al.*, 2008).

Extensive research has been undertaken to characterise various South African clays for diverse applications, leveraging the country's abundant natural resources (Jacobson, 2005; Akintola, 2018; Aniyikaiye *et al.*, 2021; Akintola *et al.*, 2024). South Africa boasts a rich diversity of clayey soils used in multiple sectors, including brick production, geophagia, cosmetics in cultural ceremonies, and traditional ceramic applications (Morekhure, 2017; Nkosi and Thembane, 2024). Notably, clay pot making and trade have been identified as significant contributors to household income generation in rural communities, providing an essential economic stimulus. Furthermore, traditional clay pot production is widespread across Africa, transcending cultural boundaries, with artisans from diverse backgrounds engaged in this craft (Gosselain and Livingstone Smith, 2005; Mulaba-Bafubiandi and Hlekane, 2015; Busari and Odetoyinbo, 2023; Mulaba and Hlekane, 2015).

Studies on clayey soils in South Africa have revealed their potential for industrial applications. According to Mulaba and Hlekane (2015) QwaQwa's clayey soils are rich in

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silicon, aluminium, and iron, with key minerals including montmorillonite, kaolinite, illite, and quartz, making them ideal for producing durable ceramic products. Similarly, Akintola *et al.* (2024) conducted an empirical assessment which validated the suitability of clay from Mukondeni village, Thulamela, Limpopo, for various ceramic applications including pottery, roofing tiles, and masonry bricks. Further research by Akintola *et al.* (2020) analysed clayey raw materials, discovering they mainly consist of kaolinite and chlorite clay minerals, iron oxide, quartz, and plagioclase. These materials met SANS and ASTM standards for single-story construction bricks, demonstrating mechanical strength and durability. However, noted that chlorite-rich clayey materials may be less suitable for lightweight masonry burnt bricks due to their higher compressive strength and low water absorption properties, whereas kaolinite-rich materials showed greater potential (Akintola *et al.*, 2024).

2.6 Different Methods of Characterising Clay and Determination of Suitability in Ceramic Use

2.6.1 Particle Size Distribution: A Review of Existing Literature

The grain size of raw materials plays a crucial role in determining the properties of the final product and the ceramic body's behaviour during manufacturing, particularly in the shaping and drying processes. Notably, clay defined as earth material with particles smaller than 2 μm in geology, soil science, agriculture, engineering, ceramic and construction exhibits unique colloid-like properties due to its extremely fine particles, allowing dispersion or suspension in various states (Xanthopoulou *et al.*, 2020). To characterise sediment particle size, multiple methods are available, each offering varying levels of precision and focusing on distinct material properties, resulting in unique definitions of particle size (Iatrou *et al.*, 2007).

Traditional techniques for particle size analysis include pipette, sieve, and aerometer methods. The pipette method, based on Stokes' law, is ideal for finer particles (Iatrou *et al.*, 2007). In contrast, the sieve method determines particle size by the hole diameter it passes, making it suitable for sand and gravel-sized sediments. Specifically, according to the Wentworth grade scale, gravel-sized particles exceed 2 mm in diameter, sand-sized particles range from 62.5 μm to 2 mm, and silt-sized particles fall between 4 μm and 62.5

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μm (Wentworth, 1922; Xanthopoulou *et al.*, 2020). Two complementary methods achieve comprehensive results: Sieve analysis for particles larger than 0.075 mm and Hydrometer analysis for particles smaller than 0.075 mm. Since many natural soils comprise coarse and fine fractions, combining sieve and hydrometer analysis is necessary to obtain a complete gradation curve, accurately representing soil characteristics.

2.6.1.1 Sieve Analysis

The characterisation of clay soil for ceramic production involves sieve analysis, a technique that determines particle size distribution (Bayat *et al.*, 2015). Sieve analysis is vital for determining soil particle size distribution, providing crucial information that impacts various industries such as construction, agriculture, and environmental studies. Accurate analysis depends on meticulous soil sample preparation and proper equipment use, including sieve shakers, screens, and accessories. A systematic approach is essential, encompassing adequate shaking, calculating results based on mass retained, and constructing particle size distribution curves. By following these steps, sieve analysis reveals soil properties and suitability for diverse applications, informing project stability in construction, crop productivity in agriculture, and research reliability in environmental studies. Practical sieve analysis ensures informed decision-making and optimal outcomes across these industries.

Sieve analysis has significant limitations for evaluating ceramic suitability, as it oversimplifies particle characterisation by solely measuring size while neglecting crucial factors like particle shape, surface area, and mineralogy. Furthermore, sieve analysis may provide inaccurate representations of particle size distribution, particularly for powders with agglomerates or irregular shapes. Additionally, its limited resolution makes distinguishing between closely sized particles challenging, potentially leading to incomplete or misleading information for ceramic processing and property optimisation.

2.6.1.2 Hydrometer Analysis

For soils with significant silt and clay content, a combined sieve and hydrometer analysis approach is necessary to determine particle size distribution accurately. Sieve analysis is limited to particles larger than 0.075 mm (#200 sieve), while hydrometer analysis estimates particle sizes from 0.075 mm to 0.001 mm, with results plotted on a semi-log

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graph (Figure 2.2). This dual approach, standardised by ASTM D7928, ensures reliable and reproducible results for natural soils comprising coarse and fine fractions. Although hydrometer analysis offers the convenience of single measurements, it generates more waste and requires longer cleaning times. Ultimately, soil texture classification is determined by calculating sand, silt, and clay percentages and referencing the USDA textural triangle, providing a comprehensive understanding of soil composition (Groenendyk *et al.*, 2015).

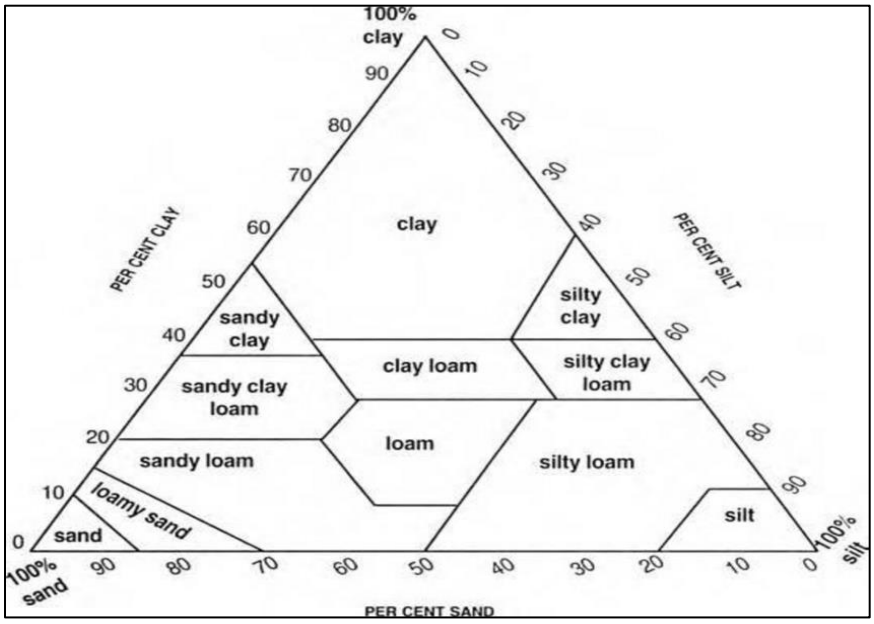

Figure 2. 2: USDA textural triangle (Moreno and Alonso, 2022)

2.6.1.3 Atterberg Limits

The Atterberg limits of soil serve as a critical criterion for differentiating between silts and clays based on their plasticity characteristics (Adeagbo *et al.*, 2016). The ability of fine-grained soils to change shape without breaking, known as plasticity, is mainly determined by two important properties: the liquid limit and the plastic limit. These properties are very important in several fields, including civil engineering, geotechnical engineering, farming, the ceramic industry, and the process of making bricks (O'Kelly, 2021). The Atterberg limits comprise three tests: Liquid Limit (LL), Plastic Limit (PL), and Shrinkage Limit (SL)(Das, 2019). These tests assess the soil's consistency, plasticity, and shrinkage potential, influencing ceramic processing and quality. The Liquid Limit indicates the soil's

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moisture content when it transitions from liquid to plastic, while the Plastic Limit marks the boundary between plastic and semi-solid states. The Shrinkage Limit determines the soil's volume reduction upon drying.

The moisture content of soil determines its state, which can range from solid to semisolid, plastic, and liquid (Figure 2.3). As soil transitions between these states, its consistency, behaviour, and engineering properties change significantly. Well-defined boundaries separate each state based on distinct changes in soil behaviour. By analysing Atterberg limits, ceramic manufacturers can predict soil's behaviour during mixing, shaping, and firing, ensuring optimal clay blending, moisture control, and processing conditions (Karakan, 2022).

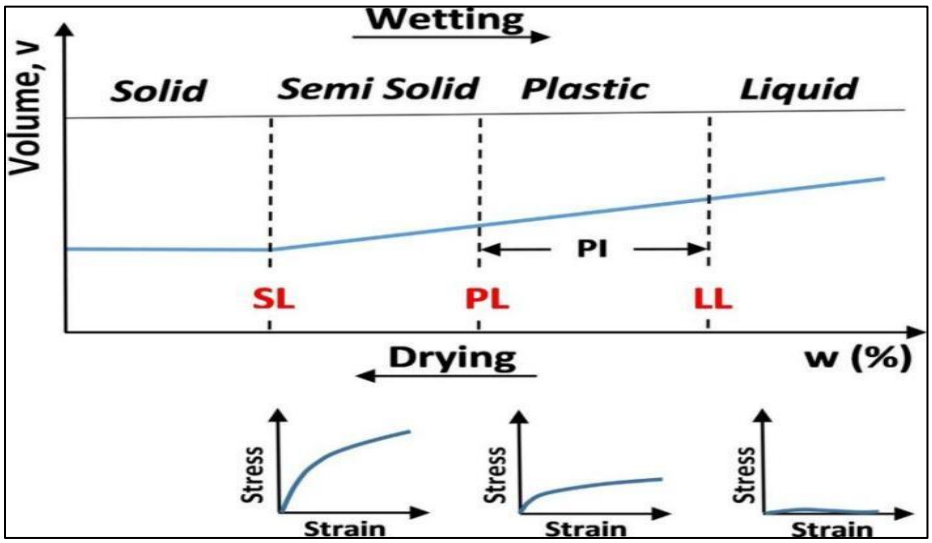

Figure 2. 3: Four Fundamental States of Soil Behaviour (Karakan, 2022)

Soil's liquid and plastic limits are influenced by clay type and amount, while the plasticity index is primarily driven by clay content. As particle size decreases, both limits increase, but the liquid limit rises more sharply, elevating the plasticity index. Adding silts to clay reduces both limits, decreasing the plasticity index. When analysed with the liquid limit, the plasticity index measures particle fineness and reveals clay type. The Plasticity Chart, plotting the plasticity index against the liquid limit, is essential for classifying fine-grained soils. Notably, soils with low to medium plasticity, such as silty clays, exhibit moderate toughness. In contrast, soils with lower plasticity, including silty, sandy, and peaty soils, display relatively low toughness (O'Kelly *et al.*, 2022). This toughness variation reflects

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these soil types' differing mechanical properties, influencing their behaviour under various environmental and engineering conditions. Liquid limit also indicates compressibility, which increases with higher values. These Atterberg limits are vital for soil classification, distinguishing sands with abrupt liquid-to-semi-solid transitions from other soil types (Spagnoli and Shimobe, 2023).

The thread rolling test is the predominant technique for determining the plastic limit (PL) in soils, but its widespread adoption belies significant limitations (Moreno and Alonso, 2016). Notably, the test's accuracy is compromised by the substantial subjective judgment required from the operator, potentially leading to variability in results. Other methods have been suggested to overcome existing limitations, but they haven't proven more efficient, user-friendly, or cost-effective than the traditional rolling test, which remains the preferred choice in soil testing (Moreno and Alonso, 2016)

2.6.2 Chemical Characterisation of Clay Soils: Existing Research and Findings

The characterisation of clay soil for ceramics using X-ray fluorescence (XRF) involves analysing the elemental composition to determine its suitability for ceramic production (Maltsev *et al.*, 2021). XRF provides rapid and non-destructive analysis of major and minor elements, including silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), potassium (K), magnesium (Mg), titanium (Ti), and manganese (Mn) (Ceccarelli *et al.*, 2016). This information helps determine the clay's plasticity, shrinkage, thermal properties, and colour stability. The XRF spectrum reveals the presence of quartz, feldspar, kaolinite, and other minerals, allowing for the identification of clay type and potential impurities. Key parameters analysed include SiO_2, Al_2O_3, Fe_2O_3, and Cao content, which influence ceramic properties such as strength, durability, and glaze fit. By characterising clay soil using XRF, ceramic manufacturers can optimise processing conditions, predict final product quality, and ensure consistency (Maltsev *et al.*, 2021).

X-ray fluorescence (XRF) characterising clay soil for ceramics offers many advantages. XRF provides swift and precise analysis of elemental composition, enabling the identification of clay minerals and the prediction of ceramic properties (Menne *et al.*, 2020). This technique is known for its rapid analysis, non-destructive testing, high accuracy, detection of trace elements, and minimal sample preparation (Hou *et al.*, 2004).

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However, one of its most significant advantages is its comprehensive analysis of major and minor elements (Maltsev *et al.*, 2021). This thoroughness enhances quality control and consistency, making the audience feel secure about the process. By harnessing the power of XRF, ceramic manufacturers can optimise processing conditions, glaze fit, material selection, and production planning. The comprehensive analysis provided by XRF ensures the thoroughness of the process, making it an indispensable tool in ceramic production.

2.6.3 Mineralogical Characterisation of Clay Soils: A Review of Existing Research

Ceramic raw materials are characterised compositionally using various analytical techniques, with X-ray diffraction (XRD) being a pivotal method for determining mineralogical content. XRD effectively identifies crystalline phases, even when they are too delicate to be detected by other techniques like optical microscopy. As a result, XRD is a valuable tool in ceramic raw material analysis, providing crucial information on both coarse constituents and finer clay minerals, enabling a comprehensive understanding of material composition (Quinn and Benzonelli, 2018). The presence of key minerals such as kaolinite, halloysite, illite, and quartz in clay determines its properties and suitability for various ceramic applications. Manufacturers can predict clay's processing and firing behaviour by analysing clay's mineral composition, optimising strength, durability, and thermal resistance. Kaolin, a crucial industrial mineral, plays a vital role in various applications, including ceramics, refractories, paper, paints, and pharmaceuticals, making kaolinitic clays the primary raw material for these industries and informing producers' selection of clay types tailored to their desired end-product characteristics (Quinn and Benzonelli, 2018).

X-ray diffraction (XRD) in analysing clay soil for ceramic production offers numerous benefits. XRD provides accurate identification and quantification of mineral phases, enabling the prediction of ceramic properties such as plasticity, shrinkage, thermal stability, strength, and colour stability (Xanthopoulou *et al.*, 2020). This information optimises material selection, processing conditions, and final product quality. XRD analysis also detects potential impurities, allowing removal or adjustment to prevent defects. Additionally, XRD enables rapid and non-destructive testing, reducing analysis

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time and preserving sample integrity. The comprehensive mineralogical analysis provided by XRD facilitates improved quality control, increased productivity, and reduced production costs. Furthermore, XRD data helps ceramic manufacturers anticipate and mitigate potential issues during firing, ensuring consistent and reliable results. Overall, XRD analysis is an indispensable tool for ensuring the quality and reliability of ceramic products (Xanthopoulou *et al.*, 2020). XRD identifies and quantifies the mineral phases present in the clay, providing valuable information on its composition and structure (Ali *et al.*, 2022). XRD also helps predict potential defects or issues during firing, optimising processing conditions.

2.7 A Comprehensive Literature Analysis of Clay Soil for Ceramic Applications

A comprehensive study was conducted by Manoharan *et al.* (2012) to analyse the characteristics of clay materials from Tamilnadu, India, and their potential use in ceramics. The research employed various sophisticated techniques, including X-ray fluorescence, thermogravimetric-differential thermal analysis, Fourier Transform Infrared spectroscopy, X-ray diffraction, particle size analysis, and Atterberg limits. These methods were used to investigate the physicochemical, mineralogical, and thermal properties of two distinct clay types from four locations in Tamilnadu. The mineralogical analysis revealed that alluvial clays were composed of quartz, illite, kaolinite, plagioclase, and minor amounts of chlorite. In contrast, the red clays were rich in quartz, well-ordered kaolinite, and iron-bearing minerals like goethite and hematite.

The chemical composition analysis provided further depth, showing that one clay contained high SiO_2 levels, low Al_2O_3 content, and minimal loss on ignition. In contrast, the other clay exhibited moderate SiO_2 and Al_2O_3 levels, high Fe_2O_3 content, and significant ignition loss. The study's thoroughness and attention to detail instil confidence in the findings, which concluded that clays from alluvial deposits possessed suitable characteristics for standard brick fabrication, and red clay deposits exhibited adequate properties for roofing tile manufacturing and, with modifications, could be used for standard brick production (Manoharan *et al.*, 2012).

Idrissi *et al.* (2016) conducted a study to assess the suitability of clayey materials from the Agafay region for ceramic production. The researchers collected clay samples from

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semi-arid soil and river sediments and analysed them using various techniques, including particle-size analysis, X-ray diffraction, and X-ray fluorescence. These analyses characterised the physical, mineralogical, and chemical properties of the clay samples. Atterberg limits and Bigot curve analysis evaluated the physical behaviour of the clays during shaping and drying. The final products were tested for porosity, flexural strength, and compressive strength, and the results indicated that the raw materials had suitable characteristics for earthenware production. Furthermore, the study's recommendations improved the quality of products made from these raw materials when implemented (El Idrissi *et al.*, 2016).

Lahcen *et al.* (2014) conducted a study which examined the characteristics and ceramic properties of clayey materials from the Amezmiz region in the Western High Atlas, Morocco. Five clay samples from two regional quarries were analysed for their physical, chemical, mineralogical, and thermal properties to assess their suitability for ceramic applications. The analysis included particle size distribution, consistency limits, total organic content, XRF, XRD, and TG/DTA techniques. The results showed that the primary oxides present were SiO_2, Al_2O_3, and Fe_2O_3, with quartz, illite, and vermiculite being the dominant mineral phases. The study concluded that two of the clayey materials were suitable for structural ceramic production, while the other two required the addition of more plastic clays to enhance workability (Lahcen *et al.*, 2014).

Hmeid *et al.* (2022) conducted a study to characterise raw clay materials in the Nador region of northeast Morocco and assess their potential use in ceramic production. The research involved physical, chemical, mineralogical, and geotechnical analyses of the clay materials. The results showed that the primary minerals present were feldspars and cristobalite, with carbonates found in all samples. Some samples had smectite as the dominant clay phase, along with smaller amounts of kaolinite, illite, and chlorite. The study concluded that the clay materials needed to be blended with other clay types or less plastic materials to improve their properties, making them suitable for producing structural ceramics (Hmeid *et al.*, 2022)

Tsozué *et al.* (2022) conducted a study to investigate the genesis and assess the suitability of clay materials for earthenware production in northern Cameroon. To achieve

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this, researchers described and sampled four representative clay pits, conducting various analyses, including grain size analysis, Atterberg limits determination, mineralogical and geochemical analyses, and technological tests. The results showed significant sand fractions in all samples, with varying plasticity, and identified kaolinite, illite, and smectite as primary clay minerals, accompanied by quartz and feldspar. Geochemical analysis revealed principal oxides, including SiO_2, Al_2O_3, Fe_2O_3, and flux elements such as CaO, MgO, K_2O, and Na_2O, which were present in varying proportions. Smectite formation was attributed to low landscape positions, clay-rich parent material, and regional hydrological conditions characterised by low rainfall and high temperature. Kaolinite formed through the decomposition of orthoclase feldspar. The simultaneous occurrence of smectite and kaolinite resulted from bisiallitisation and monosiallitisation processes, which are related to variations in drainage conditions. Firing tests showed that the clay materials met standards for earthenware production, with suitable water absorption values ranging from 10.47% to 20.12% and compressive strength between 2 and 5.7 MPa. The presence of hematite gave the fired products a red colour, while kaolinite promoted mullite formation and illite and smectite facilitated glassy phase formation, leading to densification and good cohesion of the fired products (Tsozué *et al.*, 2022).

Manjate *et al.* (2020) conducted a study to evaluate the potential of clay soils from the Manjacazi district in Mozambique as raw materials for the ceramic industry. The researchers aimed to assess the suitability of these clay soils for ceramics by examining their ceramic properties, drying behaviour, and firing behaviour. To achieve this, they analysed the ceramic properties of fired clay briquettes from Manjacazi, focusing on linear shrinkage, compressive strength, and water absorption. The study found that the Manjacazi clays exhibited a range of textures, including loam, clay loam, clay, sandy clay loam, and sandy loam. Based on their plasticity and compressibility, the clays were classified into three groups: low-plastic organic silts with low compressibility, medium-plastic inorganic silts with low compressibility, and high-plastic inorganic silts with high compressibility. The results showed that the linear shrinkage of the clays was generally high and increased slightly with firing temperature. In contrast, water absorption and compressive strength decreased with firing temperature. Based on these findings, the study concluded that the Manjacazi clays were suitable for manufacturing various ceramic

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products, including walled floor blocks, clay roofing tiles, checker bricks, and solid bricks (Manjate *et al.*, 2020).

Diko and Ligege (2020) evaluated the potential of raw clays from the Mukondeni region for structural ceramics and pottery using traditional firing techniques. The researchers analysed the physical properties of the clays through particle size distribution, consistency limits, and clay activity. Mineralogical and chemical properties were investigated using X-ray diffraction (XRD) and X-ray fluorescence (XRF). The results showed that the clays had low fractions of fine particles (<2 μm) and exhibited medium to high plasticity with a clayey silt texture. Smectite was the dominant clay mineral, while quartz and feldspar were major non-clay minerals. The most abundant oxides were SiO_2, Al_2O_3, and Fe_2O_3. Characterisation based on various diagrams revealed acceptable extrusion properties and suitability for structural ceramics and earthenware. However, the clays exhibited acceptable weight loss, bulk density, linear shrinkage, and water absorption but unsatisfactory flexural strength (≤1.08 MPa). The low mechanical strength was attributed to the presence of smectites and the inert nature of feldspar at 900 °C. To improve the mechanical strength, the researchers recommended beneficiation through mixing with carbonate-rich raw materials (Diko and Ligege, 2020).

Akintola *et al.* (2024) conducted a study in Limpopo, South Africa, that evaluated the mechanical properties of soil and artisanal bricks to ensure quality masonry product management. The research aimed to assess the suitability of raw materials and product quality in the region. Twenty soil samples and twenty-seven artisanal burnt bricks were collected from three brick-making sites. Geotechnical tests revealed that all soil samples were sandy loam types, primarily containing chlorite clay minerals and non-clay minerals. The sand-size particles dominated the clay-size particles. Atterberg's limit test results indicated low-plasticity inorganic clay with low to medium compressibility. The study found that most soils were suitable for producing optimal and acceptable extrusion bricks based on empirical workability and mechanical tests. Furthermore, the bricks met SANS 227:2007 standards, making them suitable for on-site single-story construction (Akintola *et al.*, 2024).

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Raphalalani *et al.* (2022) investigated the origin and potential uses of Lwamondo and Zebediela Kaolins in Limpopo Province, South Africa. The researcher analysed the physicochemical characteristics of the kaolins using various techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), X-ray fluorescence (XRF), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The results showed that the Lwamondo Kaolin had a light colour, while the Zebediela Kaolin had a brown colour. Both kaolins had low pH levels and electrical conductivity. Texture analysis revealed that the Lwamondo Kaolin was primarily loam and clay loam, whereas the Zebediela Kaolin was clayey, silty, and loamy. The major mineral phases identified in the Lwamondo Kaolin were kaolinite, smectite, and plagioclase, while the Zebediela Kaolin consisted mainly of kaolinite. The morphology of the kaolin consisted of stacked kaolinite flakes. The dominant principal oxides were silicon dioxide, aluminium oxide, and iron oxide, with a slight depletion in light rare earth elements. The study concluded that the kaolins formed in a supergene environment and were suitable for hollow brick production due to their favourable mineralogical and geochemical characteristics (Raphalalani *et al.*, 2022).

2.8 Chapter Summary

Chapter two provided a comprehensive literature review that clarifies the complex interrelationship between climatic conditions and soil formation, explicitly focusing on clay soils and their suitability for ceramic applications. A comprehensive analysis of existing research revealed that particle size distribution, chemical composition, mineral composition, and specific clay properties requirements were critical factors in determining clay suitability for ceramic production. Additionally, the literature review delves into the physical characteristics of clay soils across diverse regions, including texture, structure, and porosity, as well as mineral and chemical characteristics such as mineralogy, chemical composition, and pH levels. The global applications of clay in ceramic industries, encompassing tile production, pottery, and refractory materials, are also explored. Furthermore, this chapter evaluated various methods for characterising clay and determining its suitability for ceramic use, revealing the efficacy of sieve analysis, hydrometer, X-ray fluorescence (XRF), and X-ray diffraction (XRD) in investigating these

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goals. By conducting a comprehensive literature analysis of clay soil for ceramic applications, this chapter identifies the methods employed in previous studies, compares their results, and synthesises the findings to provide valuable insights into the critical factors influencing clay suitability for ceramic production.

Chapter Three: Methodology

3.1 Introduction

This study was conducted in the Thulamela Municipality, where the Sibasa clayey formation of the Soutpansberg group underlies a sizeable portion of the region. According to Barker *et al.* (2006) the Sibasa formation is approximately 3000 m thick and consists

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of pyroclastic lava with minor intercalations of sedimentary and tuffaceous rocks, forming the underlying geology of Thulamela. To investigate the properties of the clayey soil in this area, samples were collected from eight dissimilar locations: Dzingahe, Ha Matsika, Lwamondo, Ngwenani ya Mapholi, Madadani, Muledane, Tshilungoma, and Tshino. These samples were then taken to a University of Venda laboratory for physical, chemical, and mineralogical analysis. The analysis methods used included particle size distribution, hydrometer, Atterberg limit, XRF (X-ray fluorescence), and XRD (X-ray diffraction). This chapter will outline the procedures used for each method to characterise the clay samples for ceramic applications.

3.2 Preliminary Work

The primary goal of preliminary work is to gather and review relevant materials and methods before commencing fieldwork. In preparation for this study, preliminary research was conducted to better understand the Thulamela Municipality, the designated study area. This involved consulting various sources, including the internet, books, journals, topological maps, and geological maps. This research yielded significant findings, including the discovery that the Sibasa formation is primarily composed of quartz, sandstone, and quartzite, with intermittent igneous intrusions of dolerite and basalt. This knowledge allowed for informed anticipation of the region's soil composition, specifically the prevalence of sandy soil, providing a solid foundation for the subsequent fieldwork.

The study collected samples from specific areas around Thohoyandou, a key region for clay brick manufacturing, through a purposive sampling strategy. This method enabled the selection of samples from specific locations known for clay brick production, which improved the chances of collecting relevant and valuable data. Focusing on areas with existing clay brick manufacturing activities allowed for collecting data rich in insight and directly relevant to the research question, providing a more targeted and accurate approach than random sampling methods.

Google Earth provided detailed satellite images of locations such as Dzingahe, Ha Matsika, and Lwamondo, enhanced with overlays of street names, weather patterns, population densities, and coordinates. A geological map was also consulted to study the Blouberg Formation, Soutpansberg Group Formations, and Sibasa Formation, offering

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insights into the region's geological characteristics and the types of clay derived from the parent rock.

3.3 Research Design

This research employed a descriptive quantitative survey approach, using a correlational design to explore the connection between variables. The study's primary aim was to assess the viability of clay soil for ceramic applications, focusing on the relationship between clay soil characteristics and their implications for ceramic production. The study evaluates various clay properties, comprising particle size analysis, hydrometer tests, Atterberg limits, mineral composition, and chemical composition. Through data analysis, the research establishes relationships between clay soil characteristics and ceramic quality factors, including strength, durability, and aesthetic appeal, ultimately informing optimal clay soil specifications for high-quality ceramic production.

3.4 Sample Collection

Eight villages, including Madadani, Lwamondo, Tshilungoma, Dzingahe, Ha-Matsika, Ngwenani ya Mapholi, Muledane, and Tshino, served as the locations for soil collection. Specifically, soil samples were taken from the locations indicated in Table 3.1. Sampling was conducted at points approximately two meters from the river, as depicted in Figure 3.1. The site selection was meticulous, informed by a thorough review of existing research and consultations with local experts. Additionally, careful consideration was given to key site selection criteria, including proximity to active brick-making sites or areas with a history of brick production and ensuring accessibility, safety, and permission for sampling.

Table 3. 1: Location and Coordinates of Sampled Sites

Location	Latitude	Longitude
Dzingahe	22°59'48" S	30°28'8"E
Ha-Matsika	22°54'43" S	30°41'15" E
Lwamondo	23°6' 14" S	30°24'02" E
Ngwenani	22°53'8" S	30°27'53" E

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Madadani	22°48'05" S	30°24'02" E
Muledani	22°59'38" S	30°28'02" E
Tshino	23°06'23" S	30°24'06" E

To ensure the accuracy and reliability of soil sampling, surface litter and vegetation were carefully removed from the designated sample spots. Following standard soil sampling protocols, a hole was dug, and a 3x3 cm vertical section of clay soil was extracted as a subsample using the trench method. The trench method is a soil sampling technique where a vertical section of soil is extracted from a dug trench for analysis. The soil was homogenised and then sampled using a shovel and stored in clean bags to minimise contamination. A composite sample was created for each unique soil area by combining five subsamples, resulting in 40 samples across eight villages, with five replicates per village. Eight representative samples, each weighing 5 kg, were then transported to the University of Venda's Mining and Environmental Geology (MEG) Laboratory for comprehensive analyses of physical, chemical, and mineralogical properties, undertaken by a researcher with the assistance of laboratory technicians.

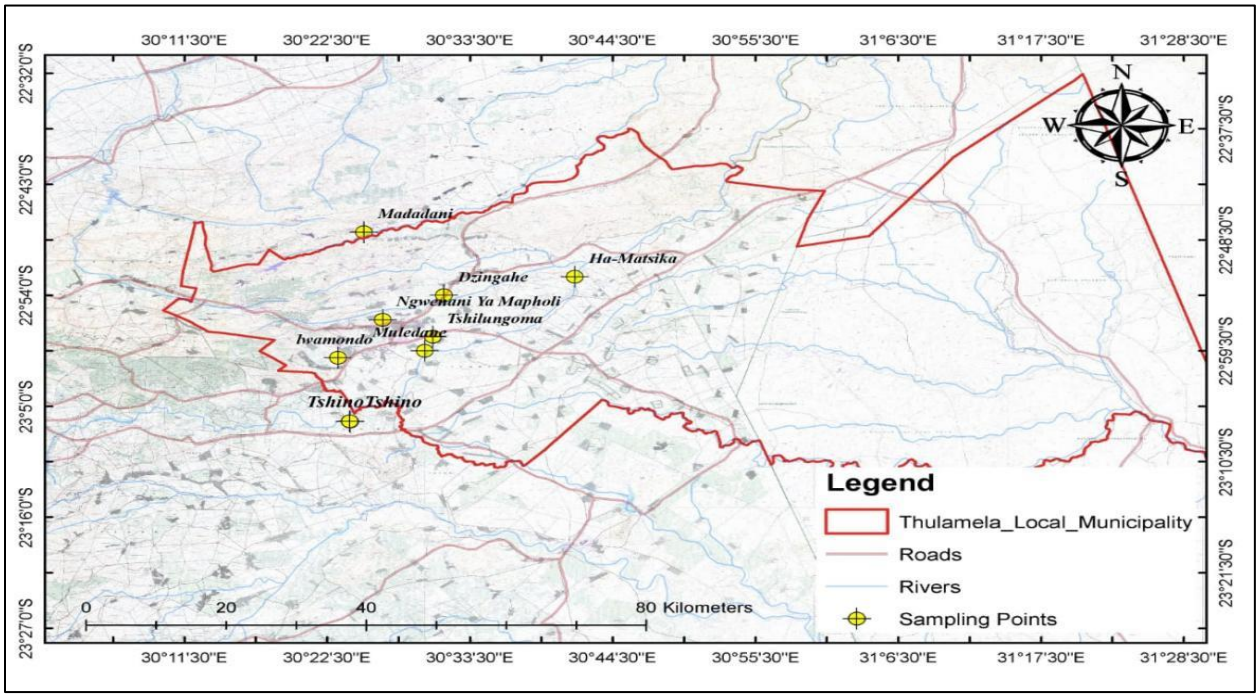

Figure 3. 1: Sampling sites

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3.5 Physical Characterisation of Clay Soil

3.5.1 Sieve Analysis

Clay samples from eight locations - Dzingahe, Ha-Matsika, Lwamondo, Ngwenani ya Mapholi, Madadani, Muledane, Tshilungoma, and Tshino underwent sieve analysis at the University of Venda's Department of Mining and Geology. A 500-gram representative sample was obtained from each village and dried in a ventilated oven (Appendix A) to remove moisture. Lumped particles were crushed to ensure uniformity. After drying and crushing, each sample was weighed, and its mass was recorded. A series of sieves with progressively smaller aperture sizes was stacked in descending order, culminating in a pan at the bottom to capture fine particles. The prepared samples were then poured into the topmost sieve, secured, and placed in a sieve shaker (Figure 3.2). The shaker was subsequently operated for 10-15 minutes. Subsequently, the sample retained on each sieve was weighed, and percentage retention was calculated as % Retained = (W sieve / W total) * 100%. The cumulative percentage passing was determined by subtracting the cumulative retention from 100%. Finally, the results were graphically represented, plotting sieve size against cumulative percentage passing.

Figure 3. 2: Sieve Shaker

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3.5.2 Hydrometer Analysis

Hydrometer analysis was conducted at the University of Venda's Department of Agriculture on soil samples collected from eight villages: Dzingahe, Ha-Matsika, Lwamondo, Ngwenani ya Mapholi, Madadani, Muledane, Tshilungoma, and Tshino. The soil texture analysis used the Bouyoucos hydrometer method (Bouyoucos, 1962). The preparation of each sample began with mixing 50 g of air-dried clay soil with distilled water in a 400-mm beaker. To this mixture, 10 mm of a 10% Calgon solution was added. The mixture was then allowed to settle for 10 minutes, as shown in Figure 3.3. Next, the suspension was transferred to a dispersing cup, and the cup was marked with distilled water. An electric high-speed stirrer (Appendix A) was used to mix the suspension thoroughly for 2 minutes. After mixing, the suspension was transferred to a graduated cylinder, and any residual dirt was rinsed out using distilled water. The hydrometer was removed, and distilled water was added to the suspension to make a total volume of 1000 mm. The graduated cylinder was then covered with a tight rubber bung, and the suspension was gently inverted 10 times while recording the time spent mixing. To remove any foam that formed, 2 to 3 drops of amyl alcohol were added to the soil suspension. The hydrometer was carefully inserted into the suspension column and left there for 20 seconds. The temperature of the suspension was recorded at 40 seconds, and a hydrometer reading was taken. Finally, the graduated cylinder was left undisturbed for 2 hours after the suspension had been mixed 10 times. After this period, the hydrometer readings and temperature were recorded again.

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Figure 3. 3: Cylinder

Temperature corrections for hydrometer readings were applied based on Table 3.2. The temperature of the water-Calgon solution was recorded using a thermometer. To account for temperature fluctuations, 0.36 units were added or subtracted from the blank hydrometer reading for every degree above or below 20°C. A control cylinder containing only sodium hexametaphosphate and water was used to obtain a blank hydrometer reading, which was then subtracted from all other readings to obtain the corrected hydrometer reading. This corrected reading was subsequently used to calculate the calibrated 40-second and 2-hour readings. Finally, the soil sample's sand, silt, and clay percentages were determined using established formulas (1,2 and 3) below.

% Clay = (calibrated 2-hour reading) x (100/sample weight) …… (1)

% Silt = (calibrated 40-second reading) x (100/sample weight) - (%clay) …… (2)

% Sand = 100 – (%silt + % clay) …… (3)

Table 3. 2: Temperature correction for hydrometer

Temperature (0°)	Hydrometer correction g/l
15	-2.0
16	-1.5

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17	-1.0
18	-1.0
19	-0.5
20	Nil
21	0.5
22	1.0
23	1.0
24	1.5
25	2.0

3.5.3 Atterberg Limit

A comprehensive study examined the physical characteristics of clay soils sourced from various locations, employing the Atterberg method to explore the relationship between clay content and Atterberg limits. The investigation involved assessing the shrinkage, plastic, and liquid limits of fine-grained soils to elucidate their physical properties. The Atterberg method is instrumental in ceramics, as it evaluates soil plasticity, categorising soils as highly, moderately, or non-plastic. Plasticity, as defined by (Xanthopoulou *et al.*, 2020), refers to the capacity of clay to deform under applied force without fracturing. This study examined the plastic and liquid limit tests to investigate the consistency of clay soils and their implications for ceramic production, where soil plasticity plays a vital role. To assess clay plasticity, the study employed standardised testing protocols, as outlined by the American Society for Testing and Materials (ASTM), to determine the liquid and plastic limits, as well as the plasticity index.

3.5.2.1 Liquid Limit

The liquid limit test was performed using a specialised apparatus comprising a spatula, liquid limit apparatus, soil specimen, grooving tool, and moisture containers, as depicted in Figure 3.4. A 250 g sample of air-dried soil, passing through a 0.075 mm mesh sieve (sieve 200), was blended with water to form a homogeneous paste. This paste was then uniformly distributed within the liquid limit apparatus's cup to a maximum depth of 10 mm. The soil specimen was prepared by removing air pockets. The unused portion was stored in its designated vessel. A groove was then created along the centreline of the soil cup using the grooving tool. The liquid limit apparatus was operated to create a raised and

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lowered cup at two drops per second. The apparatus was turned until the two halves of the soil specimen merged at the bottom of the groove, ensuring a separation distance of 13 mm. The number of drops required to seal the groove was recorded.

To determine the water content, a portion of the soil was removed for analysis. The amount of water added or removed was adjusted based on the number of impacts needed to close the groove in the previous round. The liquid limit was defined as the moisture content percentage required to seal a 12 mm groove after 25 impacts in the liquid limit apparatus. However, achieving the precise 12 ± 2 mm closure at 25 impacts proved challenging. Multiple tests (at least three) were conducted on the same soil at varying moisture contents, using a range of impacts (N=15) to overcome this challenge.

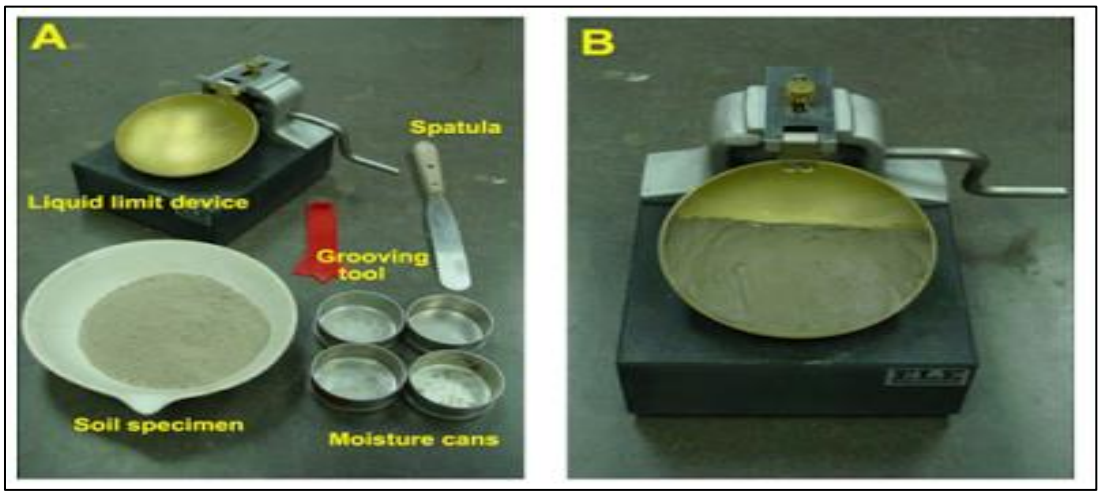

Figure 3. 4: Liquid Limit Tools

3.5.2.2 Plastic Limit

In ceramic production, the plastic limit is a critical physical property of clay, representing the minimal water content necessary to achieve a workable, pliable state. This threshold signifies the optimal moisture level for shaping and molding clay. To determine the plastic limit, a thread of clay is subjected to a diameter test, where it is considered optimal when it consistently disintegrates at a 3 mm diameter, indicating an ideal balance between moisture and workability.

The plastic limit of the soil was determined through a controlled process involving mixing 20 g of dry soil with water, followed by division into three ellipsoidal masses and insertion

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into the plastic limit device. A uniform thread was created by rolling each soil mass between the fingers and thumb on a glass plate until it maintained a consistent 3 mm diameter. The soil's water content was measured at this point, and the plastic limit was calculated by weighing the dry soil and the moisture content. The plasticity index, representing the moisture range within which a clay sample exhibits plasticity, was calculated using the liquid and plastic limits. This index signifies the moisture content range where the clay transitions from semi-solid to liquid while remaining plastic. The plasticity index was determined by subtracting the plastic limit from the liquid limit using formula (4).

$$PI = LL - PL \quad \ldots\ldots (4)$$

3.5.4 Firing Clay Blocks

Five soil samples from each of the eight study areas (Dzingahe, Ha-Matsika, Lwamondo, Madadani, Muledane, Ngwenani, Tshilungoma, and Tshino) were processed into uniform ceramic blocks to assess their suitability for ceramic production. The clay masses were moulded into rectangular samples (25 cm x 12 cm x 6 cm) using plastic moulds, ensuring uniformity in shape and size. The clay masses were allowed to air dry for seven days under ambient conditions, away from direct sunlight. Subsequently, they underwent oven (Appendix A) drying at 105°C for 24 hours. This sequential drying protocol facilitated gradual moisture removal and optimised drying efficiency. The dried clay masses (Figure 3.5) were then fired in a furnace (Appendix A) at various temperatures (300°C, 700°C, 800°C, 900°C, and 1150°C) for three hours, with a heating rate of 10°C/min. After firing, the samples were allowed to cool naturally. Further technical tests were conducted to evaluate the temperature-dependent physical properties of the clay blocks, including strength, cracking behaviour, and water absorption.

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Figure 3. 5: Clay blocks in sequence before furnace firing

Linear shrinkage (LS) was determined by measuring the length of the briquettes before firing (Lo) and after firing (L) using a formula (5). This measurement, expressed as a percentage, evaluates the plasticity of the material, providing insight into its shrinkage properties.

$$LS\ (\%) = [(Lo - L)/L0] \times 100 \quad (5)$$

Water absorption (Wa) was measured by drying the fired briquettes in an oven at 105°C until they reached a constant weight. The briquettes were then submerged in distilled water for 24 hours. After soaking, the mass of each wet briquette was measured to calculate the percentage of water absorption using a specific formula (6). This test evaluates the degree of porosity and sintering of the material. The calculation involves comparing the mass of the wet briquette (W) after soaking to the mass of the fired briquette (Mf).

$$WA\ (\%) = [(W - Mf)/Mf] \times 100 \quad (6)$$

3.6 Chemical Analysis of Clay Soil using X-Ray Fluorescence (XRF)

Soil sample preparation for elemental analysis involved oven-drying 100 g of soil at 105°C overnight, followed by pulverisation into finer particles. A 50 g subsample was then accurately weighed after a 5-minute pulverisation period. X-ray fluorescence (XRF)

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analysis was subsequently employed to examine the correlation between elemental concentrations and X-ray intensity. To ensure consistency, the soil was thoroughly mixed and homogenised using a pulveriser machine, eliminating potential compositional variations within the sample. This subsample was then placed in an XRF sample cup, distributing it evenly and filling it (Figure 3.6). The S1 Titan handheld XRF analyser (Appendix A) was used to perform chemical analysis on the homogenised soil. The XRF instrument was checked for residual contaminants that could impact the analysis results. With the subsample adequately prepared, it was ready for XRF analysis. The X-ray fluorescence (XRF) instrument directed a beam of X-rays at the sample, which then emitted characteristic fluorescent X-rays that were measured to quantify the elemental composition of the soil.

Figure 3. 6: XRF Sample Cup

3.7 Mineral Analysis of Clay Soil Using X-Ray Diffraction

A thorough mineral characterisation of the soil was undertaken using X-ray diffraction (XRD) analysis at the University of Venda's Mining and Environmental Geology (MEG) laboratory—sample preparation involved pulverising the soil into finer particles and storing them in an Eppendorf tube. Using a spatula, the pulverised sample was then

carefully loaded into the XRD holder, ensuring uniform distribution from the centre outward. XRD analysis was performed using the XRD machine, with each sample requiring approximately one hour. The resulting diffractograms were analysed using

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XRDWIN 2.0 software (Appendix A), facilitating the identification of the mineral phases present in the soil (Oyebanjo *et al.*, 2021).

To determine the mineral composition of the sample, X-ray diffraction (XRD) analysis was conducted using a Bruker D2 Phaser diffractometer to identify the mineral composition of the sample. This analytical method was also used by (Arkame *et al.*, 2024). X-ray diffraction (XRD) analysis was performed using a Bruker D2 Phaser diffractometer to identify the mineral composition of the sample. A representative, pulverised portion of the sample was measured over a range of 3 to 90° 2θ, with a step size of 0.02° and a counting time of 1 second per step. Mineral identification was based on their unique crystal structure, utilising the net intensity of prominent peaks. The XRD method detected crystalline phases present in amounts greater than 3% by mass, providing a comprehensive analysis of the sample's mineral composition.

Figure 3. 7: Sample Holder's Ring

3.8 Research Matrix

This study used a research matrix (Table 3.3) to systematically organise and integrate its key concepts. The matrix provides a clear framework for identifying, categorising, and developing research ideas. By aligning research objectives, research questions, vital variables, data sources, analytical tools, and expected outcomes, the matrix ensures a cohesive and structured approach to the investigation.

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Table 3. 3: The Research Matrix

Research Objectives	Research Questions	Key Variables	Data Sources	Analytical Tools	Key Deliverance
To characterise the physical properties of clay soils found in Thulamela Municipality	What are the physical properties of clay soils found in Thulamela Municipality?	➢ Physical properties ➢ Clay soil	➢ Primary data (field)	➢ Sieve analysis ➢ Hydrometer analysis ➢ Atterberg limit test	➢ Percentage of clay, silt and sand ➢ Plasticity
To characterise the chemical and mineral composition of the clay found in soils in Thulamela Municipality	What is the chemical and mineral composition of clay soils found in Thulamela Municipality?	➢ Chemical Composition ➢ Mineral composition ➢ Clay soil	➢ Primary data (field)	➢ X-ray fluorescent (XRF) ➢ X-ray diffraction (XRD	➢ Chemicals in soil (sio_2) ➢ Minerals in soil (e.g. kaolin)
To characterise the chemical and mineral composition of clay soils found in Thulamela Municipality	How do the chemical and mineral compositions of clay soils vary across different locations within Thulamela Municipality?	➢ Chemical Composition ➢ Mineral composition ➢ Clay soil varies across different locations	Secondary data (based on analysed data)	➢ X-ray fluorescent (XRF) ➢ X-ray diffraction (XRD	➢ Bricks, porcelain, earthenware, and tiles

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3.9 Ethics

This study adhered strictly to the principles of research ethics, prioritising the rights, dignity, and well-being of all participants. Informed consent was secured from each participant before data collection, ensuring they were fully aware of the research's purpose, methodology, potential risks, and benefits. This research received ethical clearance from the Faculty Research Ethics Committee, Faculty of Science, Engineering and Agriculture, University of Venda. The researchers took every precaution to minimise harm and maximise benefits to participants. Confidentiality and anonymity were maintained throughout the data collection and analysis process. The researchers took rigorous steps to safeguard participants' privacy and confidentiality. The study was conducted with utmost honesty, integrity, and transparency, avoiding any form of deception or misrepresentation. By upholding these fundamental principles of research ethics, the researchers ensured that the study was conducted responsibly, respectfully, and ethically.

3.10 Chapter Summary

This chapter delineated the research methodology employed to explore the ceramic potential of clay soil sourced from Thulamela Municipality. A quantitative research approach was adopted to scrutinise the soil's physical, chemical, and mineralogical properties. Sub-samples underwent expert examination at the University of Venda laboratory, leveraging specialised expertise in mineralogy, chemistry, and physical analysis. Various analytical techniques were deployed, encompassing sieve analysis, hydrometer analysis, X-ray fluorescence (XRF), and X-ray diffraction (XRD). The findings are presented in a combination of graphical, narrative, and tabular formats, facilitating a comprehensive interpretation of the data.

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Chapter Four: Results and Discussion

4.1 Introduction

This chapter presented the key findings of an in-depth study that investigated the physical, chemical, and mineralogical properties of raw materials used in ceramic production, as well as the characteristics of fired clay blocks. A comprehensive range of tests was conducted, including sieve analysis, hydrometer analysis, Atterberg limit tests, X-ray fluorescence (XRF) spectroscopy, and X-ray diffraction (XRD) analysis. The results of these tests provide a detailed understanding of the materials characteristics, shedding light on their suitability for ceramic production and the potential implications for the final product.

4.2 Physical Analysis of Clay Soil

The chemical composition and particle size distribution of clay materials are critical factors in ceramic production, particularly in determining their plasticity. Notably, the clay fraction is pivotal in influencing plasticity, making it a key consideration in ceramic fabrication.

4.2.1 Characterising Clay Samples through Particle Size Analysis

Eight clay samples' particle size distribution curves were analysed, revealing substantial differences in their particle size gradation profiles, as shown in Figure 4.1. The clays from Lwamondo, Ngwenani, Madadani, Matsika, Muledane, Tshilungoma, and Tshino showed a well-graded arrangement of particles, with a uniform distribution of fine, medium, and coarse particles (Appendix B). This balanced composition suggests that these clays exhibit desirable engineering properties. In contrast, the clays from Dzingahe have a uniformly graded arrangement, with particles mainly within a single size range. The variations in particle size distribution patterns can significantly impact the physical and mechanical properties of each clay type, which in turn affects their potential uses in different engineering and industrial contexts.

An examination of the effective sizes (D10) of the various clay types revealed notable variations. The Ha-Matsika clay particles exhibited the most significant practical size, measuring 0.25mm. In contrast, the Dzingahe, Lwamondo, Muledane, and Tshino clays had significantly smaller effective sizes, measuring 0.075mm. Meanwhile, Ngwenani,

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Madadani, and Tshilungoma clay fell in between with effective sizes of 0.125mm. This indicates that these three clays had smaller effective sizes than Ha-Matsika but were still more significant than the other four clay types. This disparity in effective sizes suggests differences in the physical properties of these clay types and potential behaviours.

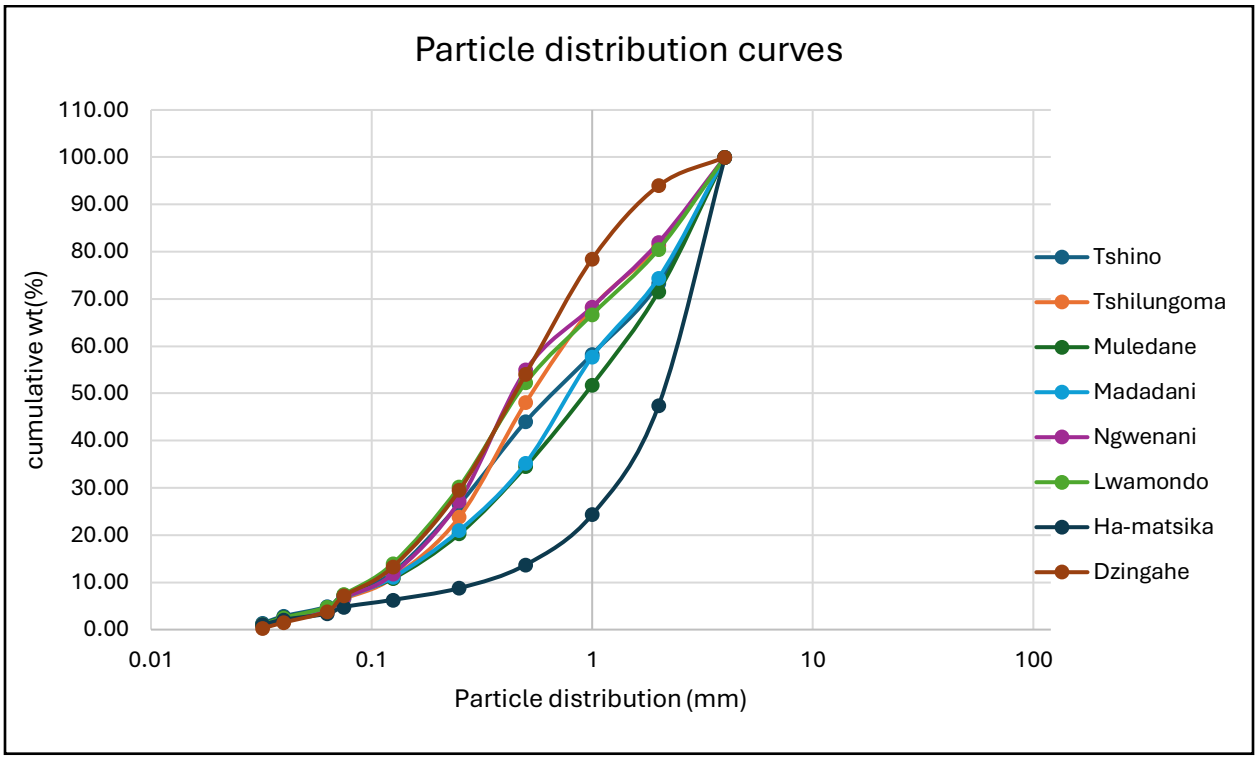

Figure 4. 1: The particle distribution curves of eight different areas

The uniformity coefficients (Cu) of eight distinct clay types were analysed, yielding a range of values. The clay particles from Ha-Matsika, Lwamondo, Ngwenani, Madadani, Muledane, Tshilungoma, and Tshino exhibited uniformity coefficients greater than four. This indicates that these clays are well-graded, meaning they contain a diverse range of particle sizes evenly distributed. In contrast, the clay from Dzingahe had a uniformity coefficient of less than four, suggesting that it is poorly graded or uniformly graded with particles tending to be more similar in size. This distinction is significant as well-graded clays exhibit more desirable engineering properties than poorly graded or uniformly graded clays. The variation in uniformity coefficients among these clay types highlights their unique characteristics and potential applications.

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The coefficient of gradation (Cc) is a key parameter that reflects the distribution and arrangement of grain sizes within a soil or clay sample. A well-graded soil typically has a Cc value between 1 and 3 (Onakunle *et al.*, 2019). Analysis of the experimental results revealed that Dzingahe, Ha-Matsika, and Lwamondo clays exhibited the most well-graded arrangement of particles with a coefficient of gradation (Cc) of 2. This suggests that these clays have an optimal distribution of particle sizes, which is desirable for engineering applications. Additionally, Ngwenani, Madadani, Muledane, Tshilungoma, and Tshino clays also displayed well-graded characteristics, although with a slightly lower Cc value of 1. This indicates that these clays have a good distribution of particle sizes, although slightly more uniform than the former group. Overall, the results demonstrate that these clay types have favourable gradation properties, with Dzingahe, Ha-Matsika, and Lwamondo being particularly well-suited for applications requiring optimal particle arrangement.

4.2.2 Hydrometer Analysis: Determining Clay Particle Size and Distribution

A comprehensive hydrometer analysis of the particle content showed significant differences among the samples (Appendix C). The sand proportion varied widely from 31.8% to 71.2% while the silt fraction ranged from 12% to 26%. The clay fraction also exhibited considerable variation from 24% to 48.2%. Figure 4.2 provides a detailed illustration of the particle size distribution. Notably, the analysis revealed substantial variations in clay content among the samples. Specifically, Lwamondo, Ha-Matsika, Dzingahe, and Muledane exhibited high clay percentages with values of 44.2%, 48.2%, 34.2%, and 38.2%, respectively. Furthermore, Karaman *et al.* (2006) conducted a hydrometer analysis that demonstrated a direct correlation between the percentage of fine particles and the settlement rate, indicating that samples with higher proportions of fine particles tend to settle more rapidly.

These findings suggest that these samples have distinct textural characteristics which may influence their physical and engineering properties. The observed variations in particle content and size distribution underscore the unique composition of each sample, highlighting the importance of thorough analysis in understanding their behaviour and potential applications.

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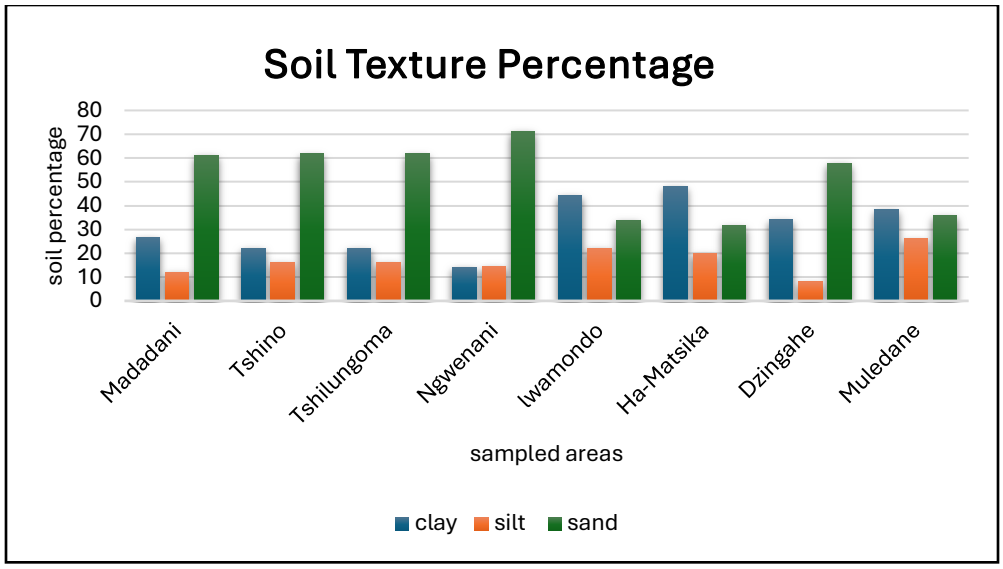

Figure 4. 2: Soil Particle of eight different areas

The comprehensive textural analysis of the collected soil samples provided crucial information regarding their viability for ceramic production. Specifically, the analysis revealed that Ha-Matsika and Lwamondo possess exceptionally clay-rich soils with clay percentages surpassing 40%. This high clay content renders these soils ideal for ceramic applications, as they are likely to exhibit superior plasticity, workability, and durability. Furthermore, Muledane's clay loam soil with a clay content of 38.8%, demonstrated significant potential for ceramic production, indicating favourable strength and stability properties. Additionally, Dzingahe's sandy clay soil containing 34.2% clay emerged as a promising candidate, suggesting its suitability for producing ceramics with desirable texture and consistency.

In contrast, the remaining samples displayed lower clay percentages, falling below the 30% threshold which may compromise their ceramic suitability. Specifically, Ngwenani's sandy loam soil with a clay content of 14.2% appears less suitable, whereas Madadani, Tshilungoma, and Tshino with clay percentages of 26.8%, 22.2%, and 22.2%, respectively, fall into the moderately suitable category. The preference for soils with higher clay content (>30%) in ceramic production stems from their enhanced plasticity, strength, and durability. These desirable properties enable the creation of high-quality ceramics with improved performance characteristics. Consequently, Ha-Matsika,

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Lwamondo, Muledane, and Dzingahe emerge as the most suitable candidates for ceramic production. At the same time, the remaining samples may require additional processing or blending to achieve optimal ceramic properties.

The results showed that Dzingahe, Madadani, Ngwenani, Tshiulungoma, and Tshino clays have a higher sand content than clay content. In contrast, Ha-Matsika, Muledane, and Lwamondo clays exhibit the opposite trend with higher clay content. This finding is consistent with the study by (Akintola *et al.*, 2024), which reported a higher proportion of sand-size particles than clay-size particles. According to their study, most soils demonstrated suitable workability and mechanical properties for producing high-quality extrusion bricks, making them suitable for single-story construction projects.

4.2.3 Atterberg Limits Test Results: Characterising Clay Consistency

Various ceramic masses Plasticity Index (PI) values were evaluated to determine their suitability for ceramic production (Appendix D). The results showed that the analysed samples exhibited favourable plasticity levels, with some demonstrating exceptionally high plasticity (Figure 4.3). Specifically, the clay samples from Dzingahe, Ha-Matsika, Madadani, and Tshilungoma displayed exceptionally high plasticity with PI values spanning 25.21 to 31.63 (Table 4.1). The high plasticity of these clay materials can be attributed to their high clay content, whereas the samples with lower plasticity had lower clay fractions and higher proportions of silt and sand (Manoharan *et al.*, 2012). This characteristic makes them well-suited for ceramic applications that demand high workability and strength, such as pottery, tiles, and sanitary ware production (Mefire *et al.*, 2018). Ngwenani also showed high plasticity, albeit to a lesser extent.

In contrast, Lwamondo, Muledane, and Tshino displayed moderate plasticity with PI values ranging from 8.45 to 12.78. While these samples are still suitable for ceramics, they may require adjustments in processing to achieve optimal results. Fortunately, none of the samples exhibited low plasticity indicating overall suitability for ceramic production. These clays' moderate to high plasticity levels make them versatile and suitable for various ceramic applications, including tableware, decorative items, and building materials.

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Table 4. 1: The values of Atterberg Limits (liquidity limit, plasticity limit, and plasticity)

	Dzingahe	Ha-Matsika	Lwamondo	Madadani	Muledane	Tshilungoma	Ngwenani	Tshino
Liquid Limit	64.54	62.87	50.29	40.26	65.68	59.84	47.19	41.17
Plastic Limit (Pl)	32.91	44.26	37.51	15.05	33.19	28.87	30	32.73
Plasticity Index (Pi)	31.63	18.61	12.78	25.21	10.45	30.97	17.19	8.45

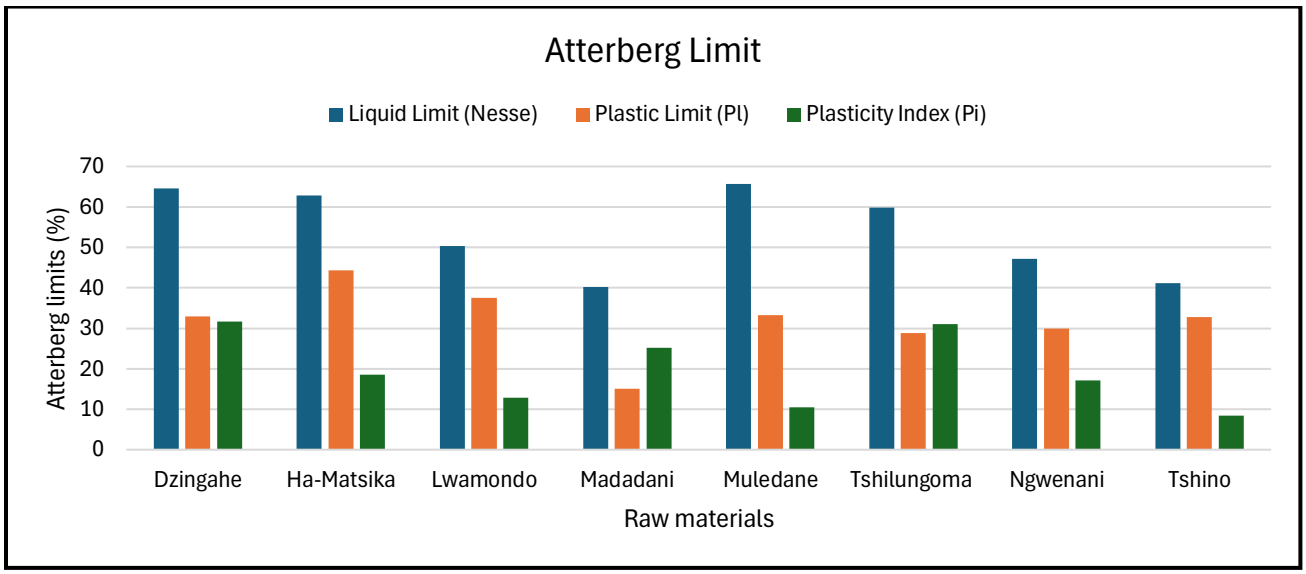

Figure 4. 3: The values of Atterberg Limits (liquidity limit, plasticity limit, and plasticity index)

4.3 Chemical Characterisation of Clays

X-Ray Fluorescence (XRF) analysis revealed varying chemical compositions of clays from Ha-Dzingahe, Ha-Matsika, Muledane, Tshino, Lwamondo, Madadani, Tshilungoma, and Ngwenani (Appendix E). The soil composition analysis revealed substantial variability across the samples, characterised by a wide range of oxide content. Silica content fluctuated between 27.7% and 37.9% while aluminium oxide content varied significantly from 0.9% to 17.9%. Additionally, the analysis showed calcium oxide, potassium oxide, and titanium oxide contents ranging from 0.2% to 1.1%, 0.2% to 1.1%, and 0.9% to 1.8%

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respectively. Furthermore, iron oxide content exhibited considerable variation falling between 6.5% and 15.5% (Table 4.2).

The chemical analysis of the clay samples showed a varied composition of key oxides, which is essential for assessing their suitability for ceramic production. Notably, the presence of substantial amounts of aluminium oxide (Al_2O_3), silicon dioxide (SiO_2), and iron (III) oxide (Fe_2O_3) suggests that these clays have the potential to yield ceramics with favourable characteristics, such as strength, durability, and aesthetic appeal. The silica content, ranging from 27.7% to 37.9% suggests that these clays can produce ceramics with good thermal resistance and durability. This is consistent with previous research by (Yami and Umaru, 2007) which showed that Nigerian clays with silica content of between 50.26% and 71.35% fell within the standard range of 46-62% required for producing suitable refractory materials.

The amount of iron oxide in the clay samples affects how well they can be used to produce ceramics. Lwamondo, with a notably high iron oxide content of 16% may be less suitable for ceramic production due to the potential for undesirable properties. Ha-Matsika and Muledane containing 13% and 11% iron oxide respectively, may require careful control of firing conditions to achieve optimal ceramic properties. In contrast, the remaining samples - Dzingahe, Madadani, Ngwenani, Tshilungoma, and Tshino - exhibit moderate to low iron oxide content, making them potentially more suitable for ceramic production. However, according to Jiang *et al.* (2017), a high concentration of iron oxide can have detrimental effects on ceramic properties. Specifically, high levels of iron oxide can cause ceramic products to warp, allow iron ions to penetrate the glassy and crystalline structures, and result in unappealing dark colours, ultimately compromising the ceramic's overall quality, aesthetics, and functionality.

The amount of alumina in the clay samples indicates that they have diverse levels of suitability for making ceramics. Lwamondo and Ngwenani with high alumina content of 17.9% and 15.9% may be well-suited for high-temperature ceramic applications. In contrast, Dzingahe, Ha-Matsika, and Madadani, with moderate alumina content ranging from 13.9% to 14.9%, may be more suitable for general ceramic production. However, Muledane and Tshino may be less suitable for ceramic production with extremely low

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alumina content of 0.9% and 1.2%. Additionally, Tshilungoma with an alumina content of 11.9% may require careful control of firing conditions to achieve optimal ceramic properties.

The variability in the composition of the soils, particularly in terms of aluminium, calcium, potassium, titanium, and iron oxide content, implies that each clay sample may be suited for specific ceramic applications. For instance, clays with higher aluminium oxide content may be more suitable for producing refractory ceramics. In comparison, those with higher iron oxide content may be better suited for producing ceramics with specific colour requirements. Knowing the chemical makeup of these clays is crucial for maximising their potential in ceramic production and achieving the desired characteristics in the end products.

Table 4. 2: X-ray Fluorescent (XRF)

	X-ray Fluorescent (XRF)					
	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3
Dzingahe	14.875	35.1	0.938	0.287	1.422	10.022
Ha-Matsika	14.53	33.643	0.392	0.4	1.72	12.887
Lwamondo	17.967	27.674	0.205	0.229	1.867	15.55
Madadani	13.866	33.415	0.242	0.435	1.315	9.945
Muledane	0.949	34.129	0.45	0.582	1.888	10.558
Tshilungoma	11.988	37.314	0.695	0.953	1.159	7.753
Ngwenani	15.673		0.393	0.454	1.348	9.795
Tshino	12.236	37.961	1.119	1.083	0.961	6.574
ASIA (Kütahya)(Taşçı *et al.*, 2024)	13.95	78.66	0.05	0.18	0.73	0.50
Morocco (Ameskroud) (Idoum *et al.*, 2024)	15.53	47.66	4.02	5.51	0.73	5.51
South Africa (Limpopo) (Akintola *et al.*, 2024)	13.89	52.44	0.05	0.18	0.89	5.79

Local clays from the Thulamela region have unique properties, making them suitable for specific ceramic applications. For instance, Ha-Matsika and Tshilungoma clays are rich

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in alumina, making them ideal for producing refractory ceramics that can withstand extremely high temperatures. On the other hand, Tshino clay is rich in iron oxide, making it perfect for creating vibrant ceramic pigments or colours, and these findings match the findings of (Masheane *et al.*, 2018).

In contrast, international clays from Asia, Morocco, and South Africa have distinct compositions, making them suitable for various ceramic applications. The Asian clay from Kütahya, for example, has exceptionally high alumina content, making it suitable for producing high-alumina ceramics, such as refractories or technical ceramics (Taşçı *et al.*, 2024). Research by Taşçı *et al.* (2024) confirmed that clay from Thulamela is also suitable for manufacturing wall tiles. Similarly, the Moroccan clay from Ameskroud is rich in iron oxide, making it ideal for creating ceramic pigments or colours (Idoum *et al.*, 2024). Meanwhile, the South African clay from Limpopo has properties that make it suitable for general-purpose ceramics, such as pottery and tableware or decorative items (Diko and Ligege, 2020). Research by Akintola *et al.* (2024) confirmed the suitability of this clay for artisanal brick production in rural Limpopo, South Africa.

4.4 Characterisation of Clay Minerals using XRD

X-Ray Diffraction (XRD) analysis of clay minerals from Ha-Dzingahe, Ha-Matsika, Muledane, Tshino, Lwamondo, Madadani, Tshilungoma, and Ngwenani revealed diverse mineral compositions (Appendix F). The Examination of clay samples from various locations showed notable differences in mineral composition especially in quartz and kaolinite content as presented in Table 4.3. The substantial presence of quartz ranging from 38.0% to 79.2% indicates that these clays have the potential to produce ceramics with high thermal resistance and durability.

Lwamondo clay with a kaolinite content of 49.6% may be particularly suitable for producing ceramics that require high whiteness and plasticity such as porcelain and fine bone china. The results of this study match the results of a previous study done in Bangladesh (Mousharraf *et al.*, 2011) which also found that the clay is suitable for producing whiteware ceramics. XRD analysis identified Quartz and kaolinite as the primary minerals present in the clay. In contrast Tshilungoma and Tshino clays with

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relatively low kaolinite contents may be more suitable for producing ceramics that require lower plasticity and whiteness such as earthenware and terracotta.

The analysis of clay soils from various locations revealed the presence of haematite clay minerals in varying proportions, indicating significant differences in their composition. The high haematite content in Dzingahe (33%) and Lwamondo (13.2%) clays suggests they may be suitable for producing ceramics with specific colour requirements such as terracotta and earthenware. The presence of haematite in these clays can impart a reddish-brown colour to the final product. In contrast, the lower haematite content in Madadani, Ngwenani, Ha-Matsika, and Muledane clays may make them more suitable for producing ceramics that require a whiter or more neutral colour.

The analysis also revealed varying mineral compositions in the clay soils, impacting their suitability for different ceramic applications. For example, hornblende minerals in Tshilungoma and Tshino clays may make them more suitable for producing ceramics that require high thermal resistance and durability. The high albite content in Tshilungoma's clay soil may also make it suitable for producing ceramics with specific thermal and mechanical properties. Additionally, orthoclase, anorthite feldspar, clinochlore, and ilmenite minerals in various clay soils suggest they may be suitable for producing various ceramic products, including porcelain, fine bone china, and technical ceramics.

The clays from Dzingahe, Madadani, Lwamondo, Ngwenani, and Ha-Matsika exhibit a favourable mineral composition, characterised by high concentrations of quartz, kaolinite, and hematite with Ha-Matsika also containing goethite. This mineralogical profile is typical of clays that produce high-performance ceramics such as refractory ceramics, sanitary ware (e.g. toilets, sinks) and ceramic tiles. These findings align with the study by Manoharan *et al.* (2012) indicating that red clays containing high amounts of quartz, well-ordered kaolinite, and iron-rich minerals such as goethite and hematite possess desirable properties for producing roofing tiles. Additionally, with some modifications, these clays can be suitable for manufacturing standard bricks.

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Table 4. 3: Quantitative mineralogical analysis by X-ray diffraction

Mineral	Ideal Chemical Formula	Dzingahe	Madadani	Lwamondo	Ngwenani	Matsika	Muledane	Tshilungoma	Tshino
Quartz	Sio_2	74.6	79.2	37.1	60.1	60.5	38.0	10.9	24.5
Kaolinite	$Al_2Si_2O_5(OH)_4$	22.0	17.6	49.6	31.3	26.4	12.0	3.9	7.7
Haematite	Fe_2O_3	3.3	3.1	13.2	8.6	5.3	2.2.		
Goethite	FeO(OH)					7.8	3.5		
Albite	$NaAlSi_3O_8$							35.0	
Orthoclase	$KAlSi_3O_8$						11.5	8.6	16.5
clinochlore	$(MgFe++)_sAl(Si_3Al)\ O_{10}(OH)_8$						<1		8.6
Anorthite	$CaAl_2Si_2O_8$						30.9	37.7	33.5
Ilmenite	$FeTiO_3$						1.9		
Homblende	$Ca_2(Mg,Fe,Al)_s(Al,Si,)_8O_{22}(OH)$							3.8	4.6
Talc	$Mg_3Si_4O_{10}(OH)_2$								4.6

4.5 X-Ray Diffraction (XRD) Analysis of Fired Clay Blocks

X-Ray Diffraction (XRD) analysis of fired clay blocks from Ha-Dzingahe, Ha-Matsika, Muledane, Tshino, Lwamondo, Madadani, Tshilungoma, and Ngwenani revealed temperature-dependent mineral transformations, with various minerals forming and disappearing at different temperatures (Appendix G and Appendix I). The Ha-Matsika clay underwent significant changes when fired at various temperatures. Before firing, its X-ray diffraction pattern showed a distinct peak between 10 θ and 20 θ, indicating the presence of kaolinite. When fired at 300°C, the pattern remained largely the same. However, as the temperature increased to 700°C, 800°C, 900°C, and 1150°C, subtle changes emerged. The kaolinite peak gradually disappeared while new minerals formed. Specifically, grossite appeared at 700°C and 800°C but vanished at 900°C. At 1150°C rutile emerged. Throughout the temperature range, quartz, chloritoid, and hematite remained present. This pattern was similar for other clays including Dzingahe, Ngwenani, Tshiulungoma, Tshino, Lwamondo, and Madadani. Their distinctive peaks also changed as the temperature increased with kaolinite disappearing and new minerals forming between 700°C and 900°C.

The mineral composition of Dzingahe clay underwent substantial transformations when fired at various temperatures. Initially, the clay contained quartz, kaolinite, and hematite. The presence of these minerals, particularly hematite and goethite, alongside abundant

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kaolinite, indicates that the kaolinite formed through tropical weathering processes (Manoharan *et al.*, 2012). Firing the clay at 300°C led to the formation of quartz, chloritoid, hematite, and 2M-kaolinite in small amounts. As the temperature increased to 700°C, the mineral composition became low amounts of quartz, chloritoid, hematite, and maghemite. At higher temperatures of 800°C and 900°C, the clay's mineral composition consisted of low amounts of quartz, hematite, and muscovite. Finally, firing the Dzingahe clay at 1150°C resulted in quartz, hematite, and rutile mineral composition.

The mineral composition of Ha Matsika clay underwent significant transformations when fired at various temperatures. Initially, the clay contained quartz, kaolinite, hematite, and goethite. When fired at 300°C, the clay minerals transformed into quartz, chloritoid, hematite, and kaolinite. Further firing at 700°C and 800°C resulted in quartz in low amounts, chloritoid, hematite, and grossite. At 900°C, the clay minerals simplified to quartz in low amounts, hematite, and grossite. Finally, when fired at 1150°C, Ha Matsika clay consisted of low quartz, hematite-proto, and rutile.

Lwamondo clay's mineral composition evolved significantly with temperature changes. Initially, the clay contained quartz, kaolinite, and hematite. Firing at 300°C yielded comparable results, with quartz, kaolinite, and hematite still present. However, at 700°C, the composition shifted to low quartz and hematite proto. Further firing at 800°C introduced anatase, resulting in a mix of quartz, hematite, and anatase. Finally, firing at 900°C and 1150°C simplified the mineral composition to primarily quartz and hematite.

The Lwamondo clay samples did not perform well. At 800°C, they were strong, but when the temperature was increased to 900°C and 1150°C, they started to break. This is because the Lwamondo clay absorbs much water, weakening it when it gets hot. On the other hand, the Ha Matsika clay blocks did very well. They were able to handle the heat without getting damaged. They became even stronger as the temperature increased. This shows that the Ha Matsika clay is firm and good at handling high temperatures.

Madadani clay's mineral composition underwent significant changes when fired at various temperatures. Initially, the clay consisted of quartz, kaolinite, and hematite. When fired at 300°C, the clay minerals transformed into quartz, 2M-kaolinite, and hematite. Firing at

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700°C and 800°C resulted in quartz, hematite, and anatase composition. At 900°C, the minerals present were low quartz and hematite. Finally, when fired at 1150°C, the Madadani clay consisted of quartz, orthoclase, and hematite.

Muledane clay's mineral composition underwent significant transformations when fired at various temperatures. Initially, the clay contained diverse minerals, including quartz, hematite, kaolinite, goethite, orthoclase, clinochlore, anorthite, and ilmenite. Firing at 300°C resulted in a simplified composition of quartz, hematite, kaolinite, albite, and orthoclase. As the temperature increased to 700°C, new minerals emerged, including rutile, epidote, and albite, alongside quartz and hematite. Further firing at 800°C introduced hornblende, while at 900°C, clinoenstatite appeared. Finally, at 1150°C, the clay's mineral composition consisted of hematite, hornblende, orthoclase, albite, and quartz.

Ngwenani clay's mineral composition underwent significant transformations when fired at various temperatures. Before firing, the clay consisted of quartz, kaolinite, and hematite. Firing at 300°C yielded related results, with no changes in the mineral composition (Figure 4.4). However, at 700°C, new minerals emerged, including chloritoid and grossite, in addition to quartz and hematite. Firing at 800°C resulted in a similar composition, with a decrease in quartz content. By 900°C, the mineral composition had simplified to quartz and hematite. Finally, firing at 1150°C introduced rutile, resulting in low quartz, rutile, and hematite composition (Figure 4.5).

Tshilungoma clay's initial mineral composition was complex, featuring a range of minerals, including quartz, kaolinite, orthoclase, clinochlore, anorthite, hornblende, and talc. However, when fired at 300°C, the clay's mineral composition significantly changed, resulting in quartz, albite, 2M-kaolinite, rutile, and hematite. As the firing temperature increased to 700°C, the composition was simplified to include rutile, hematite, quartz, and albite. Further firing at 800°C and 900°C introduced hornblende, while the composition remained relatively consistent. Finally, at 1150°C, the clay's mineral composition consisted of quartz, albite, orthoclase, and hematite.

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Tshino clay's initial mineral composition was quartz, kaolinite, albite, orthoclase, anorthite, and hornblende. When fired at 300°C and 700°C, the clay's mineral composition remained consistent, with quartz, kaolinite 2M, orthoclase, hornblende, anorthite, and albite still present. However, firing at 800°C introduced hematite, which joined the existing minerals. Finally, when fired at 1150°C, the clay's mineral composition was simplified to low quartz, albite, hematite, hornblende, and orthoclase.

The comprehensive analysis of eight distinct clay types, namely Dzingahe, Ha Matsika, Lwamondo, Madadani, Muledane, Ngwenani, Tshino, and Tshilungoma has yielded valuable insights into the thermal transformation of their mineral compositions. A notable trend observed across these clay types is the gradual simplification of their mineral assemblages as the firing temperature increases. Initially, the clays exhibit complex mineral compositions, but as they are exposed to higher temperatures, they transform, resulting in fewer, more thermally stable minerals. Quartz, hematite, and albite emerge as common residual minerals, suggesting their relative thermal stability.

Conversely, the disappearance of kaolinite, goethite, and talc at elevated temperatures indicates their thermal instability, highlighting the importance of temperature control in ceramic processing. Furthermore, the emergence of new minerals, including rutile, anatase, and hornblende, at higher temperatures suggests the occurrence of high-temperature reactions, which can significantly impact the final ceramic properties. The changes in mineral composition observed in these clay types may have profound implications for their ceramic applications, influencing properties such as strength, durability, and colour. Therefore, it is essential to consider the thermal transformation of clay minerals when selecting and processing clays for specific ceramic applications, ensuring the optimal utilisation of these natural resources.

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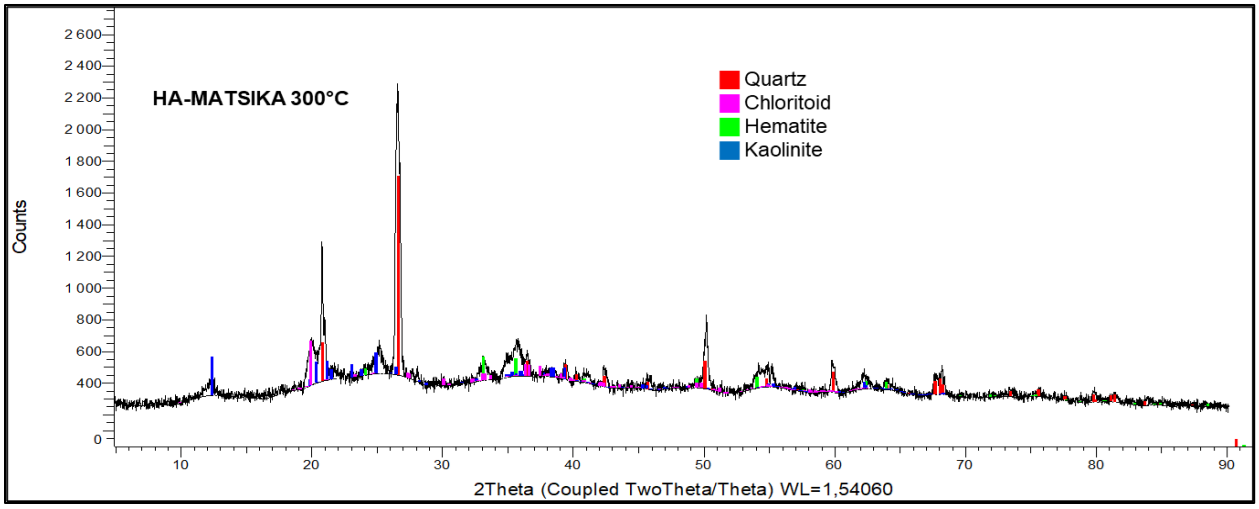

Figure 4. 4: The X-ray diffraction pattern of Ha-Matsika clay at 300°C

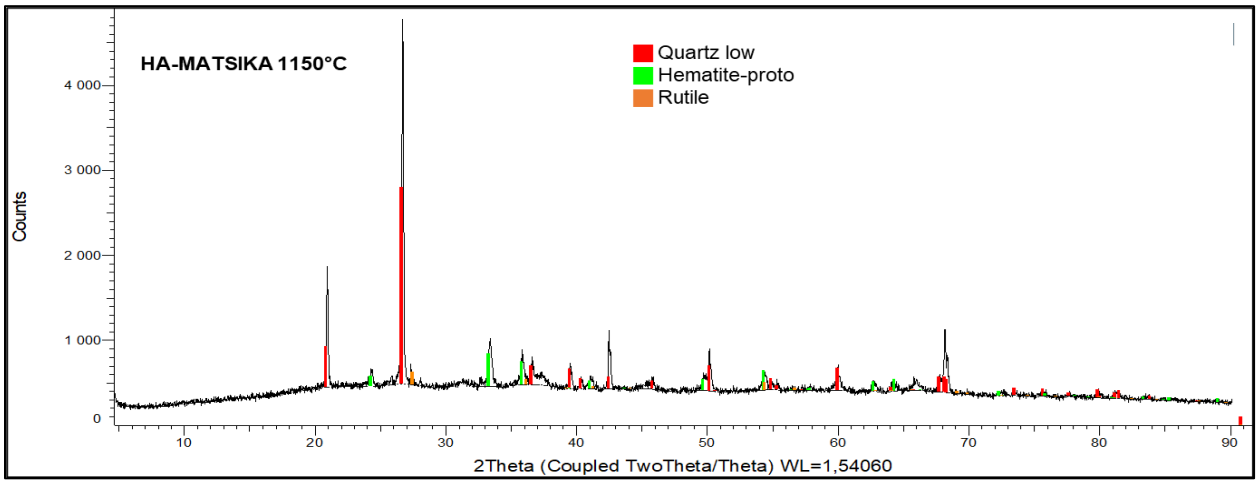

Figure 4. 5: The X-ray diffraction pattern of Ha-Matsika Clay at 1150°C

4.6 Characterising Water Absorption Behaviour in Fired Clay Blocks

Figure 4.6 illustrates the water absorption curves for diverse clay types from different sites at varying firing temperatures. The water absorption results for Dzingahe clay at various firing temperatures exhibit a multifaceted and intriguing pattern. At 300°C, the water absorption is exceptionally low, at 7.20% indicating a relatively stable and water-resistant clay structure, likely due to unaltered clay minerals and a compact morphology. As the firing temperature escalates to 700°C, water absorption increases sharply to 15.86% suggesting significant structural transformations that enhance porosity and water

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absorption. This could be attributed to breaking certain clay minerals, forming new phases or creating a more open structure.

However, as the firing temperature rises to 800°C and 900°C, water absorption decreases to 10.46% and 10.23% respectively. While higher firing temperatures typically lead to denser and less porous structures in clay materials due to the emergence of a glassier phase or intensified particle fusion, the high water absorption values in this study indicate that the clay bricks produced were highly porous, suggesting incomplete densification (Karaman *et al.*, 2006). Notably, the water absorption results take an unexpected turn at 1150°C, where the water absorption surges dramatically to 19.32%. This pronounced increase could be attributed to forming a specific mineral phase creating a more open structure or defects or flaws in the clay's microstructure.

The water absorption results for Ha-Matsika clay at various firing temperatures reveal a fascinating pattern. At 300°C, the water absorption is 10.27% denoting a moderate moisture uptake. As the firing temperature rises to 700°C, water absorption increases to 18.61% implying substantial structural modifications that enhance porosity and water absorption. Notably, at 800°C, water absorption edges up to 19.10%. However, at 900°C, it drops to 12.14% indicating a denser, less porous morphology, potentially due to the emergence of a glassier phase or intensified particle fusion. Lastly, at 1150°C, water absorption surges to 16.71% possibly attributed to the formation of a specific mineral phase, a more open structure, or microstructural defects.

The water absorption results for Lwamondo clay at various firing temperatures exhibit a fascinating and complex trend. At the lower end of the temperature spectrum, specifically at 300°C, the water absorption is remarkably low, measuring a mere 8.19%. This suggests that the clay's mineral composition and structure at this temperature are relatively stable and resistant to water penetration. As the temperature escalates to 700°C, water absorption escalates to 15.24%, signifying a moderate level of moisture uptake. This phenomenon can be ascribed to the incipient stages of vitrification wherein the clay's particles commence fusion, yielding a more porous morphology. Nonetheless, as the firing temperature soars to 800°C and 900°C, water absorption undergoes a precipitous increase, reaching 28.74% and 31.78% respectively. This pronounced surge

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in water absorption intimates that the clay's structure undergoes profound transformations at these temperatures, culminating in augmented porosity and heightened hydrophilicity. The elevated water absorption at these temperatures may compromise the clay's mechanical integrity and durability. Interestingly, at the highest firing temperature of 1150°C, water absorption undergoes a marginal decline to 28.41%. This unexpected diminution can be attributed to the advanced stages of vitrification wherein the clay's particles are more extensively fused, resulting in a denser, less porous morphology. Alternatively, this decrease may be due to the formation of a glassy phase which can mitigate the clay's water absorption.

The water absorption results for Madadani-fired clay at various temperatures reveal a notable trend. At 300°C, the water absorption is exceptionally low at 2.04% indicating a highly stable and water-resistant clay structure. As the firing temperature increases to 700°C, water absorption rises to 9.03% suggesting significant structural changes, increased porosity, and water absorption. Water absorption continues to rise at 800°C and 900°C, reaching 14.45% and 14.61% respectively. Interestingly, at 1150°C, water absorption decreases slightly to 13.30%, potentially due to the formation of a glassier phase or increased particle fusion, resulting in a denser, less porous structure.

The water absorption results for Muledane-fired clay at various temperatures reveal a notable trend. The water absorption is remarkably low at the highest firing temperature of 1150°C measuring 5.63%. This indicates that the clay's structure at this temperature is exceptionally dense and impervious to water likely resulting from developing a glassy phase or enhanced particle fusion which effectively seals pores and reduces water absorption. In contrast, the water absorption is significantly higher at lower firing temperatures. At 900°C, the water absorption is 17.90%; at 800°C it is 16.68%; and at 700°C it is 14.77%. The water absorption at 300°C is 10.32%, which is relatively moderate. The observed trend suggests that the clay's structure becomes increasingly dense and less porous as the firing temperature increases, significantly reducing water absorption. This makes Muledane clay a promising material for applications requiring low water absorption, particularly when fired at high temperatures.

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The water absorption results for Ngwenani-fired clay at various temperatures display a notable trend. At 300°C, the water absorption is relatively low at 7.02%. A slight increase to 8.70% is observed at 700°C indicating minimal structural changes. However, a pronounced surge to 18.02% occurs at 800°C, suggesting significant structural modifications, increased porosity, and enhanced water absorption. Subsequent decreases to 15.19% at 900°C and 14.45% at 1150°C imply the formation of a glassier phase or increased particle fusion, resulting in a denser, less porous structure. This trend underscores the intricate relationships between firing temperature, clay mineralogy, and microstructure, highlighting 800°C as a critical point for Ngwenani clay, where substantial structural transformations occur.

The water absorption results for Tshilungoma-fired clay at various temperatures reveal a complex trend. At 300°C, the water absorption is moderate, at 8.91%. As the temperature increases to 700°C, water absorption rises to 13.93% indicating increased porosity due to structural changes. However, at 800°C and 900°C, water absorption decreases to 11.84% and 10.14%, respectively, suggesting a denser, less porous structure, potentially due to glass phase formation or particle fusion. Surprisingly, at 1150°C, water absorption increases significantly to 15.24%, possibly attributed to forming a specific mineral phase, creating an open structure, or microstructural defects.

The water absorption results for Tshino-fired clay display a clear pattern across different temperatures. Specifically, at the lowest firing temperature of 300°C, the water absorption is moderately high, reaching 8.93%. As the firing temperature increases to 700°C, the water absorption surges to 19.31% indicating significant changes in the clay's structure, leading to increased porosity and water absorption. However, at 800°C, the water absorption decreases to 12.91%, suggesting that the clay's structure becomes more dense and less porous at this temperature. The water absorption then increases at 900°C to 15.09% and increases at 1150°C to 15.89%. This increase could be attributed to forming a specific mineral phase, creating a more open structure, or defects or flaws in the clay's microstructure. The observed trend highlights the complex interactions between firing temperature, clay mineralogy, and microstructure. The significant increase in water

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absorption at 700°C suggests that this temperature may be a critical point for Tshino clay, where the clay's structure undergoes substantial changes.

The water absorption results for the eight clay types, including Dzingahe, Ha-Matsika, Lwamondo, Madadani, Muledane, Ngwenani, Tshilungoma, and Tshino, reveal distinct trends at various firing temperatures. Generally, water absorption increases with temperature, indicating changes in clay structure and porosity. However, some clays, such as Madadani and Muledane, show decreased water absorption at higher temperatures, suggesting densification and reduced porosity. A study on Namu clay from Nigeria's Plateau State found that water absorption decreased as firing temperature increased (Oyelaran, 2014). The findings are consistent with Manjate (Manjate *et al.*, 2020), which found that higher firing temperatures reduced water absorption and increased compressive strength in a Mozambican study. Given the similar properties observed, clays from Dzingahe, Ha-Matsika, Lwamondo, Madadani, Muledane, Ngwenani, Tshilungoma, and Tshino are likely suitable for producing ceramic products like walled floor blocks, clay roofing tiles, and bricks.

In contrast, Dzingahe and Ha-Matsika clays exhibit increased water absorption at higher temperatures, while Lwamondo clay displays a significant surge in water absorption at 800°C and 900°C. The remaining clays of Ngwenani, Tshilungoma, and Tshino, exhibit complex trends, increasing and decreasing water absorption at different temperatures. These findings underscore the importance of considering the specific clay type and firing temperature when evaluating water absorption properties for various ceramic applications.

The relationship between linear shrinkage and temperature is not straightforward, as the results vary across different clay samples. While some samples from Muledane exhibit a general increase in linear shrinkage with temperature, others, like those from Ngwenani, display a non-monotonic behaviour, with shrinkage decreasing at certain temperatures before increasing again. In contrast, samples from Ha-Matsika, Madadani, and Tshiulungoma show consistent linear shrinkage values across all temperatures, indicating minimal changes in shrinkage behaviour with temperature.

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The linear shrinkage results provide valuable indications of the ceramic potential of each clay sample allowing for an assessment of their suitability for various ceramic applications (Appendix H). Clays from Muledane, Ha-Matsika, Madadani, and Tshiulungoma demonstrate favourable linear shrinkage properties, making them suitable for ceramic applications. On the other hand, Dzingahe, Ngwenani, and Tshino which display high or variable linear shrinkage values may be less suitable or require additional processing to make them viable for ceramic applications. However, it is essential to consider other factors, such as clay composition, plasticity, and strength, to determine the overall suitability of each clay sample for ceramic production.

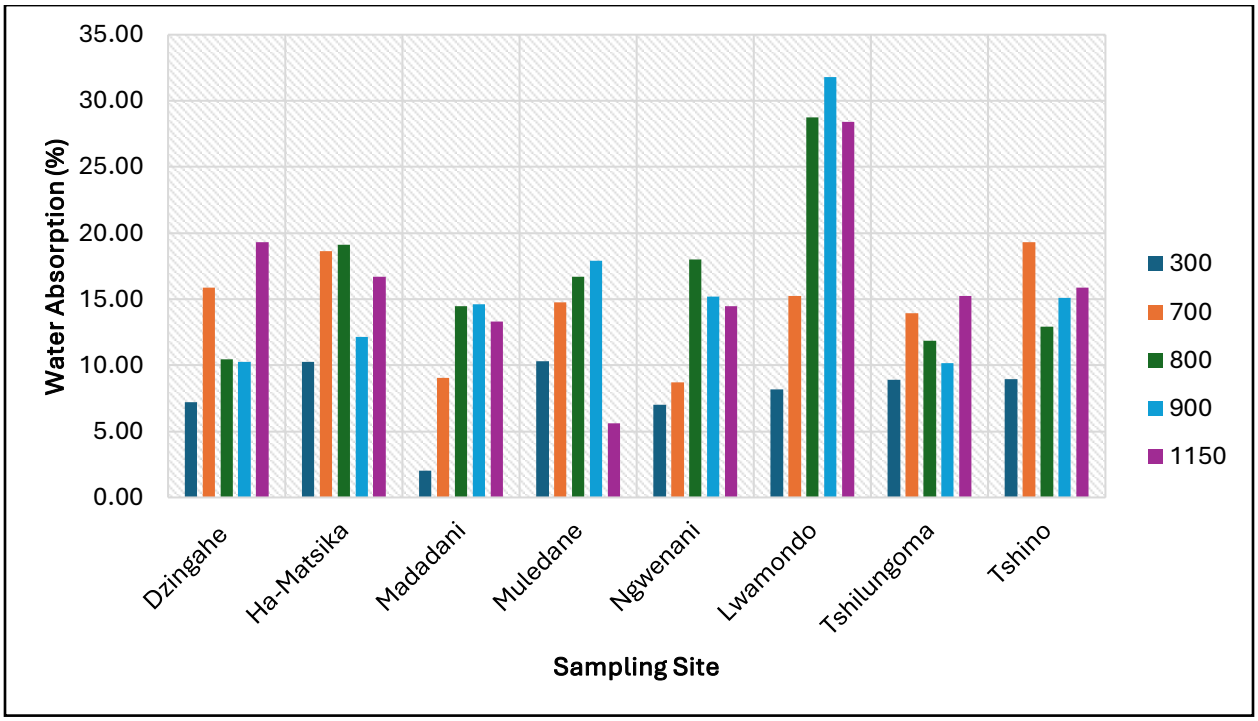

Figure 4. 6: Water Absorption Curve: Comparing Different Clay Types from Various Sites at Different Firing Temperatures

4.7 Chapter Summary

This chapter thoroughly examines the physical, chemical, and mineralogical characteristics of eight clay samples sourced from various locations, providing a detailed understanding of their composition and properties. The results show significant variations in particle size distribution, chemical composition, and mineralogy among the clay

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samples with some exhibiting well-graded particle size distributions and others having uniformly graded arrangements. The chemical analysis discloses a varied presence of principal significant oxides such as silica, alumina, iron oxide, and calcium oxide, indicating that each clay sample possesses a unique chemical profile, potentially making it suitable for ceramic uses. The mineralogical analysis reveals a complex assemblage of minerals, including quartz, kaolinite, goethite, and talc which undergo thermal transformation at different temperatures, affecting their ceramic properties. The water absorption and linear shrinkage results show distinct trends at various firing temperatures indicating that some clays are more suitable for ceramic production than others. This chapter offers a comprehensive understanding of the characteristics of clays from various sources, and their potential uses in ceramic manufacturing. It emphasises the crucial role of tailored clay selection and processing in optimising ceramic production ensuring that the chosen clays meet the specific requirements of the intended application.

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Chapter Five: Summary, Conclusion and Recommendations

5.1 Summary

The study set out to investigate the suitability of clay from Thulamela Municipality for various ceramic applications. This area is rich in clay deposits, and local communities have been using these deposits for traditional pottery and brickmaking. However, the quality of these products was uncertain due to the lack of scientific testing and oversight. By examining the physical, chemical, and mineral properties of the clay, the study aimed to determine its potential for diverse ceramic uses.

A comprehensive literature review was conducted to explore the relationship between climatic conditions and soil formation, focusing on clay soils and their suitability for ceramic applications. The review highlighted the importance of particle size distribution, chemical composition, and mineral composition in determining clay suitability for ceramic production. Various methods for characterising clay and determining its suitability for ceramic use were also evaluated. The review provided a comprehensive overview of the critical factors influencing clay suitability for ceramic applications and highlighted the importance of thorough characterisation and analysis.

The study collected clay soil samples from eight villages in Thulamela Municipality and subjected them to various analyses, including physical characterisation, chemical analysis, and mineral analysis. The physical characterisation included sieve analysis, hydrometer analysis, and Atterberg limit tests. The chemical analysis used X-ray fluorescence (XRF) to determine elemental composition, while the mineral analysis used X-ray diffraction (XRD) to determine mineral composition. The study adhered to research ethics principles, prioritising participants rights, dignity, and well-being.

The study's findings revealed that the clay soils from Thulamela Municipality have varying physical, chemical, and mineralogical properties, making them suitable for different ceramic applications. The physical analysis showed significant variations in particle size distribution, clay content, and plasticity levels, with Ha-Matsika, Lwamondo, Muledane, and Dzingahe emerging as the most suitable areas for ceramic production due to their high clay content and favourable plasticity levels. Specifically, Ha-Matsika and Lwamondo had high clay percentages of 48.2% and 44.2%, respectively, making them ideal for

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ceramic applications. The Atterberg limits test results indicated that the analysed samples had favourable plasticity levels, with Dzingahe, Ha-Matsika, Madadani, and Tshilungoma displaying exceptionally high plasticity. These properties suggest that these clays can be used to produce a range of ceramic products, including pottery, tiles, and sanitary ware. The unique physical properties of each clay sample will require tailored processing and application approaches.

The chemical and mineralogical analysis showed that the clays have unique compositions, with varying levels of silica, alumina, and iron oxide. Lwamondo clay stood out with high kaolinite content, making it suitable for producing high-quality ceramics like porcelain and fine bone china. In contrast, Tshilungoma and Tshino clays had relatively low kaolinite contents, suggesting they may be more suitable for producing ceramics that require lower plasticity and whiteness, like earthenware and terracotta. The analysis of fired clay blocks showed temperature-dependent mineral transformations, with Quartz, hematite, and albite emerging as common residual minerals. These findings highlight the importance of understanding the chemical and mineralogical properties of clays for optimal ceramic production and suggest that the clays from Thulamela Municipality can be used for a range of ceramic applications, including refractory ceramics and ceramic pigments.

5.2 Conclusion

In conclusion, this study has demonstrated that the clay soils from Thulamela Municipality have diverse physical, chemical, and mineralogical properties, making them suitable for various ceramic applications. The comprehensive analysis revealed that Ha-Matsika, Lwamondo, Muledane, and Dzingahe clays possess a unique combination of desirable properties, including high clay content, suitable particle size distribution, and favourable thermal transformation behaviour. These characteristics make them ideal for producing high-quality ceramics, such as refractory ceramics, sanitary ware, and tableware, which require high strength, durability, and thermal resistance. Furthermore, their high plasticity and moderate to low water absorption rates make them suitable for producing ceramics with complex shapes and designs, such as artistic ceramics and ceramic sculptures.

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The study also found that Ngwenani, Madadani, Tshilungoma, and Tshino clays, while not suitable for high-quality ceramic applications, can still be utilised for producing ceramics with less stringent requirements, such as decorative ceramics, plant pots, and bricks. These clays may require additional processing or blending to achieve optimal ceramic properties, but they can still be valuable resources for ceramic production. This research offers significant contributions to the understanding of the ceramic potential of the investigated clay samples, underscoring their viability for diverse applications and guiding the optimal selection of raw materials for efficient ceramic manufacturing. The findings of this study can be used to guide the development of sustainable and locally sourced ceramic materials, promoting the growth of the ceramic industry while minimising environmental impacts.

5.3 Recommendations

This study's findings inform a series of recommendations to enhance the exploitation of local clay resources for ceramic production, thereby optimising their use and promoting improved outcomes. Ha-Matsika, Lwamondo, Muledane, and Dzingahe clays are identified as the best clays for ceramic production due to their physical and chemical properties. In contrast, Ngwenani, Madadani, Tshilungoma, and Tshino clays may require additional processing or blending to attain optimal ceramic properties. Further research is necessary to explore specific ceramic applications for each clay type and to fine-tune their processing conditions. Moreover, leveraging these locally sourced clays for ceramic production can significantly contribute to developing sustainable and environmentally friendly ceramic materials. To enhance the quality and competitiveness of fired clay brick production in the study area, training programs should be implemented to educate producers on kiln temperature control, and financial assistance should be provided to facilitate the acquisition of kiln temperature-controlling devices. Ultimately, attracting domestic and international investments in the brick production sector is vital for upgrading the clay brick production system, promoting healthy competition, and enhancing the overall quality and cost-efficiency of the industry.

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Appendices

Appendix A: Equipment Used for Analysis

Electric High-Speed Stirrer

Oven Drier machine

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Furnace Machine

S1 Titan handheld XRF analyser

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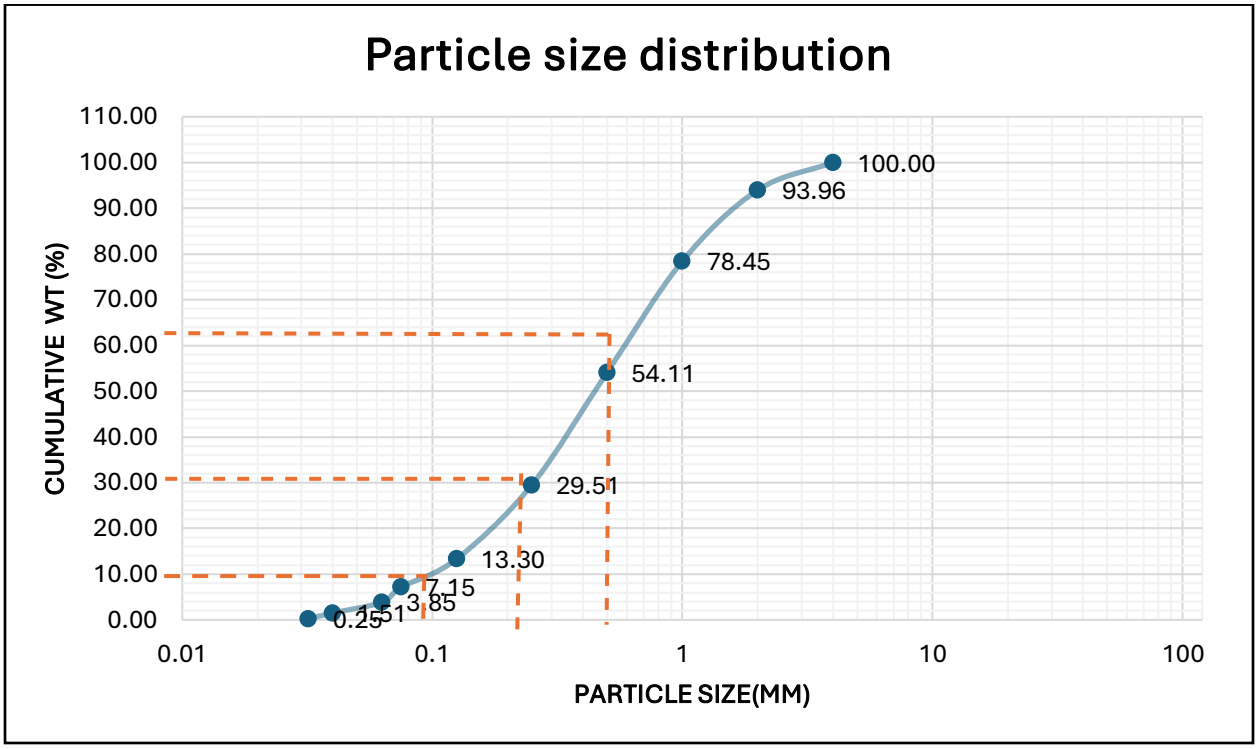
XRDWIN 2.0 software

Appendix B: Particle Size Analysis Results



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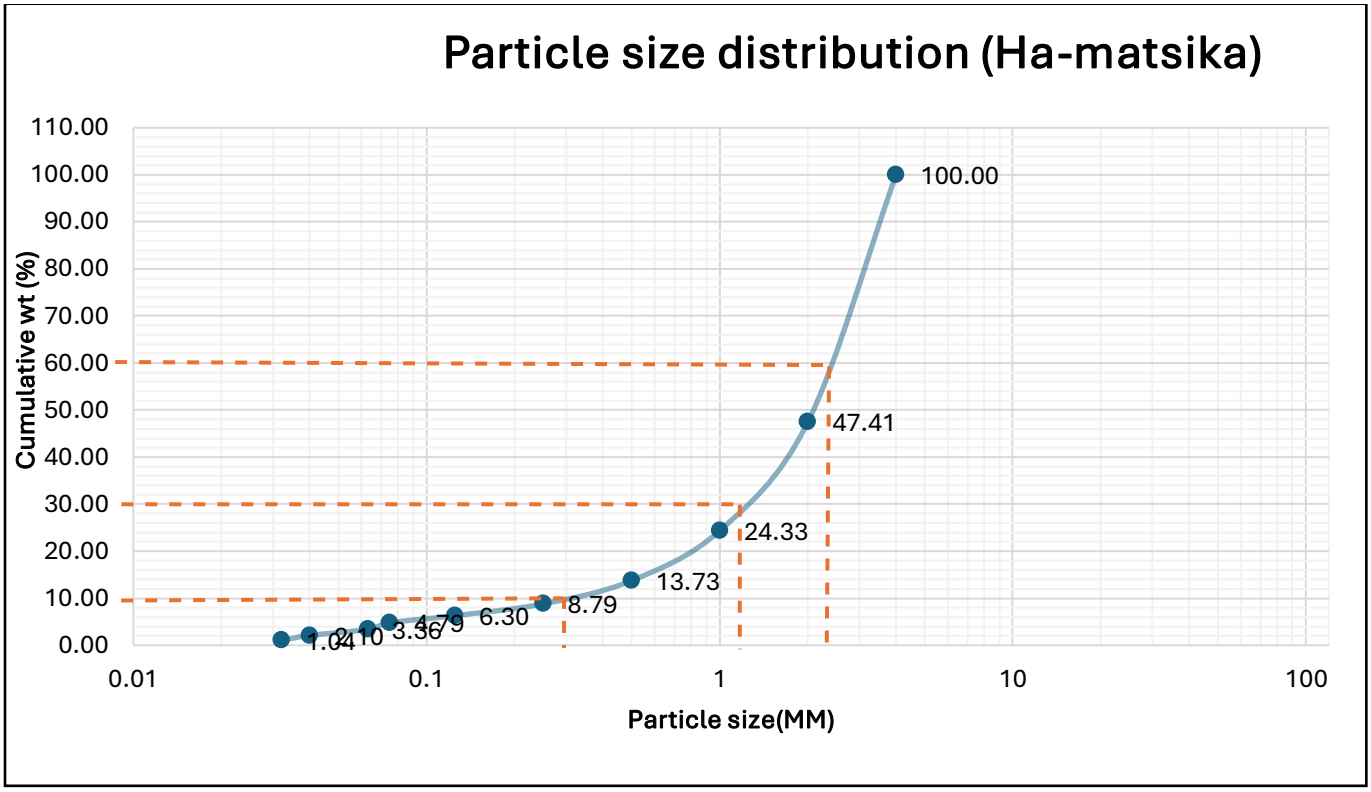

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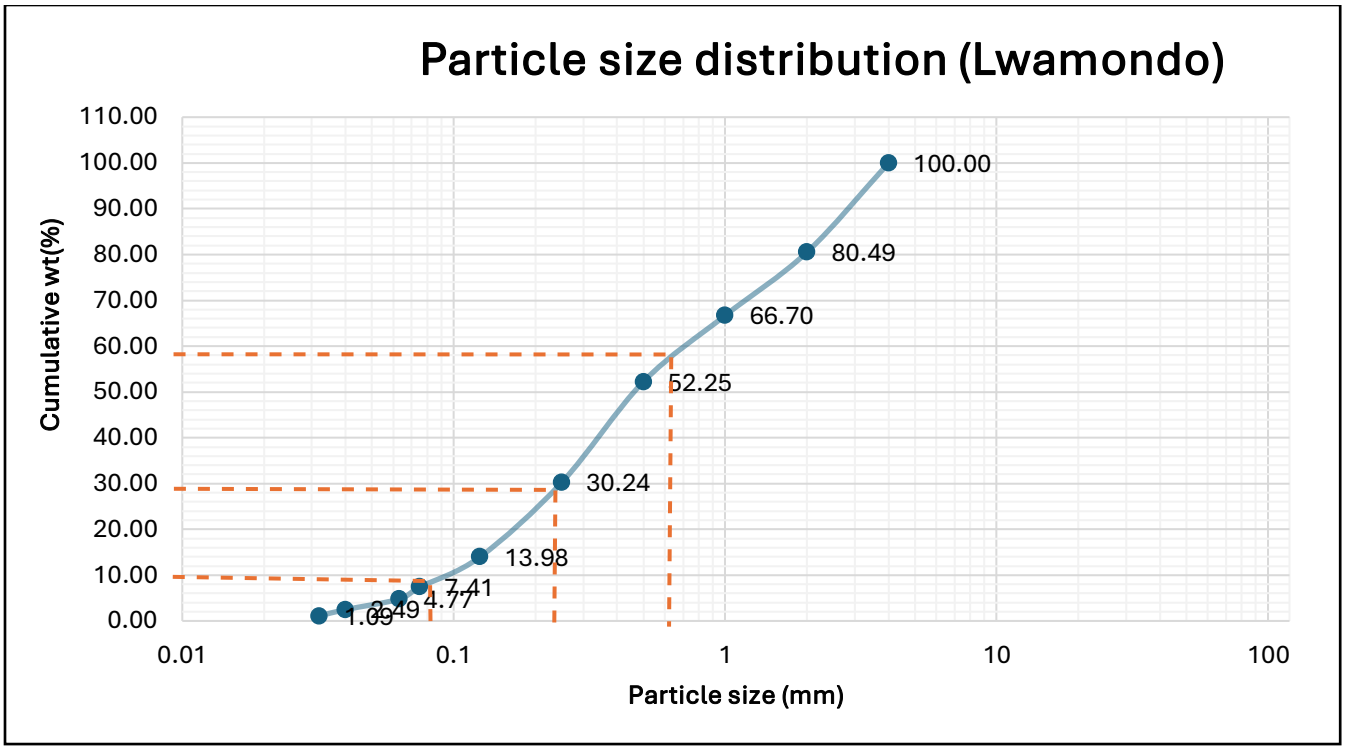

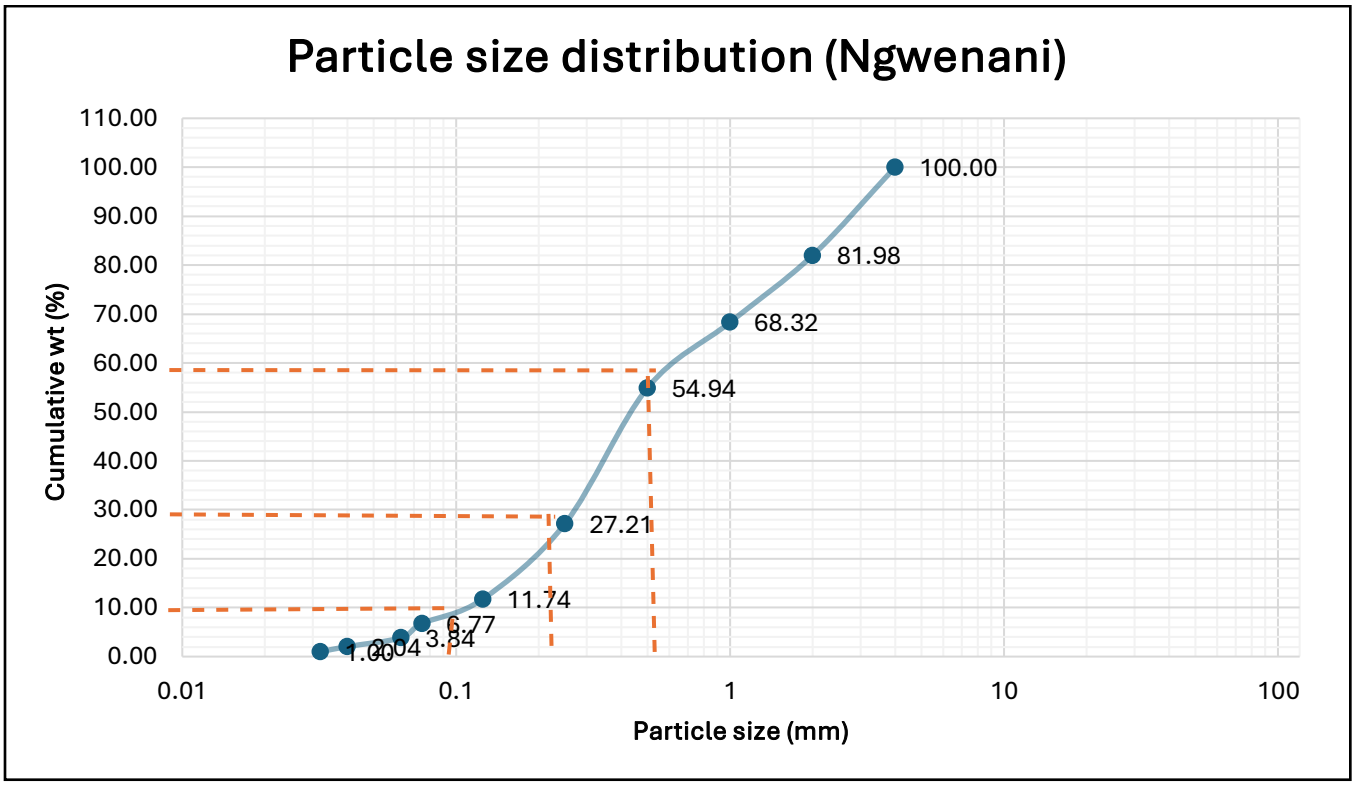

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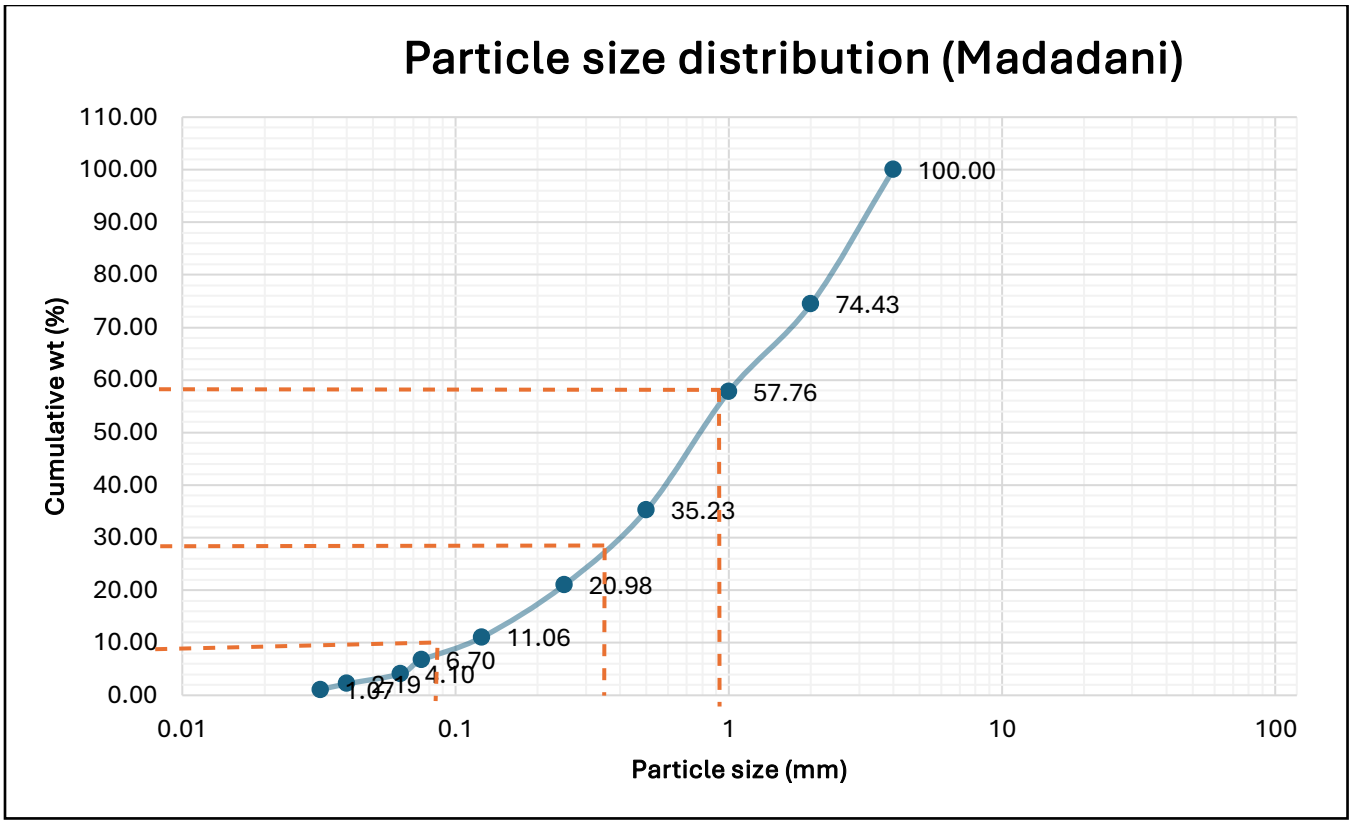

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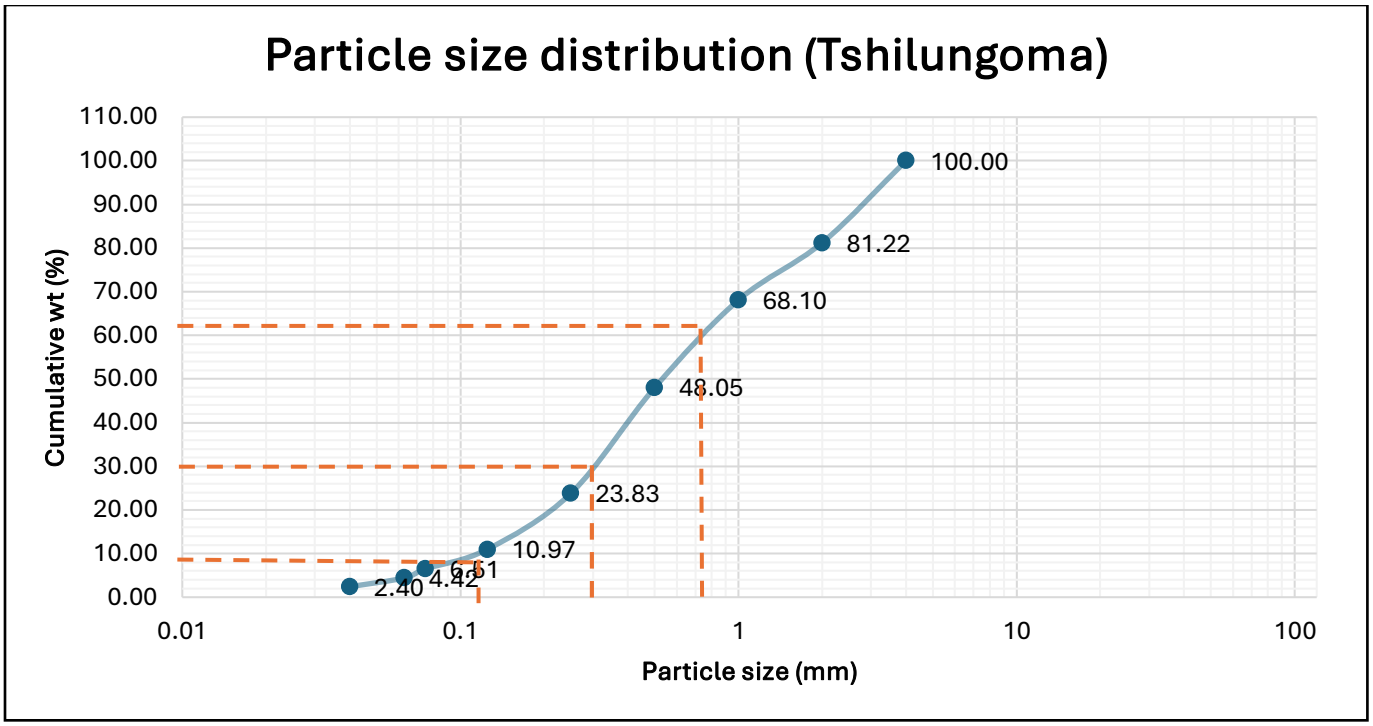

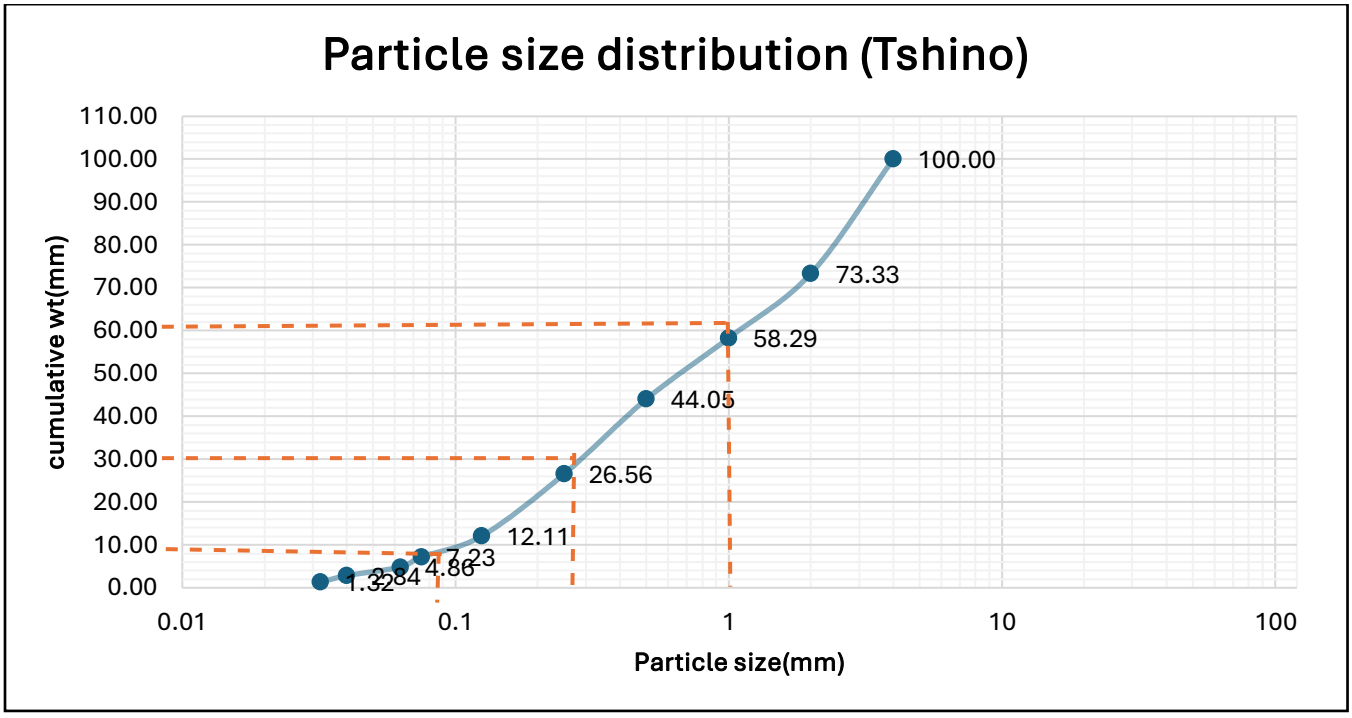

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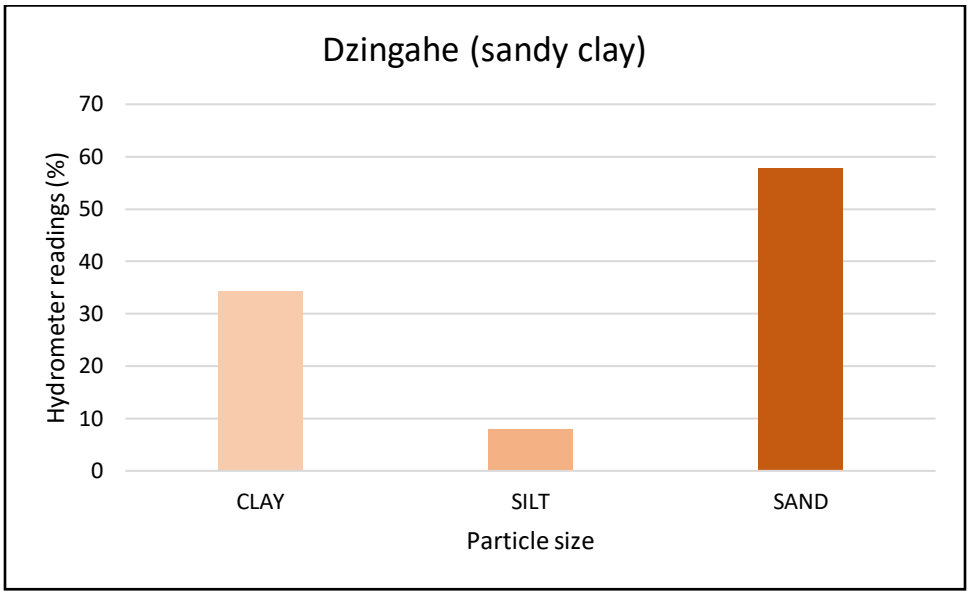
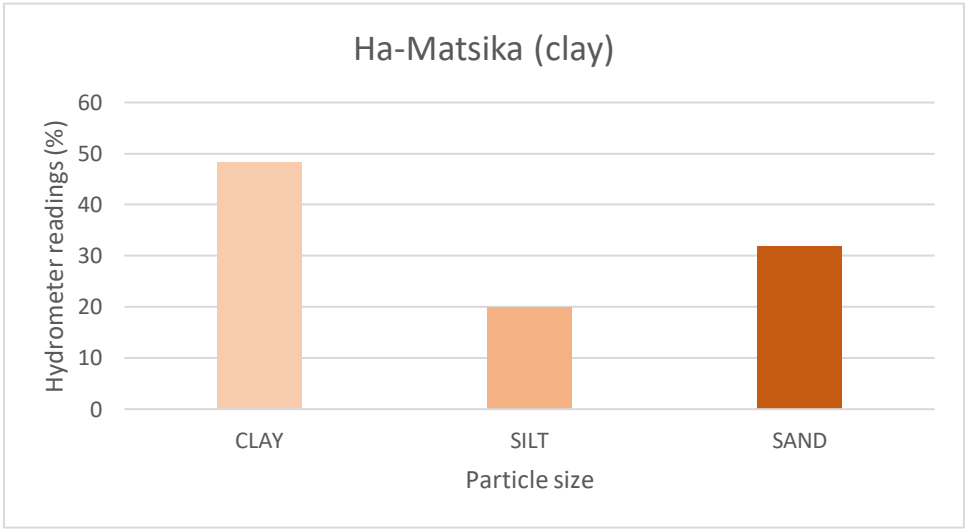
Appendix C: Hydrometer Analysis Results





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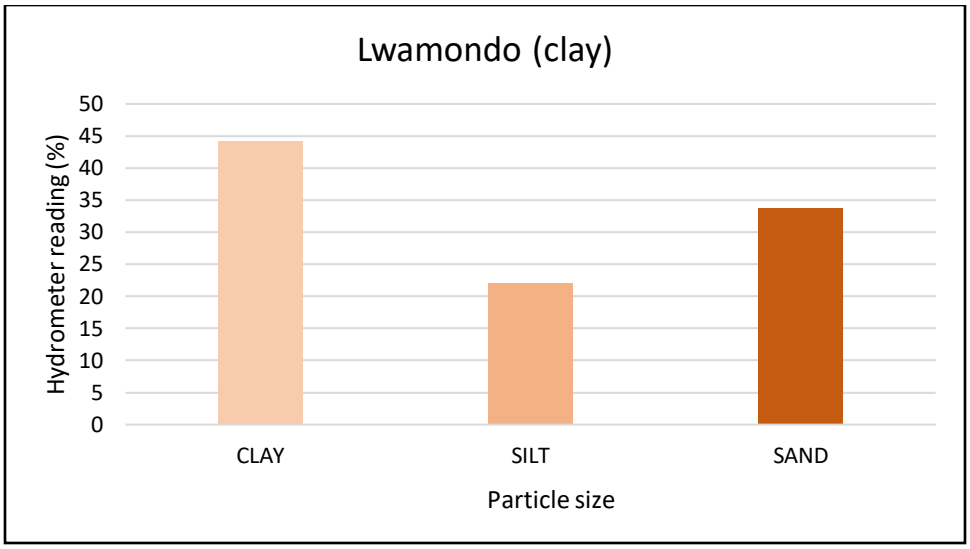

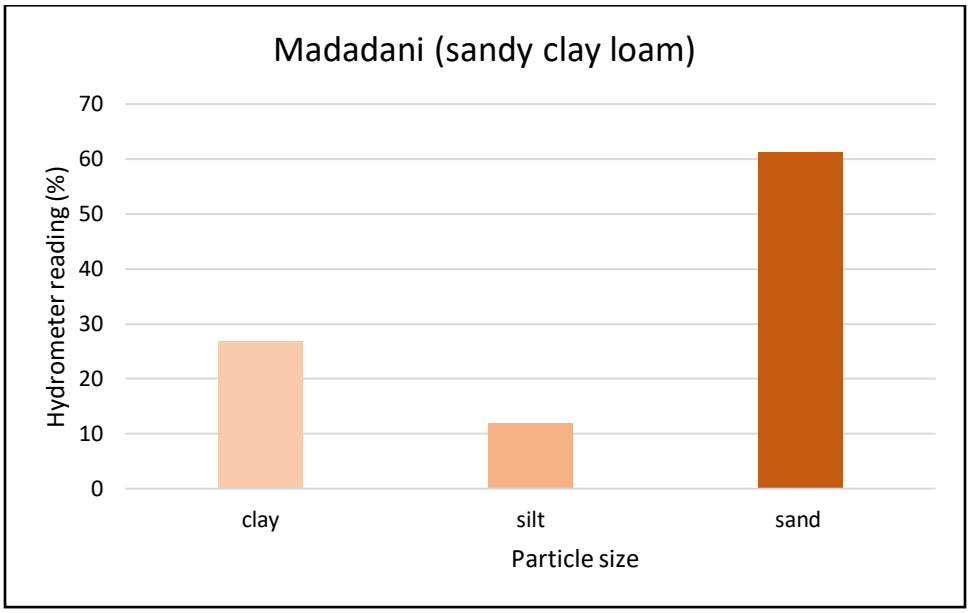

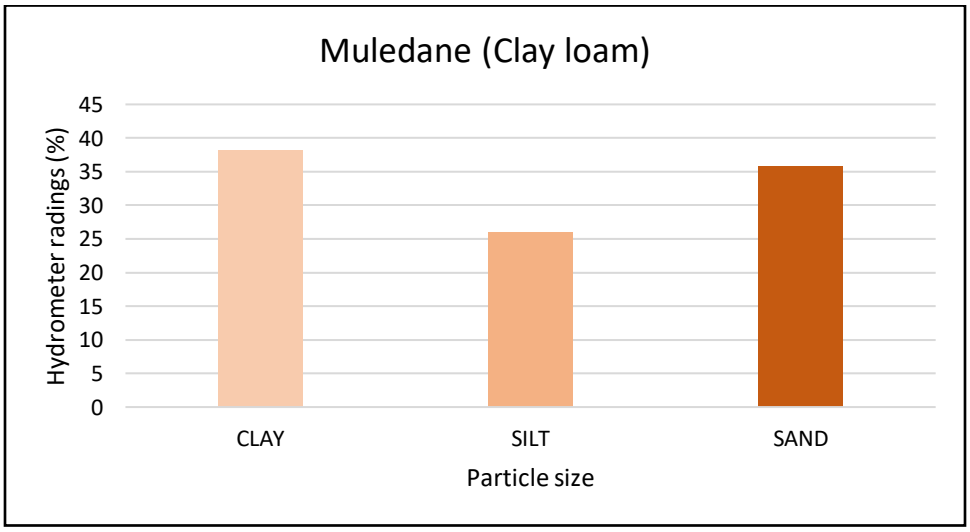

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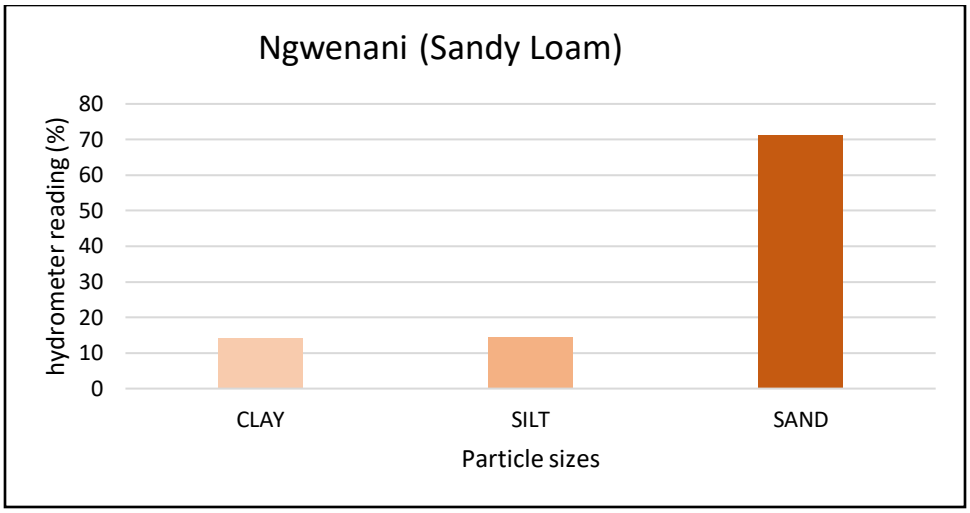

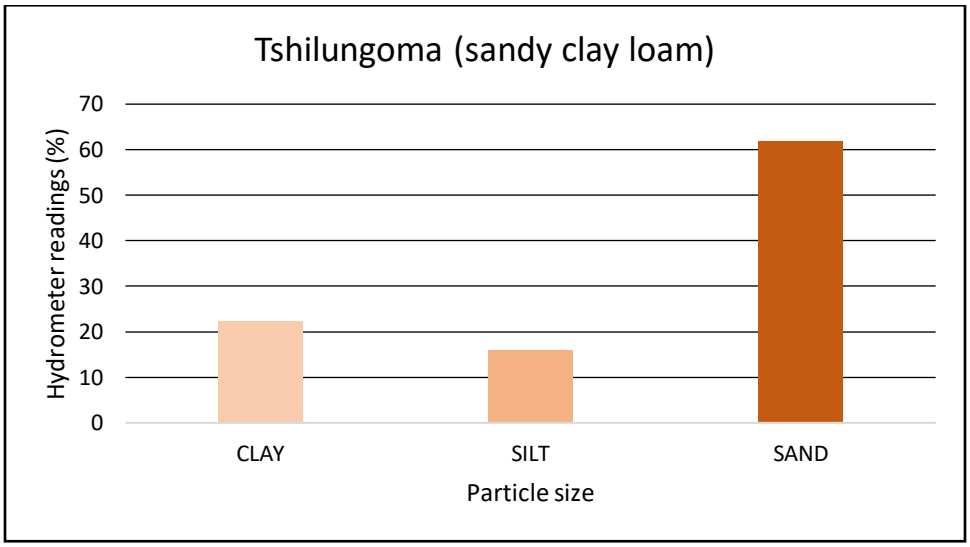

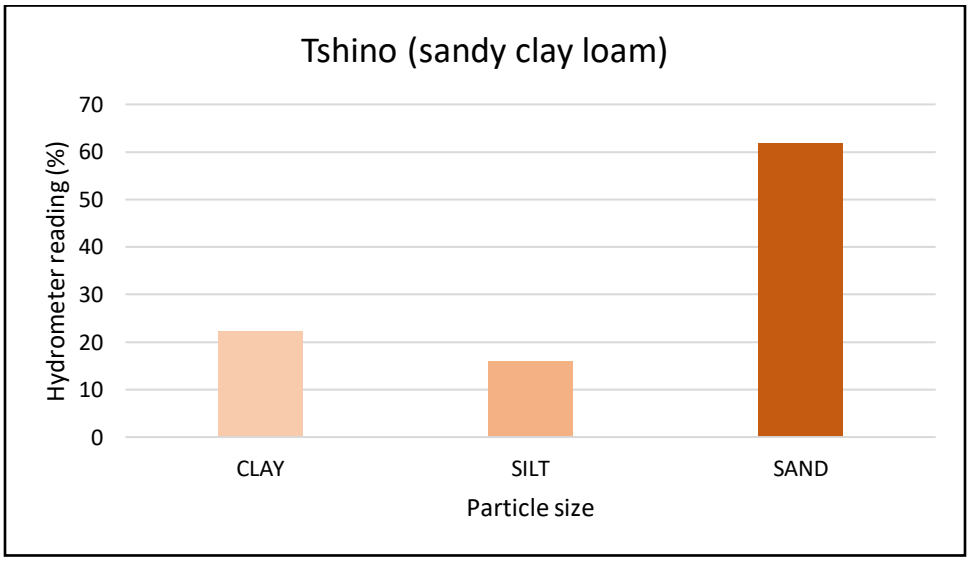

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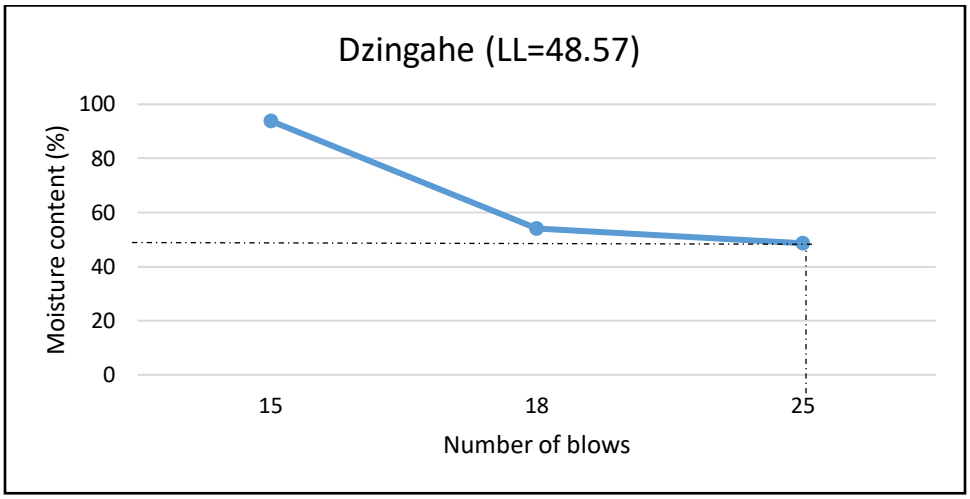
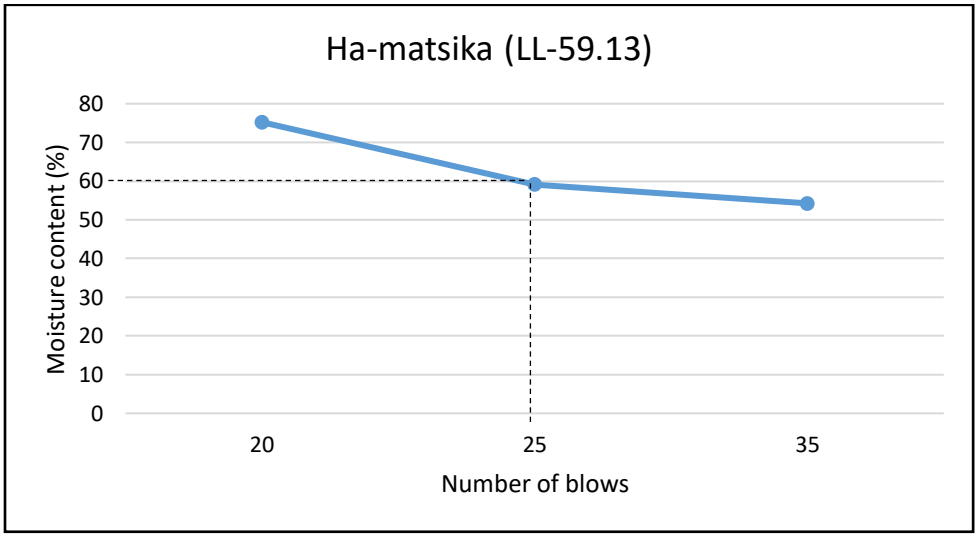
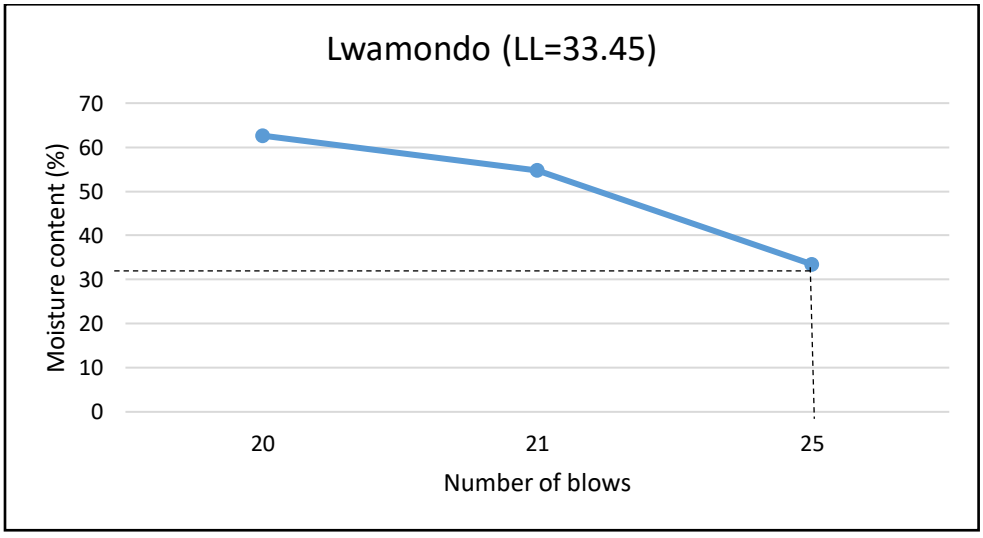
Appendix D: Atterberg Limits Results







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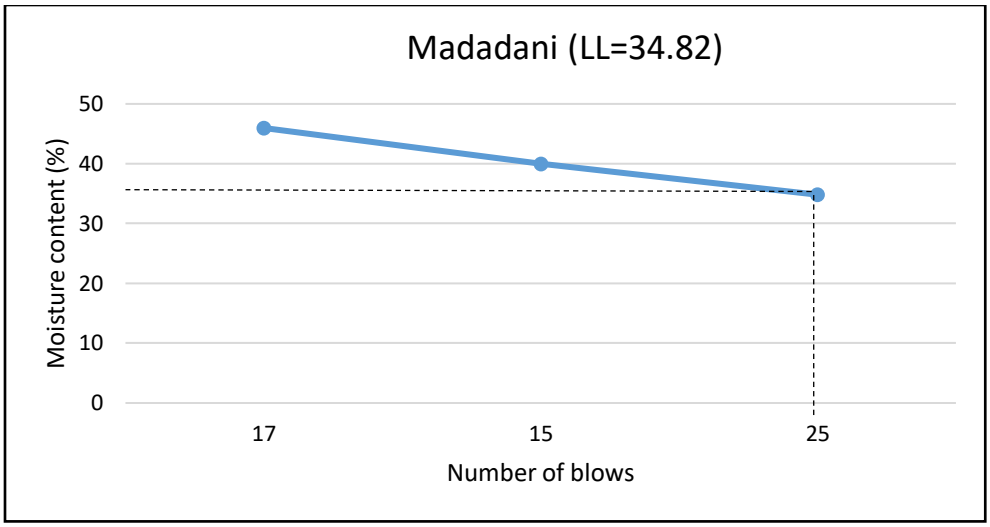

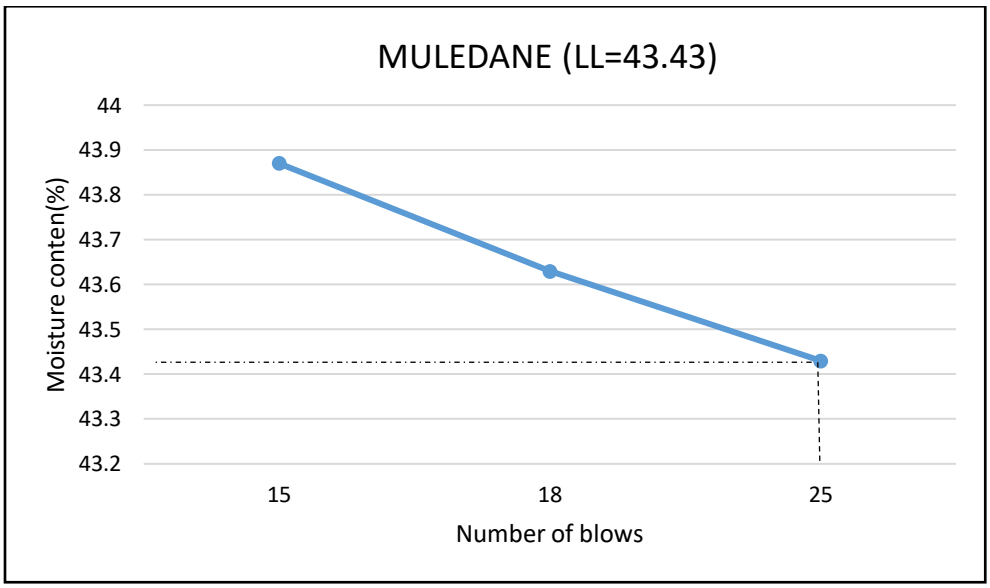

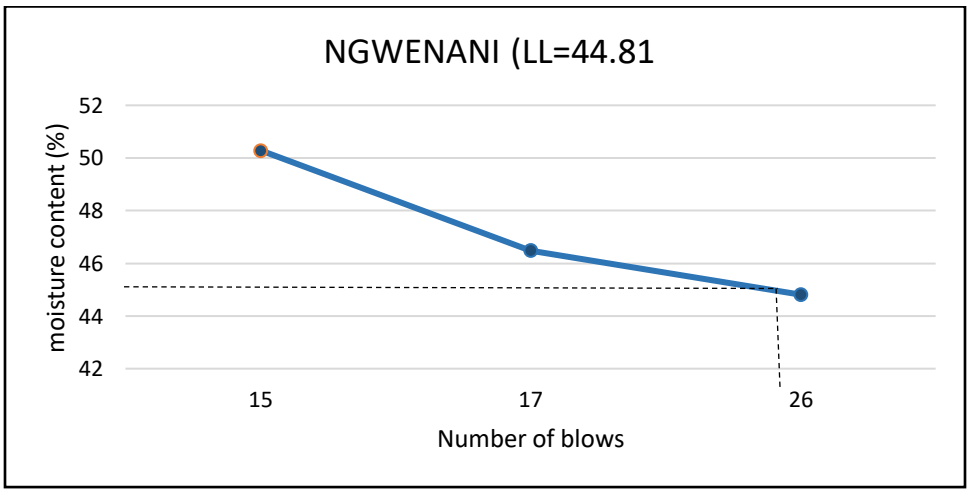

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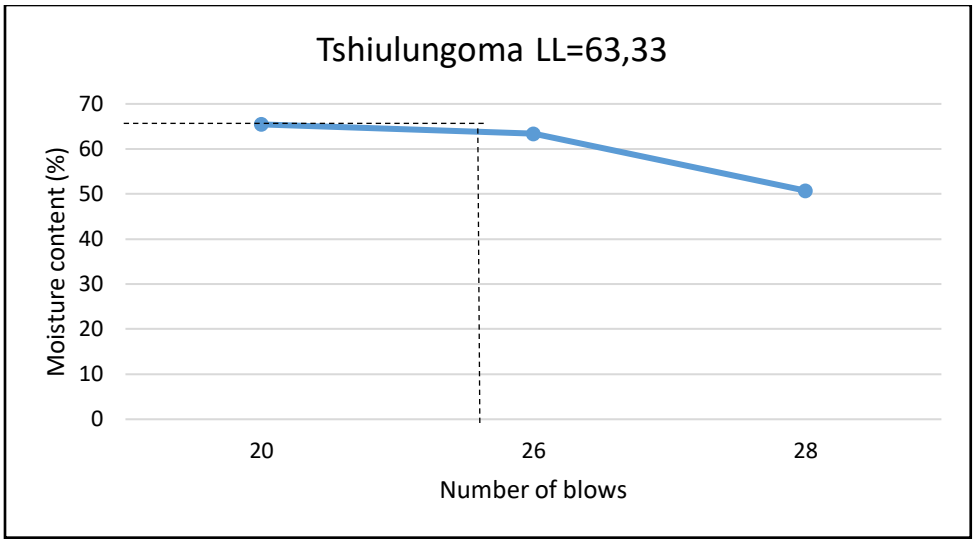

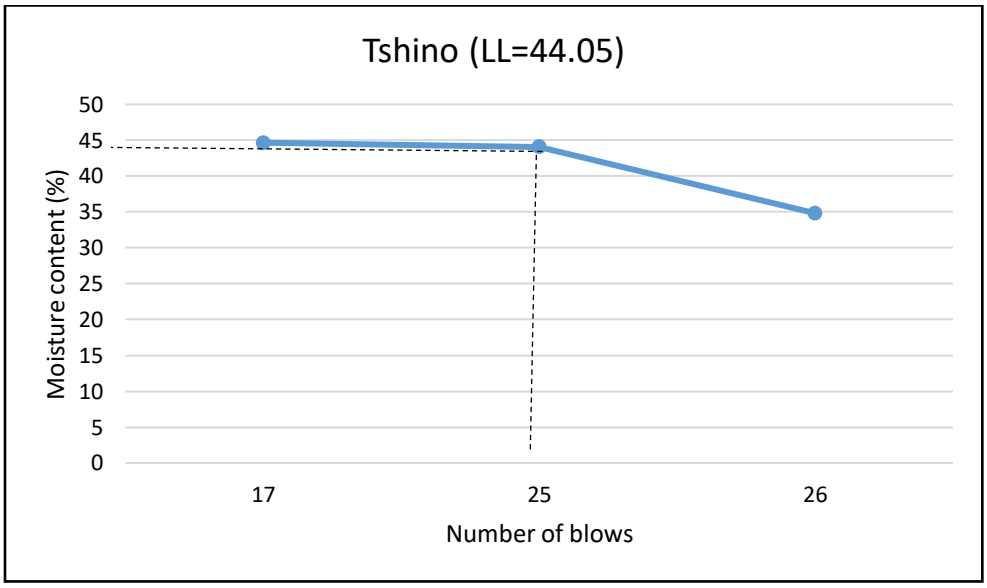

Appendix E: X-ray Fluorescence (XRF) Analysis Results

00525-GeoChem. pdz	Assay Time: 11/20/2023	Elapsed Time: 0
Dzingahe		
Alloy 1:	Match No:	
Field Info Operator	User	Name Murendeni

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Element Name	Min			
	0	0.605	0	0.415
Al_2O_3	0	14.875	0	0.229
SiO_2	0	35.100	0	0.225
TiO_2	0	1.422	0	0.009
Fe_2O_3	0	10.022	0	0.033

00533 -GeoChem. pdz	Assay Time: 11/20/2023	Elapsed Time: 0
Alloy 1:	Match No:	

Ha-Matsika

Field Info
Operator
User Name Murendeni

Element Name	Min			
	0	0.907	0	0.455
Al_2O_3	0	14.530	0	0.235
SiO_2	0	33.643	0	0.223
TiO_2	0	1.720	0	0.010
Fe_2O_3	0	12.887	0	0.037

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00537-GeoChem. pdz	Assay Time: 11/20/2023	Elapsed Time: 0

Lwamondo

Alloy 1:	Match No:

Field Info Operator	User	Name	Murendeni
		Field	

Element Name	Min			
	0	0.587	0	0.455
Al_2O_3	0	17.967	0	0.264
SiO_2	0	27.674	0	0.204
TiO_2	0	1.867	0	0.011
Fe_2O_3	0	15.550	0	0.040

00545-GeoChem. pdz	Assay Time: 11/20/2023	Elapsed Time: 0

Madadani

Alloy 1:	Match No:

Field Info Operator	User	Name	Murendeni

Element Name	Min			
	0	0.798	0	0.401
Al_2O_3	0	13.866	0	0.221
SiO_2	0	33.415	0	0.219
TiO_2	0	1.315	0	0.009
Fe_2O_3	0	9.945	0	0.033

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00514-GeoChem. pdz	Assay Time: 11/20/2023	Elapsed Time: 0
Alloy 1:	Match No:	
Muledane		
Field Info Operator User Name Murendeni		

Element Name	Min			
	0	0.819	0	0.417
Al_2O_3	0	0.949	0	0.218
SiO_2	0	34.129	0	0.222
TiO_2	0	1.888	0	0.011
Fe_2O_3	0	10.558	0	0.034

00541 -GeoChem. pdz	Assay Time: 11/20/2023	Elapsed Time: 0
Alloy 1:	Match No:	
Ngwenani		
Field Info Operator User Name Murendeni		

Element Name	Min			
	0	0.786	0	0.407
$A1_20_3$	0	15.673	0	0.231
$Ti0_2$	0	1 .348	0	0.009
Fe_20_3	0	9.795	0	0.033

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00521 -GeoChem. pdz	Assay Time: 11/20/2023 4:41	Elapsed Time: 0
Alloy 1:	Match No:	
Tshilungoma		
Field Info Operator User Name Murendeni		

Element Name	Min			
	0	0.845	0	0. 391
Al_2O_3	0	11 988	0	0.202
SiO_2	0	37.314	0	0.228
TiO_2	0	1.159	0	0.009
Fe_2O_3	0	7.753	0	0.030

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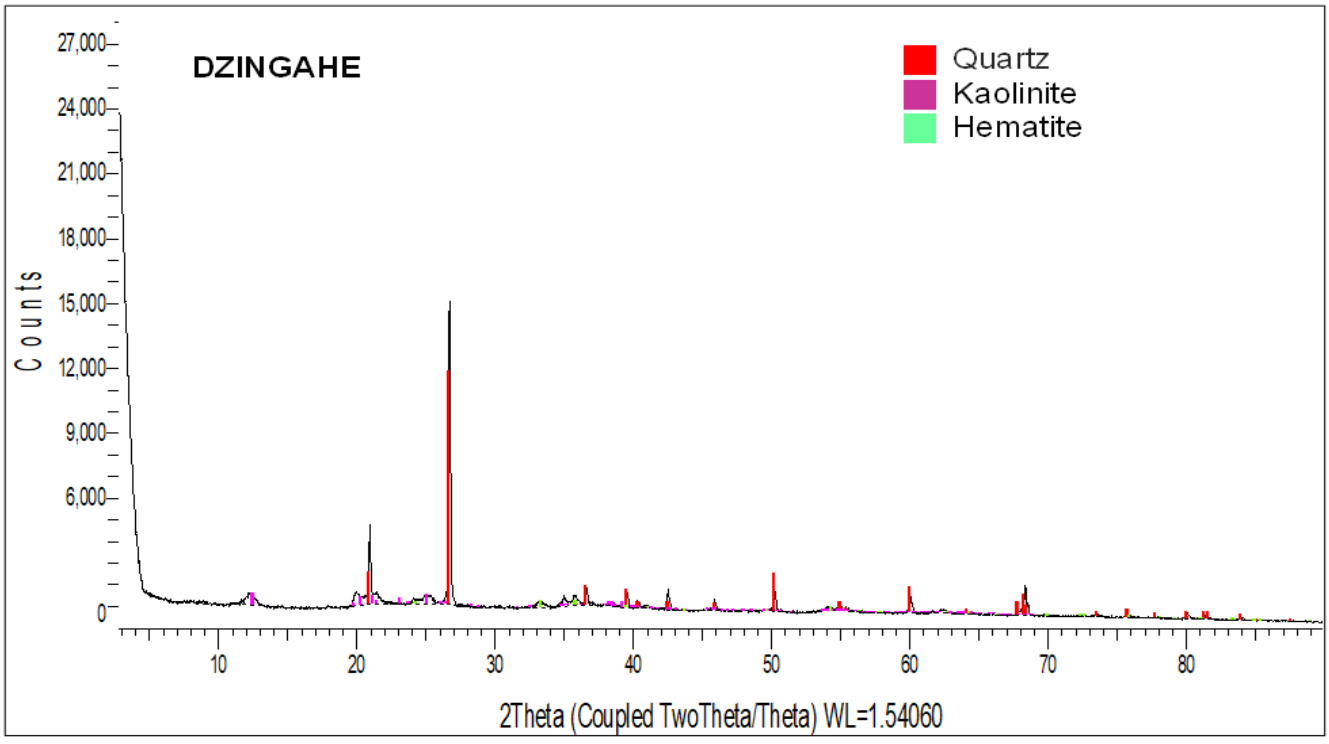
	Assay Time: 1 1 /20/2023		Elapsed Time: 0	
Alloy 1:		Match No:		
Tshino				
Field Info Operator	User	Name	Murendeni	
Element Name	Min 0	1 .190	0	0.403
Al_2O_3	0	12.236	0	0.201
SiO_2	0	37.961	0	0.229
K_2O	0	1.119	0	0.010
CaO	0	1.083	0	0.010
Fe_2O_3	0	6.574	0	0.028

Appendix F: X-Ray Diffraction (Xrd) Analysis



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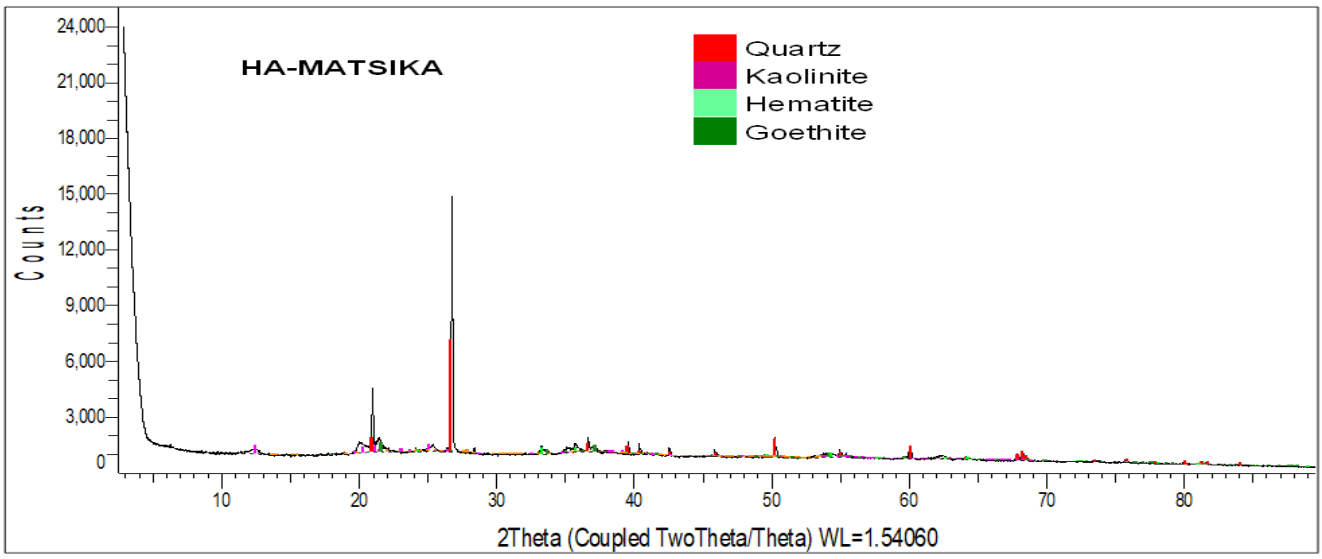

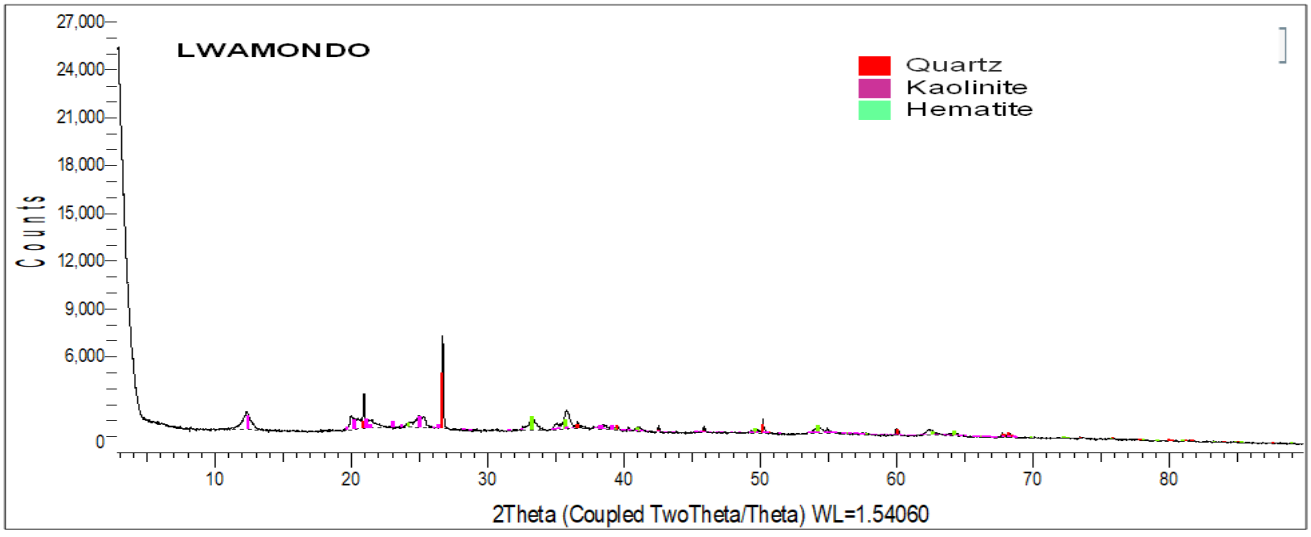

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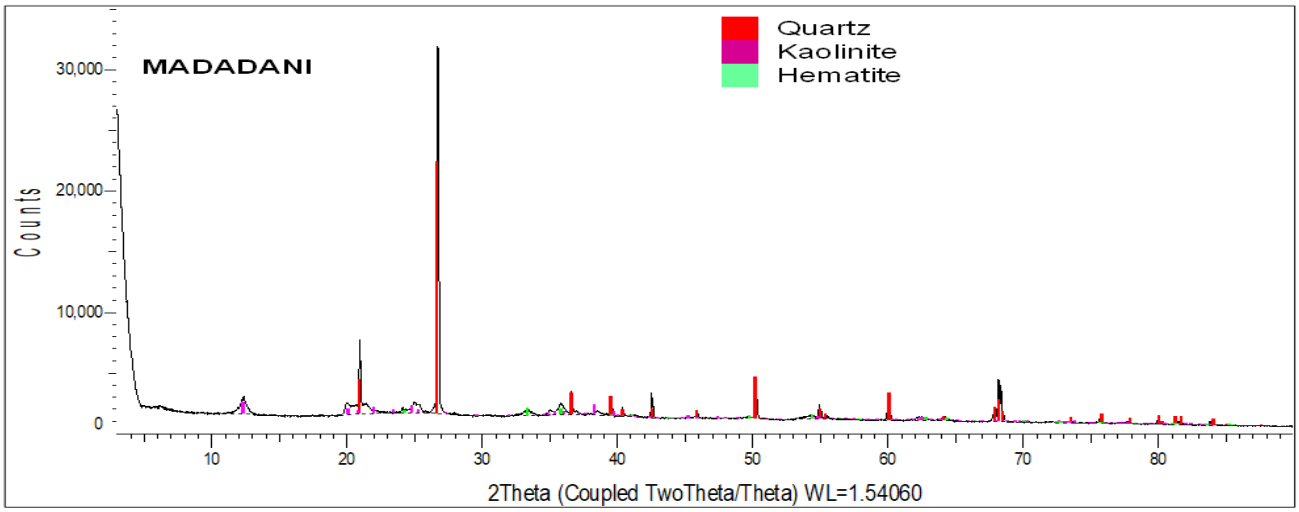

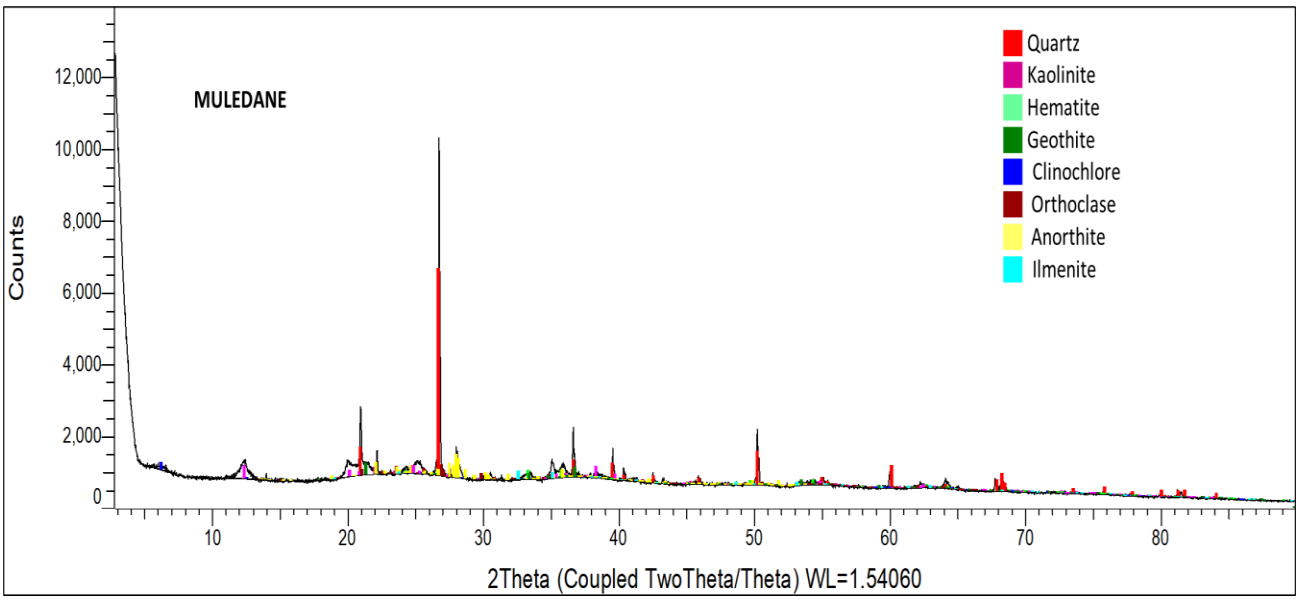

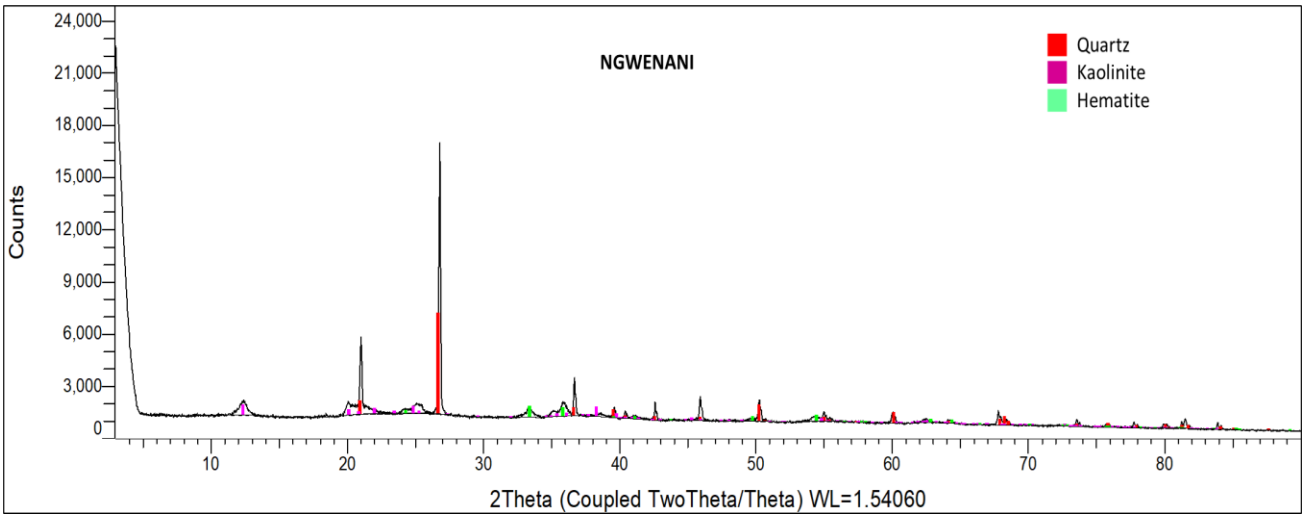

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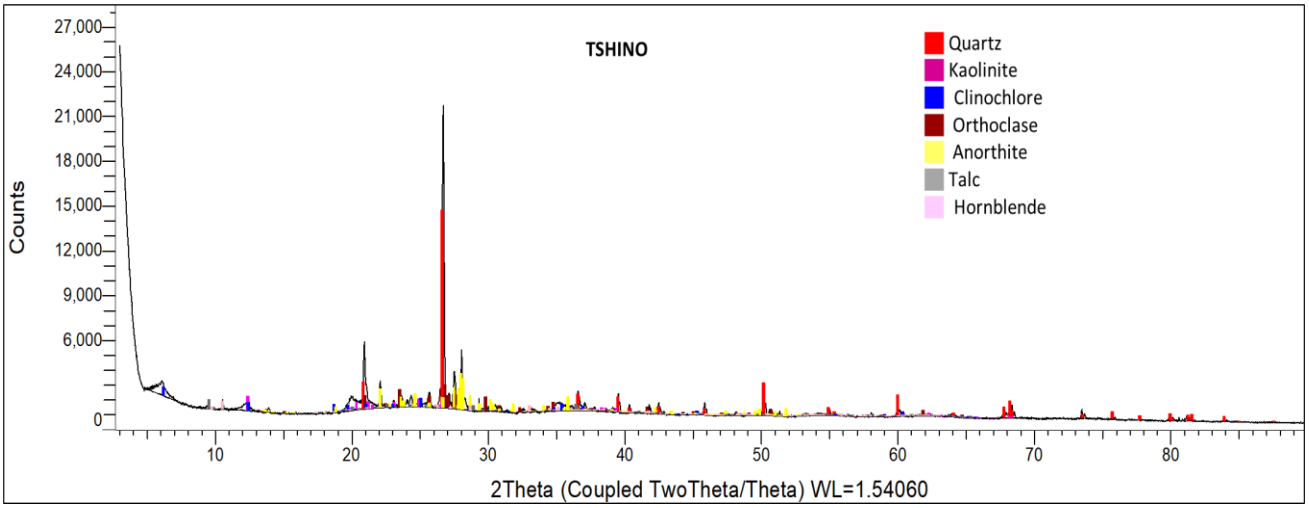
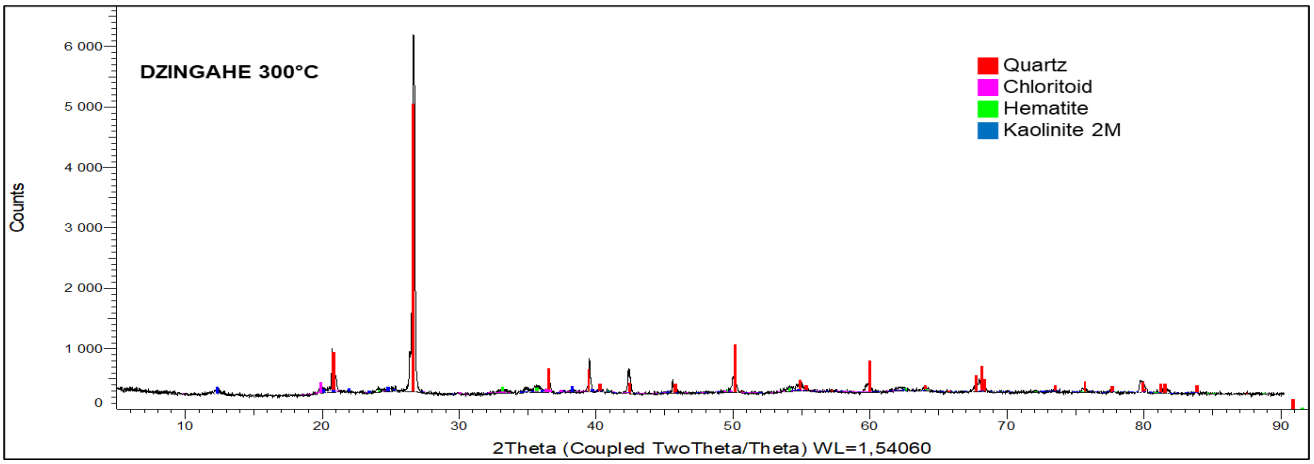
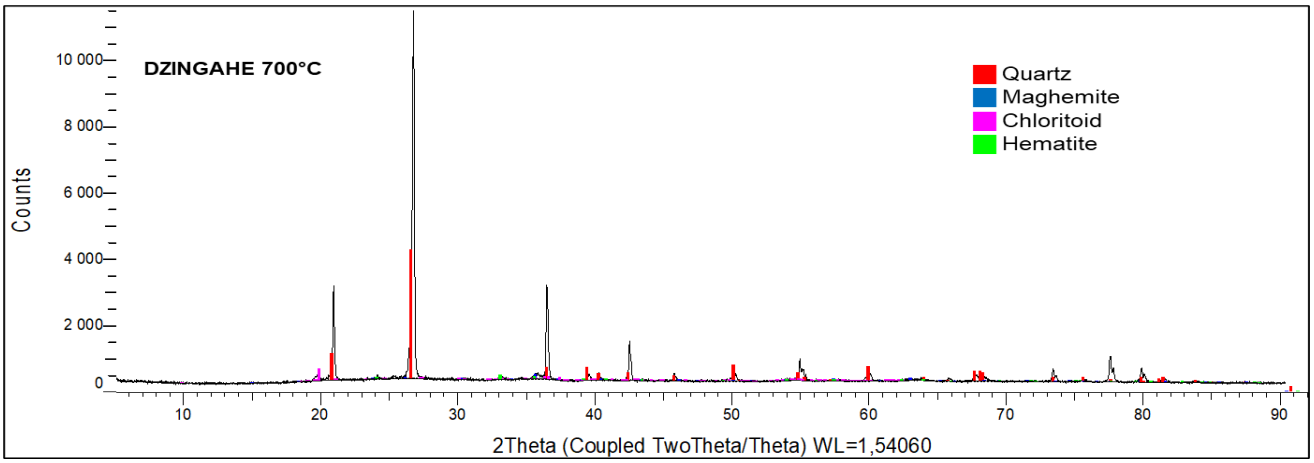


Appendix G: X-ray Diffraction (Xrd) Analysis of Fired Clay Blocks





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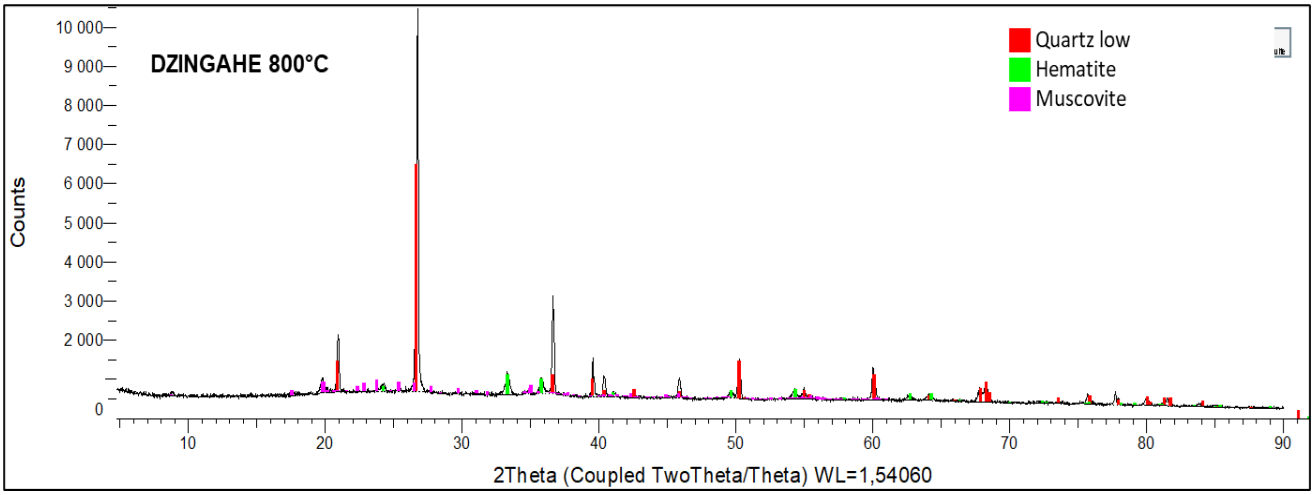

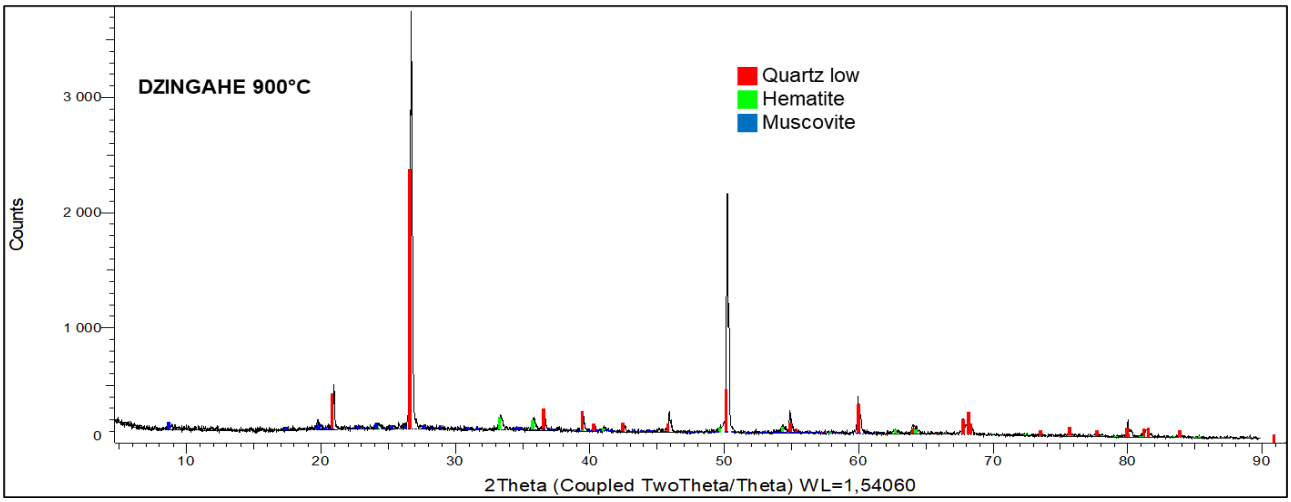

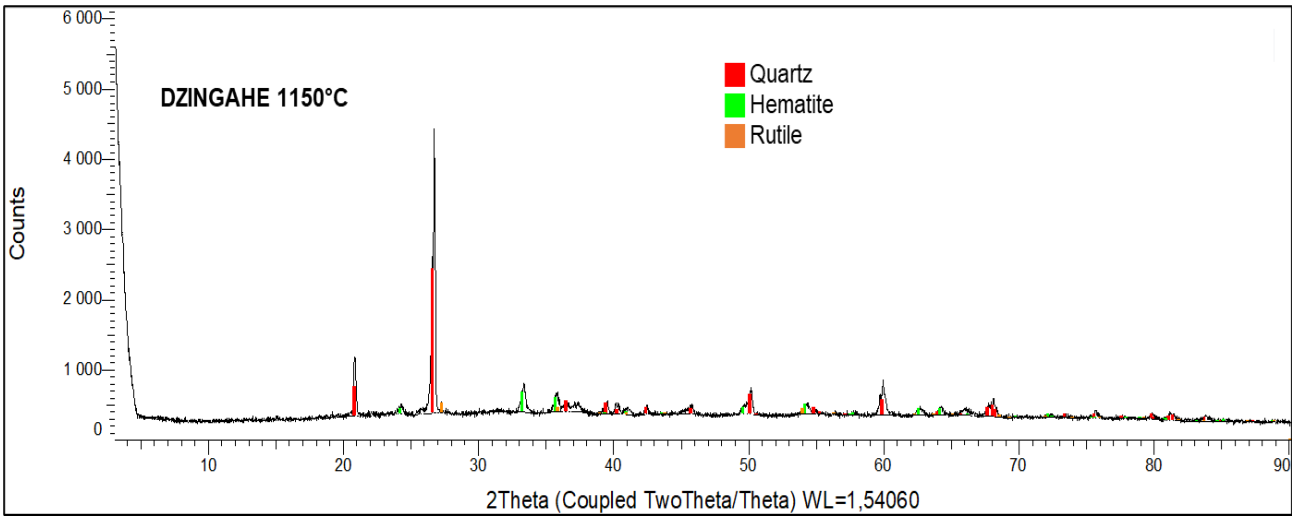

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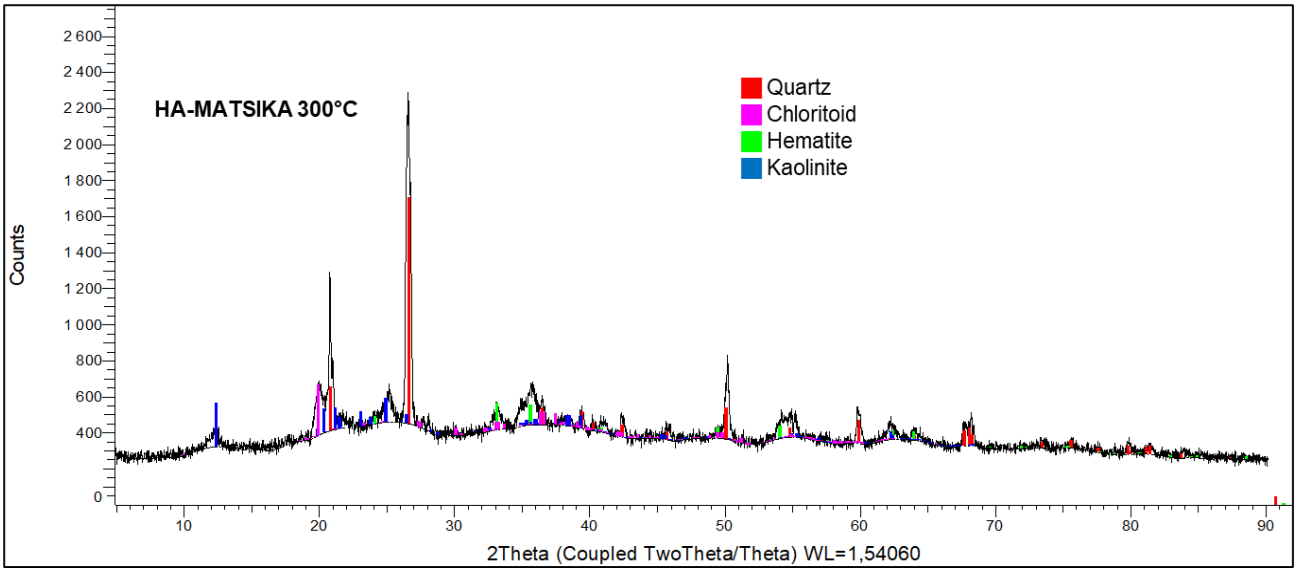

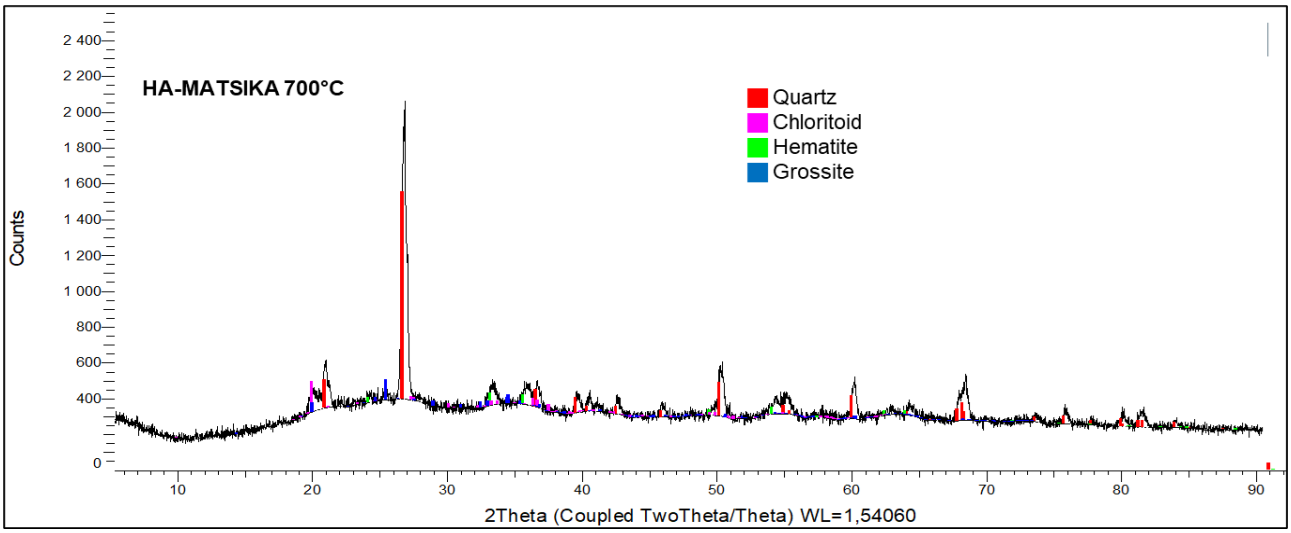

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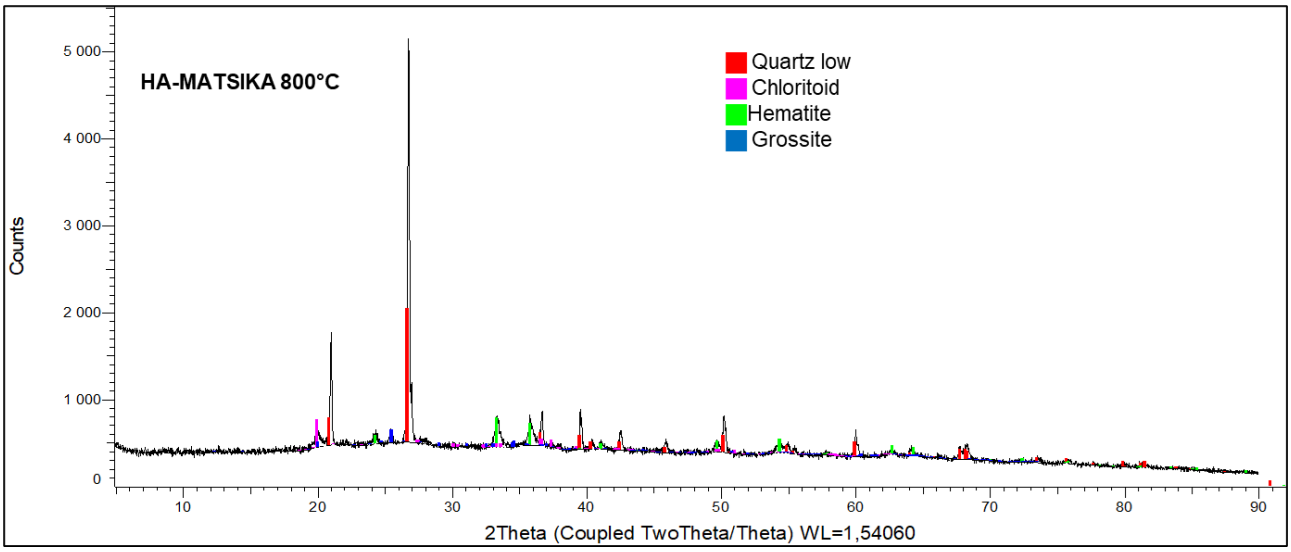

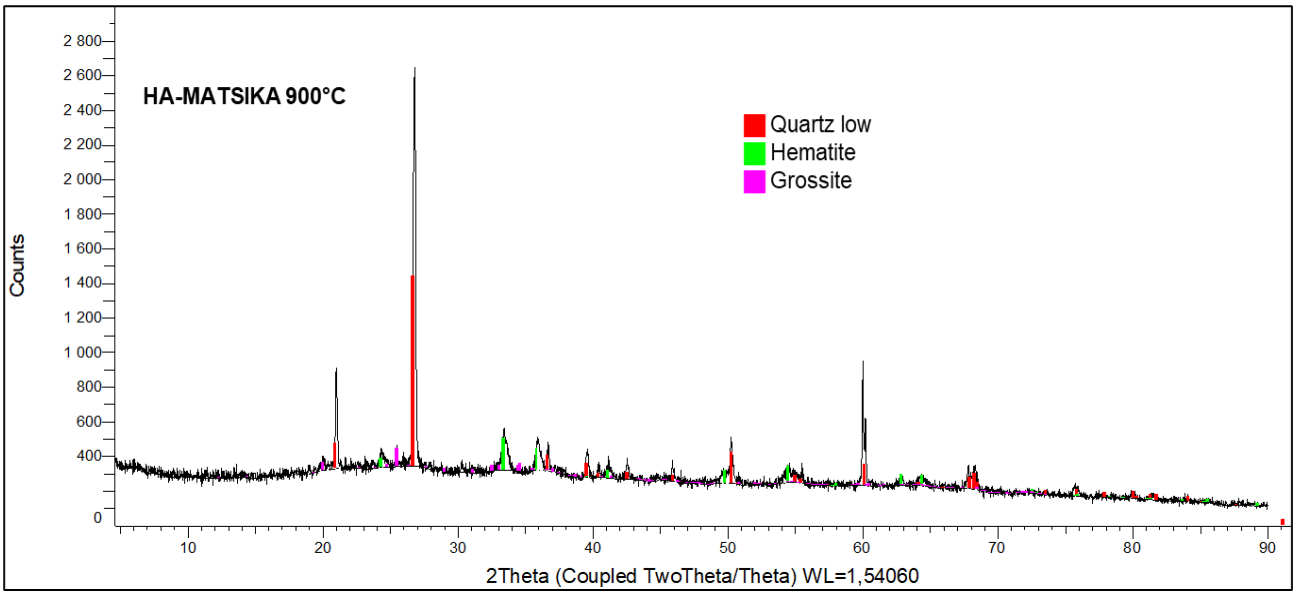

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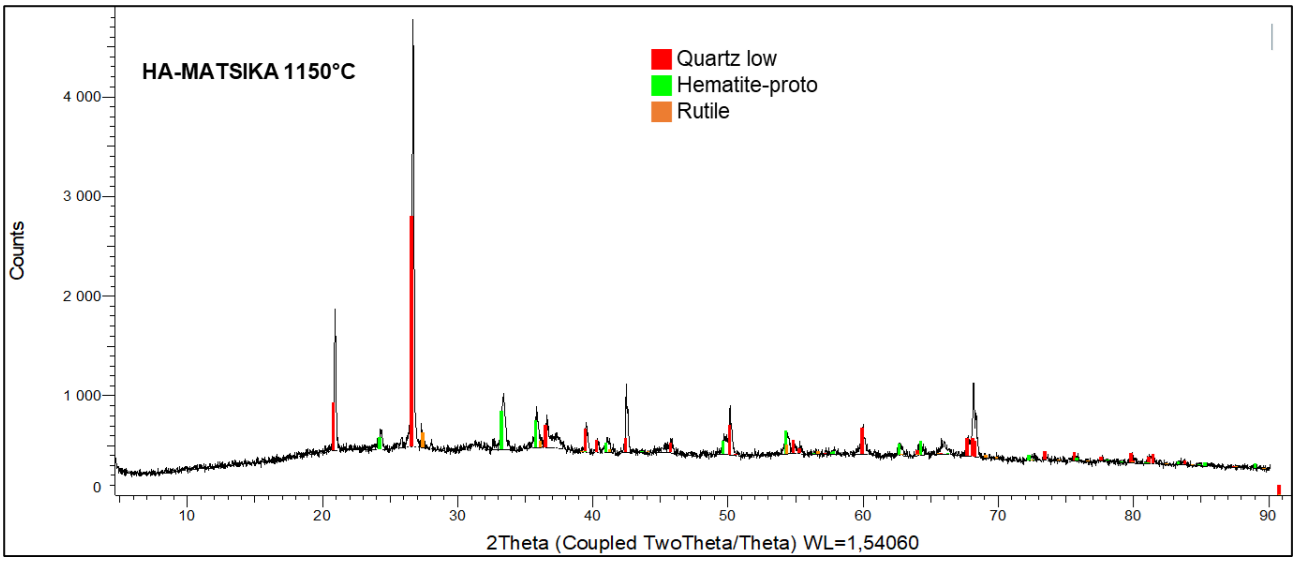

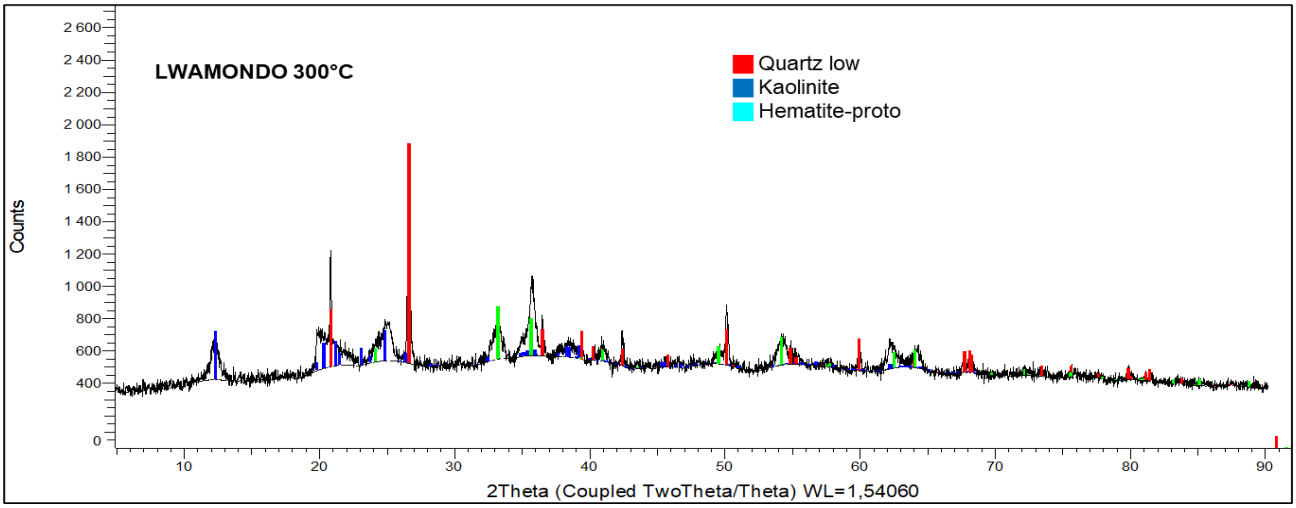

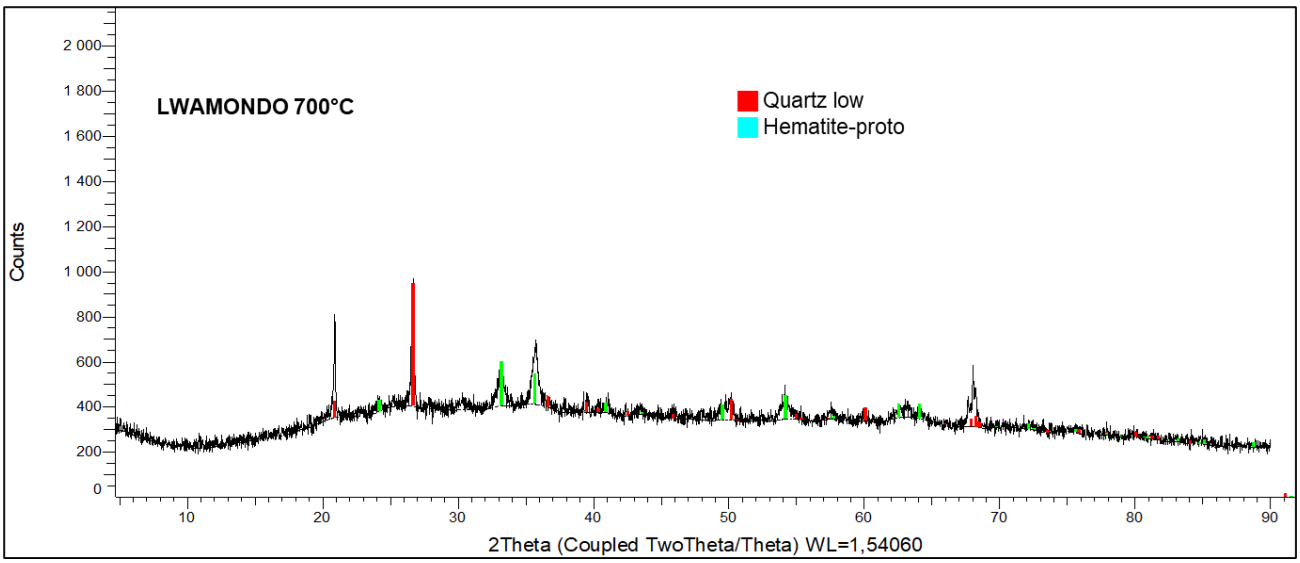

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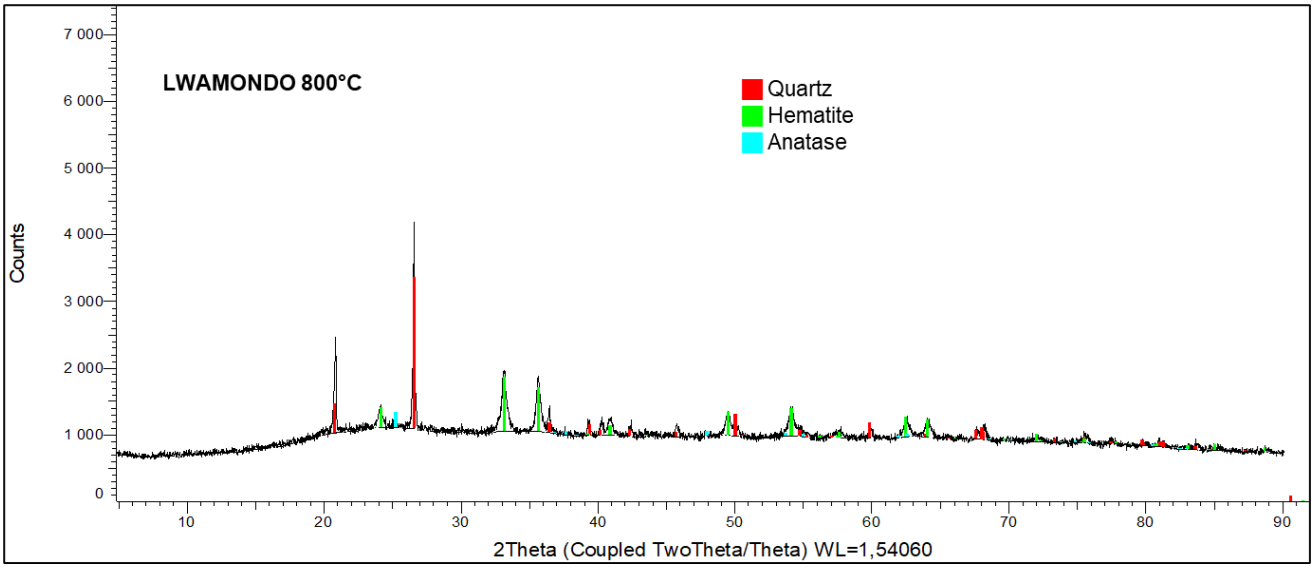

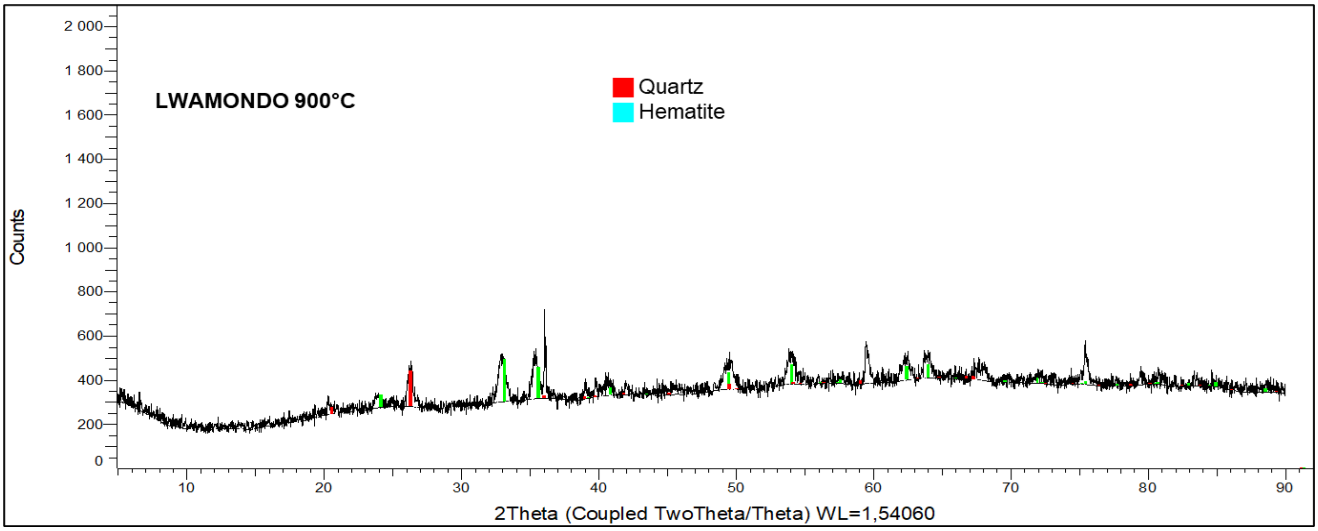

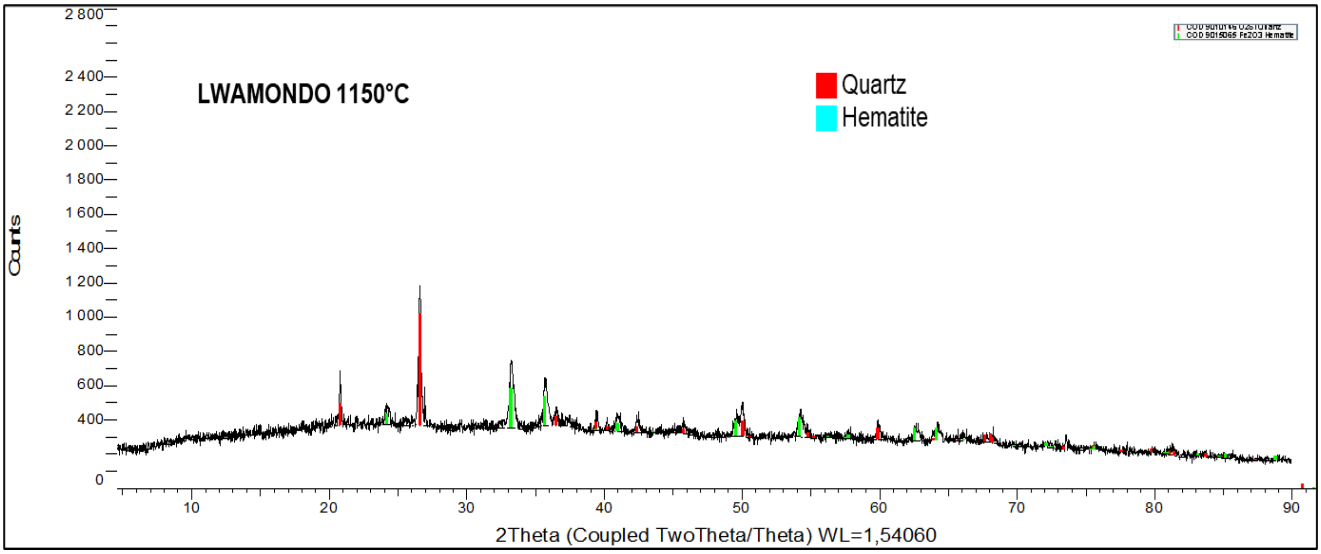

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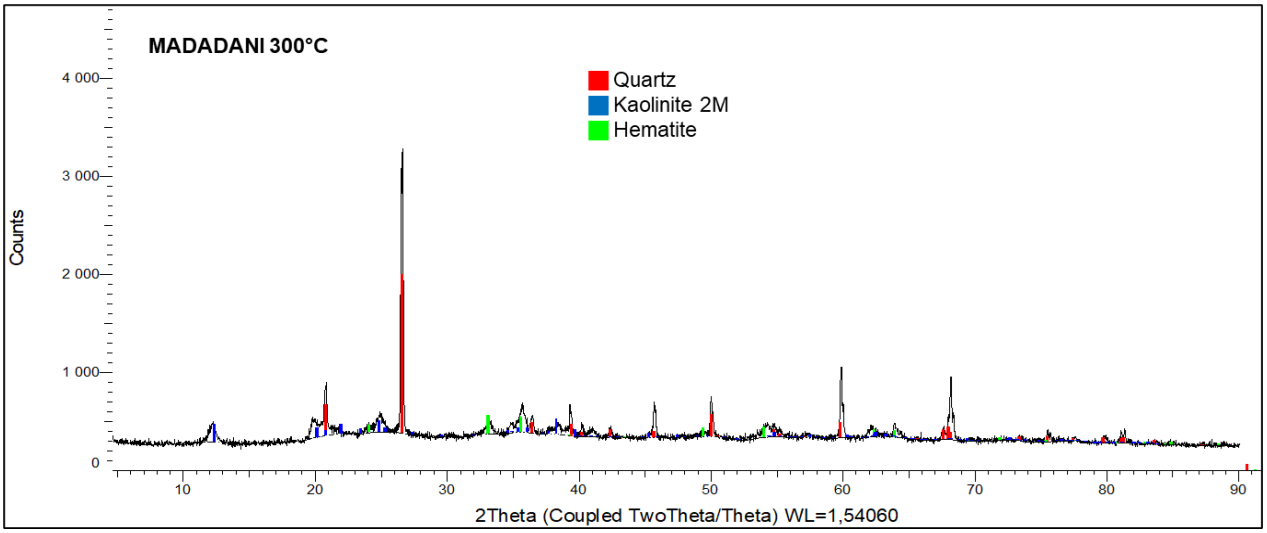

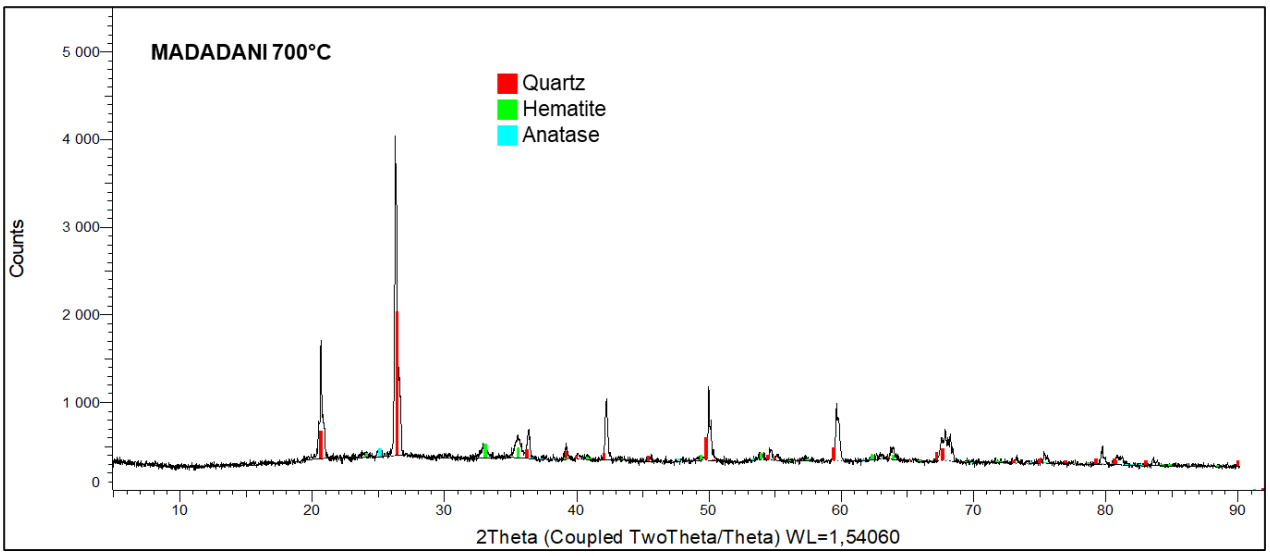

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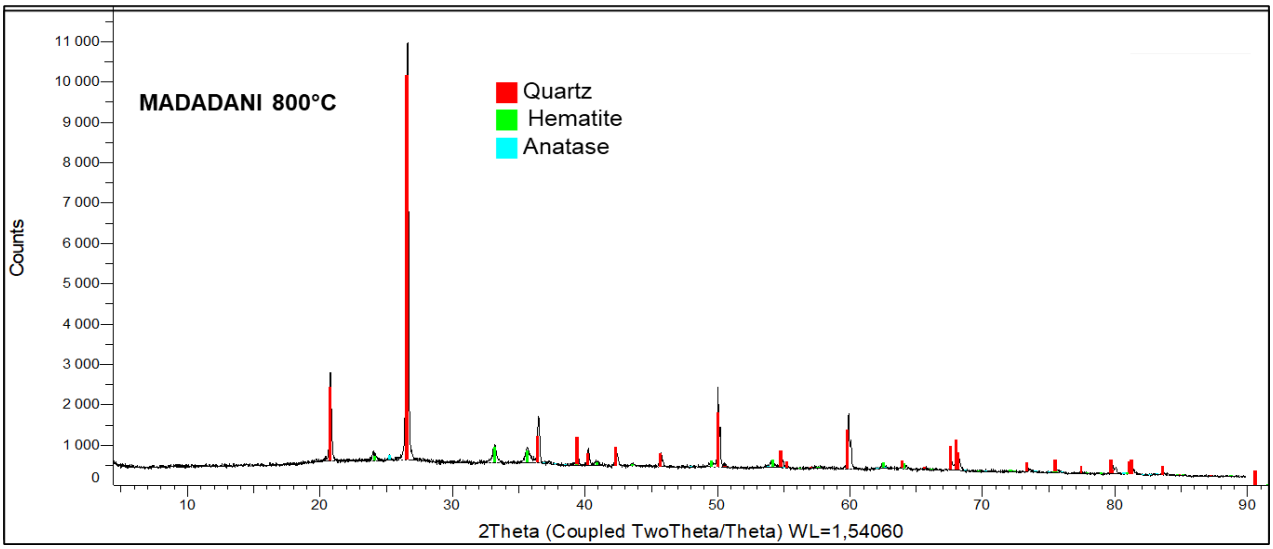

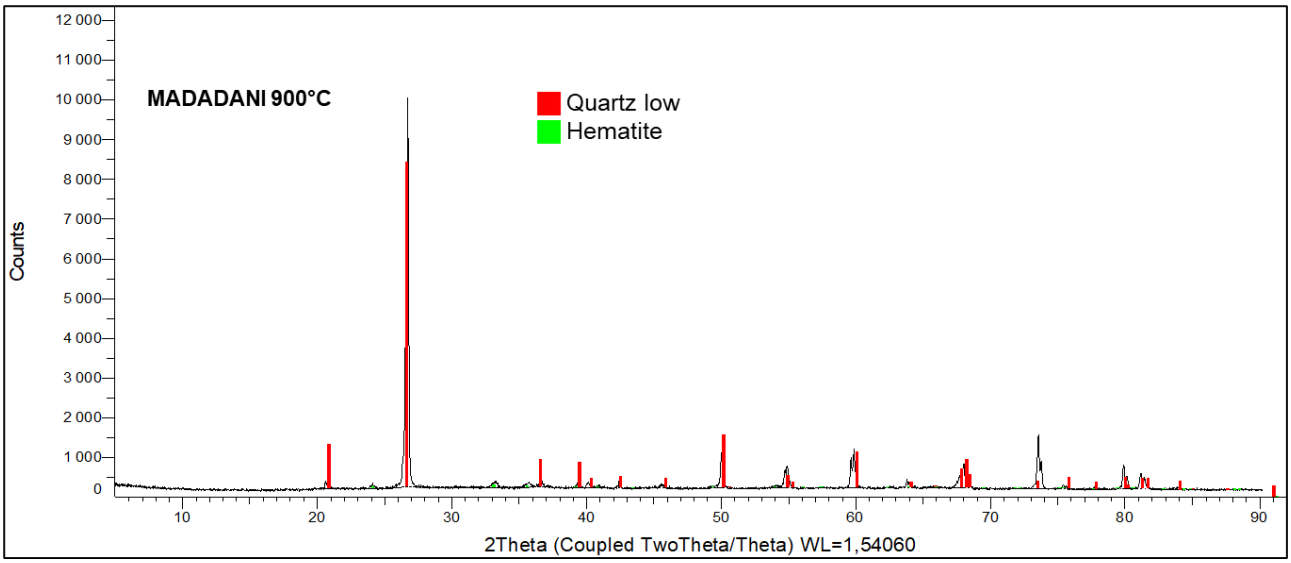

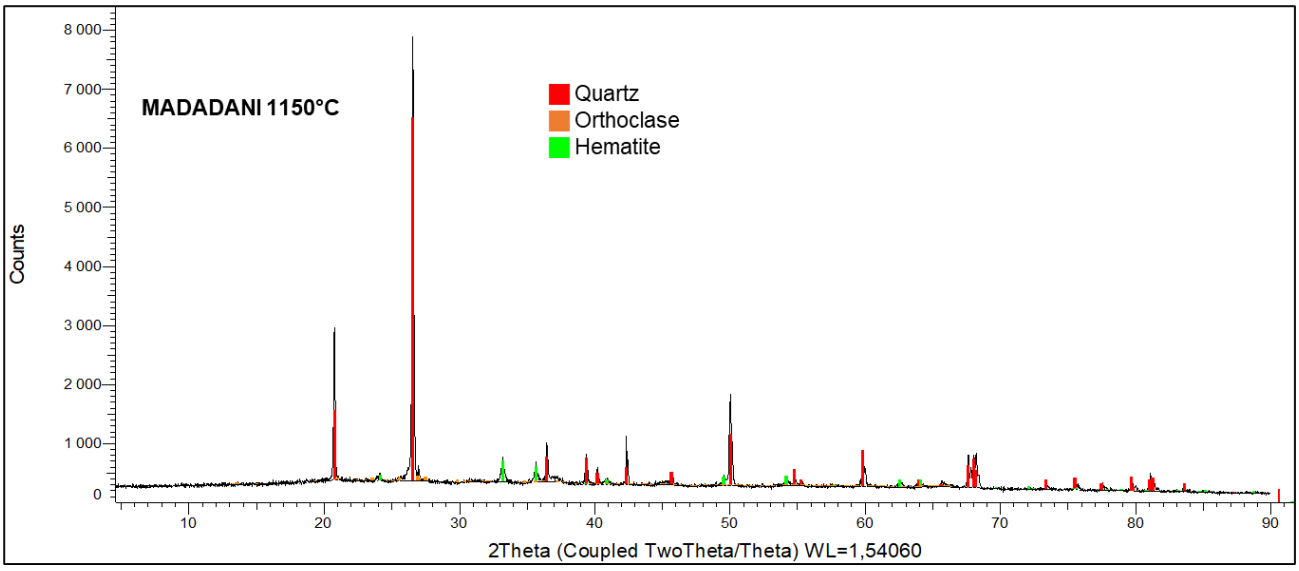

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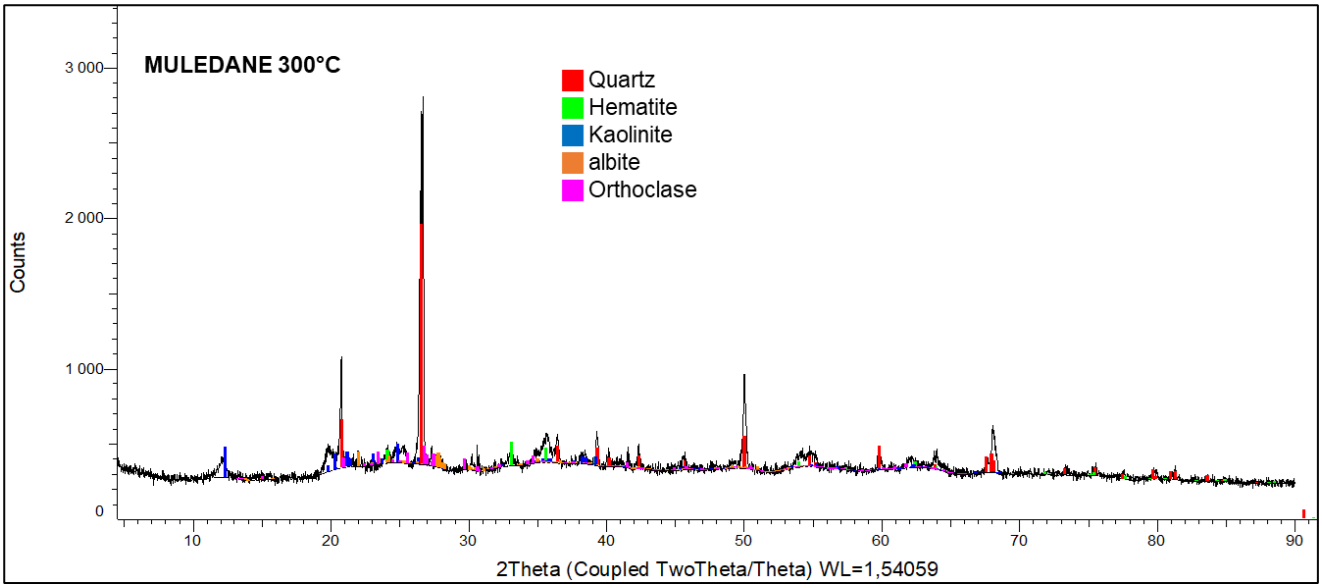

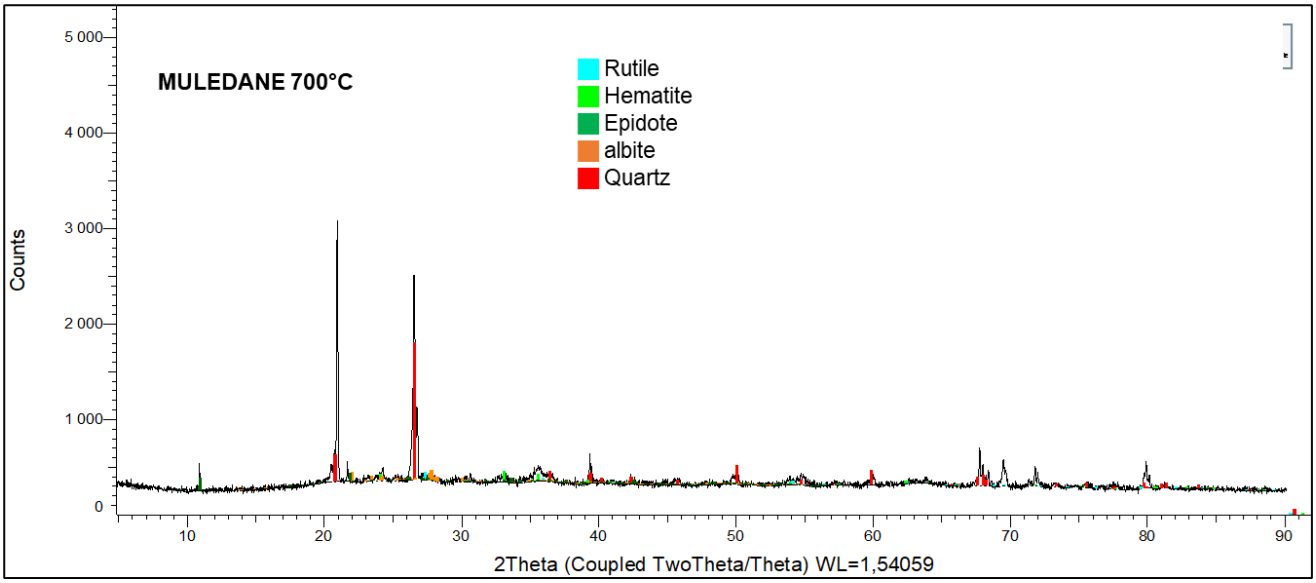

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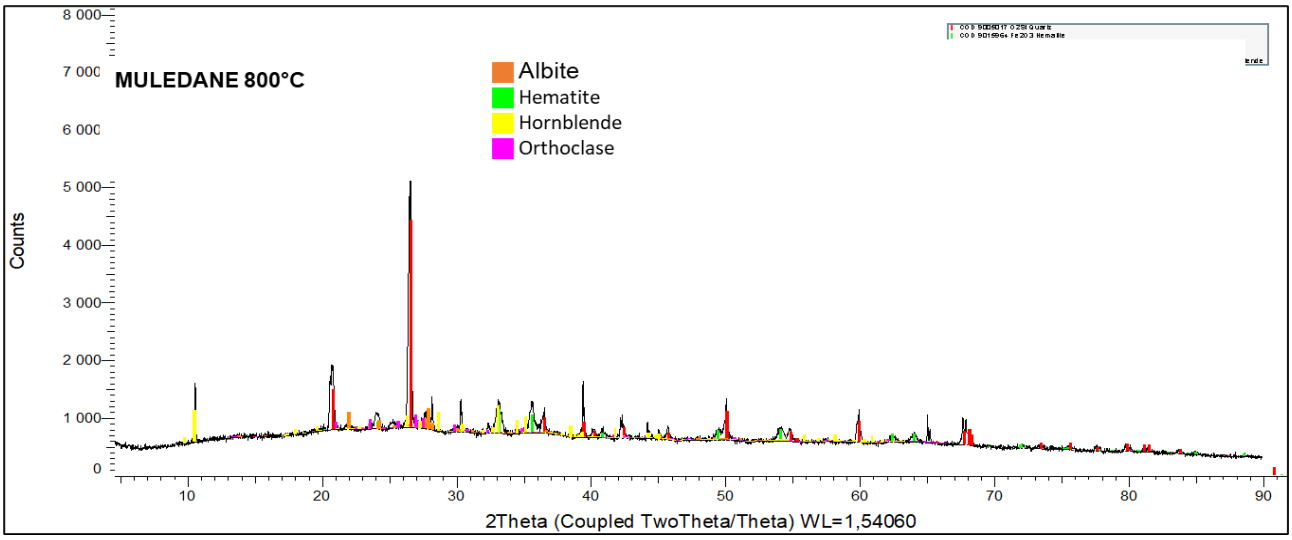

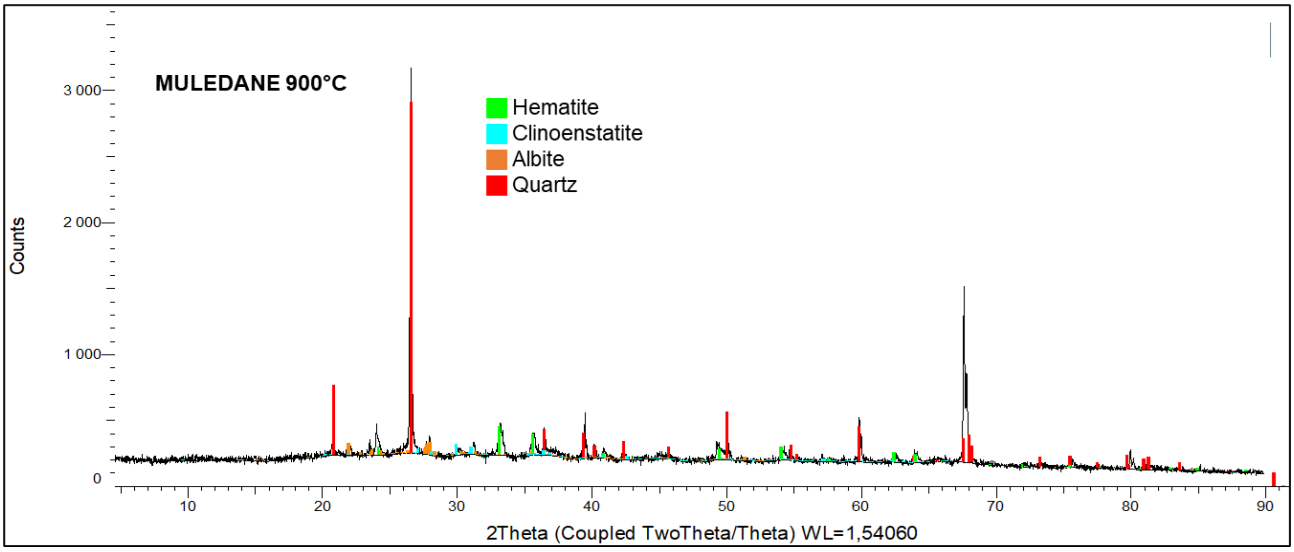

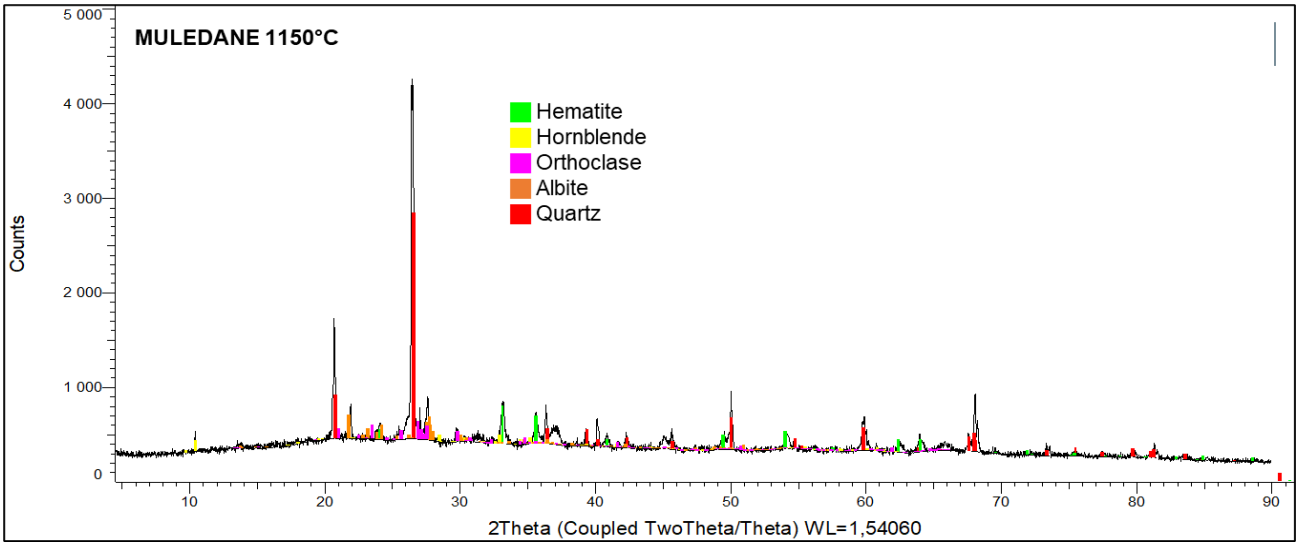

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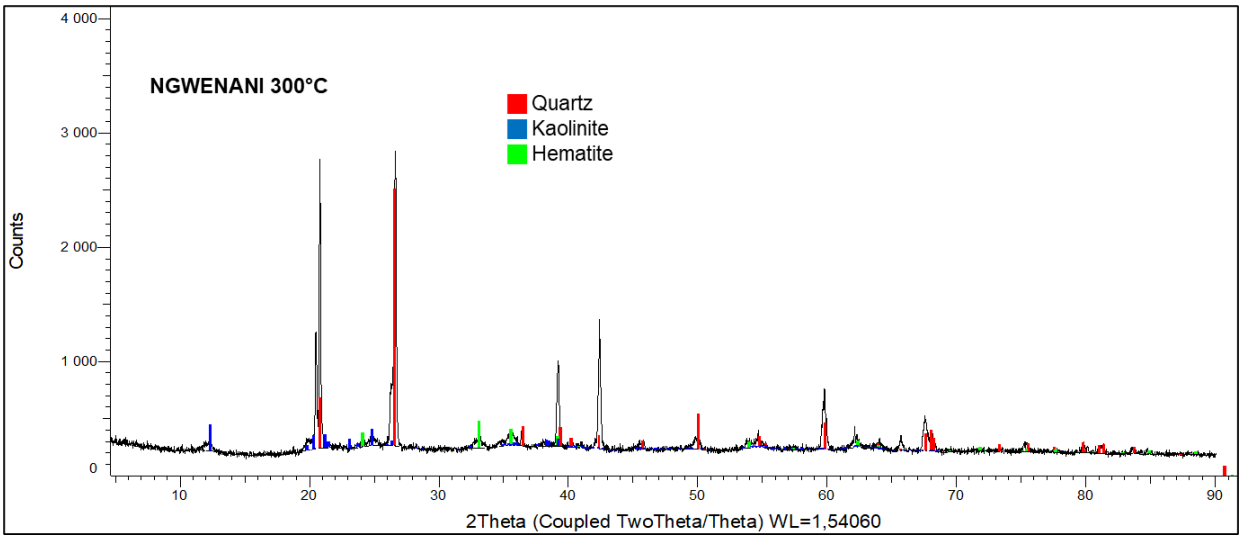

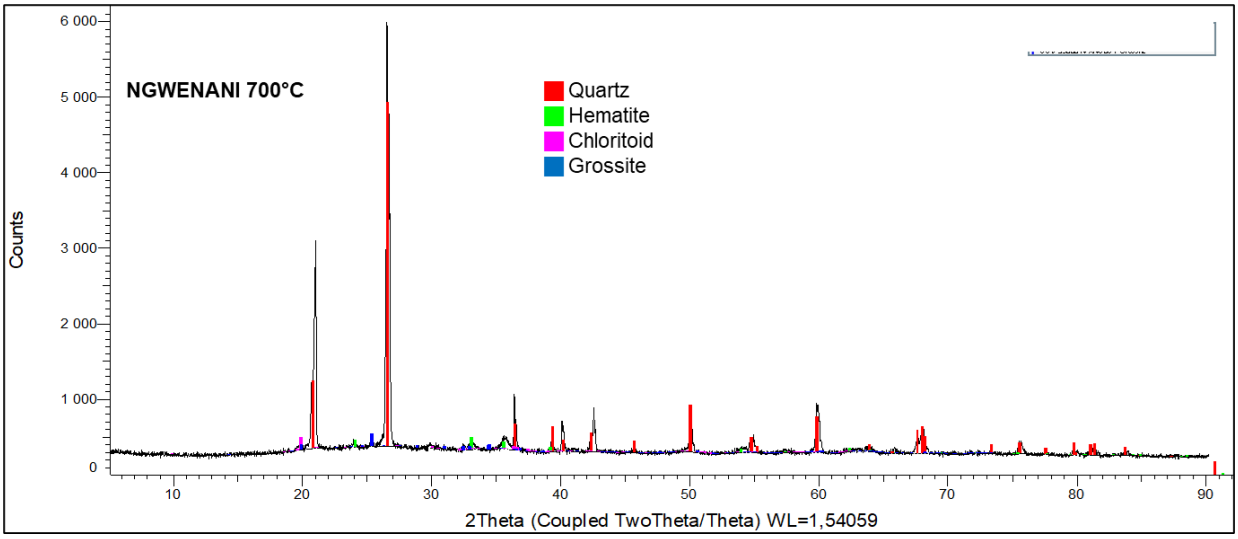

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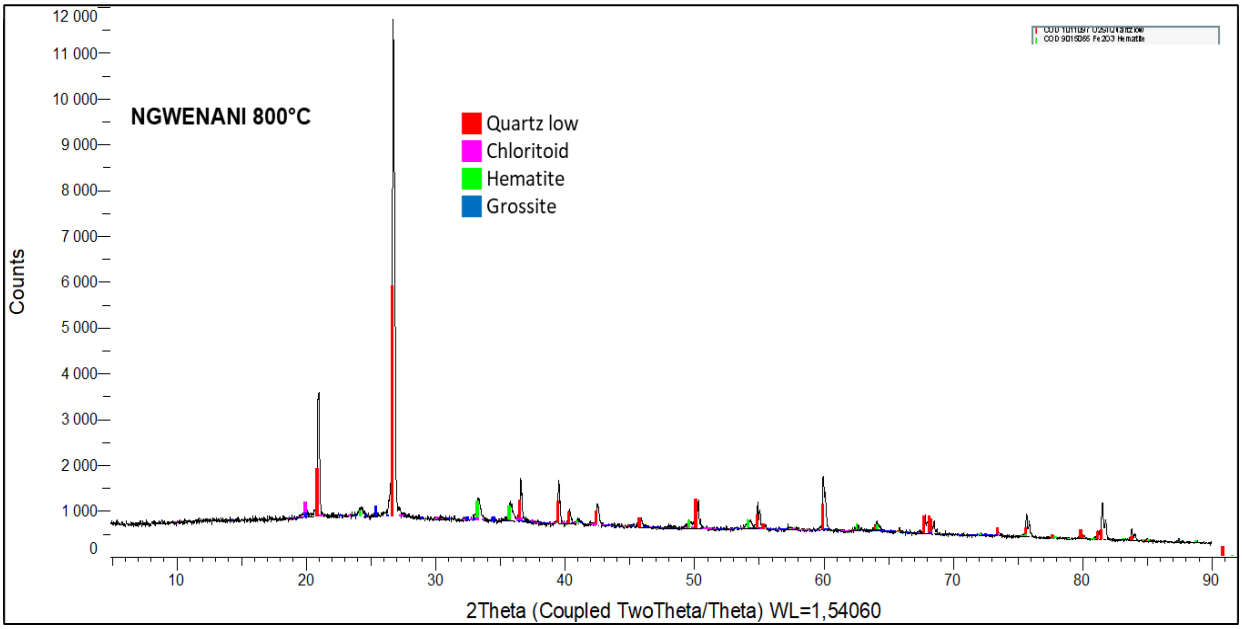

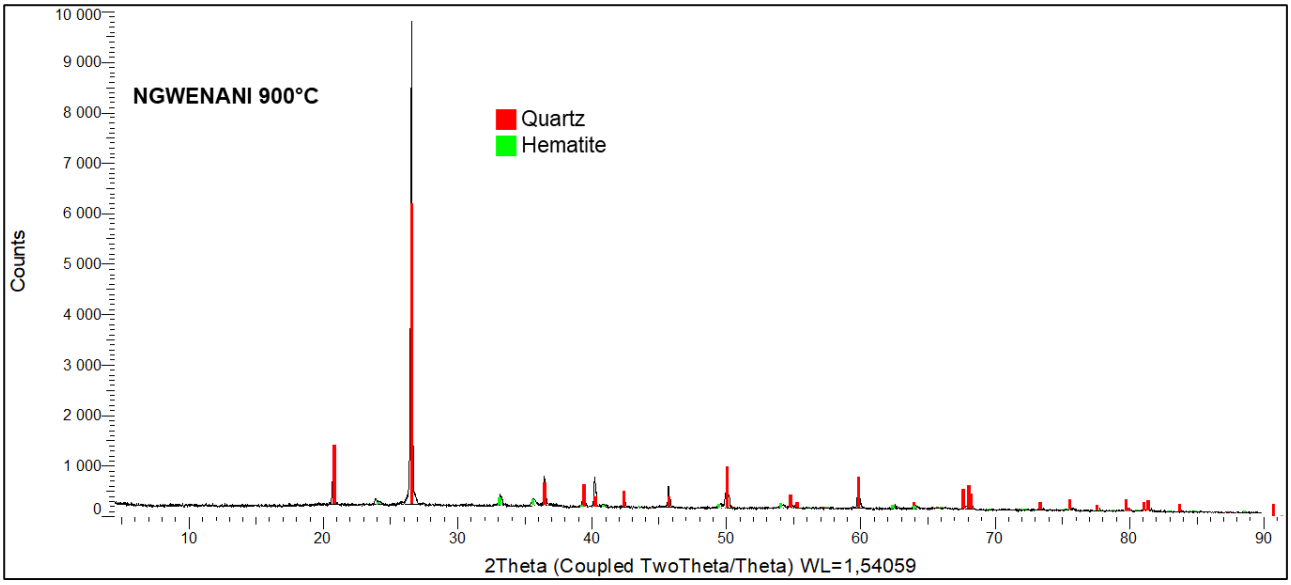

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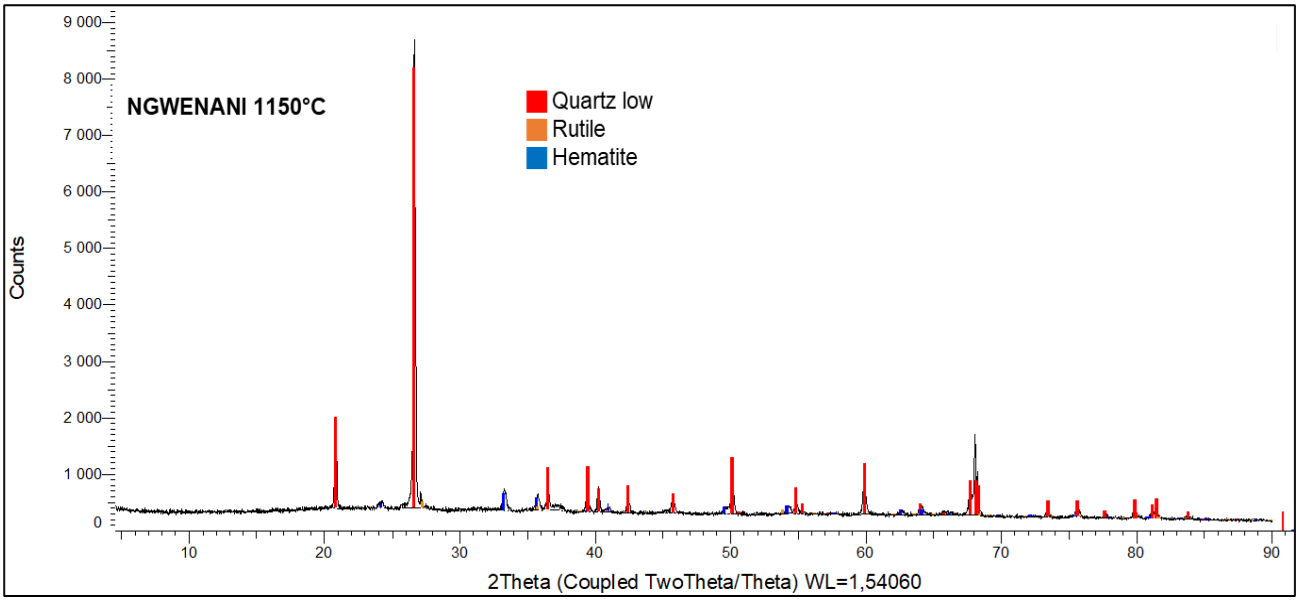

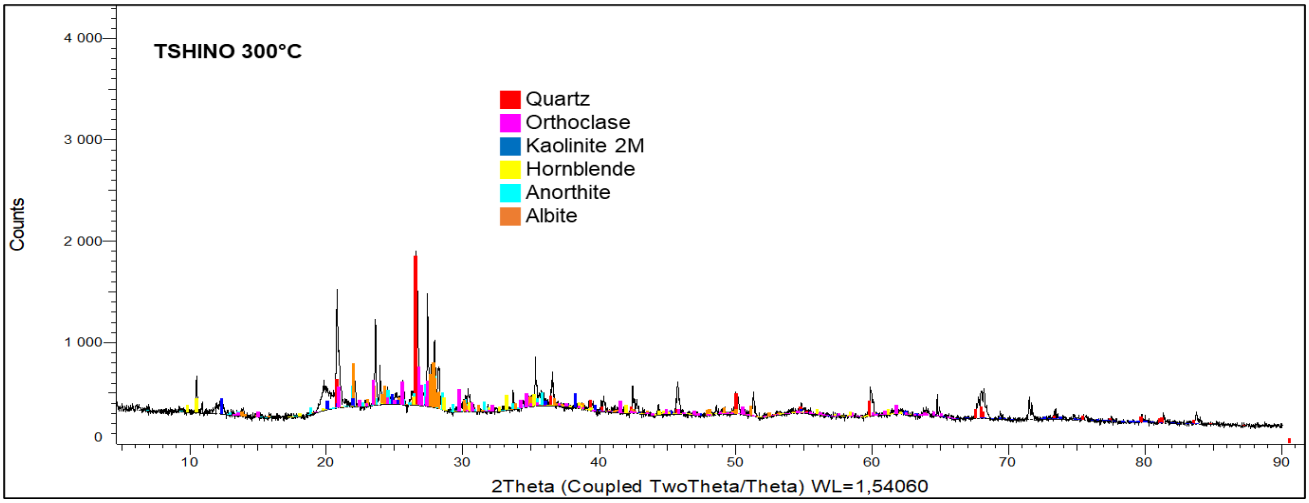

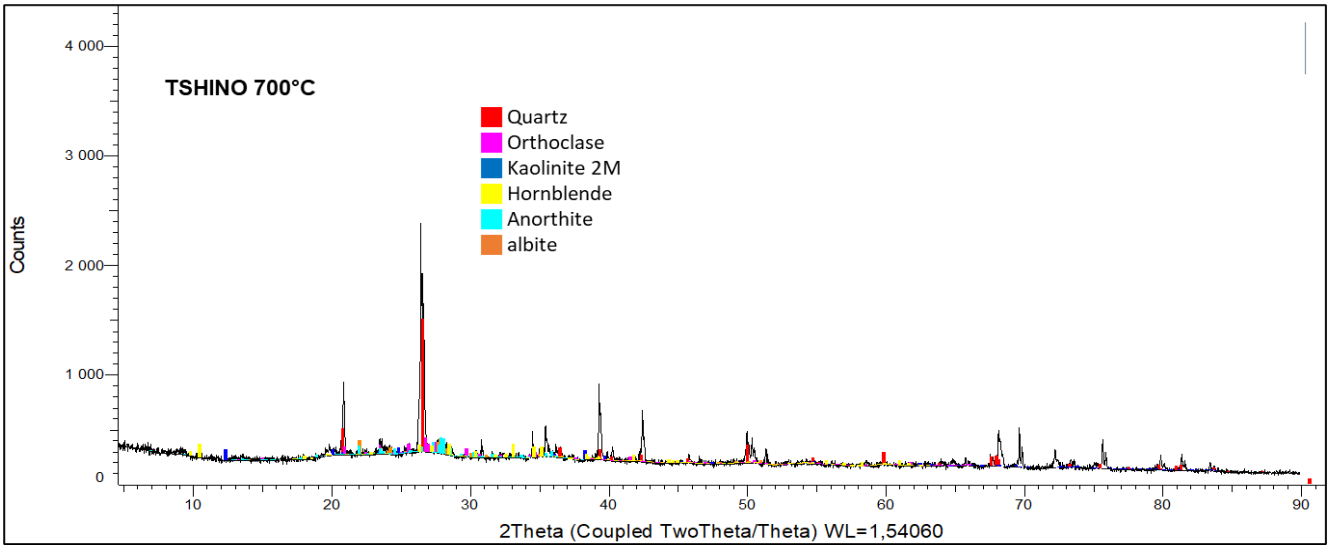

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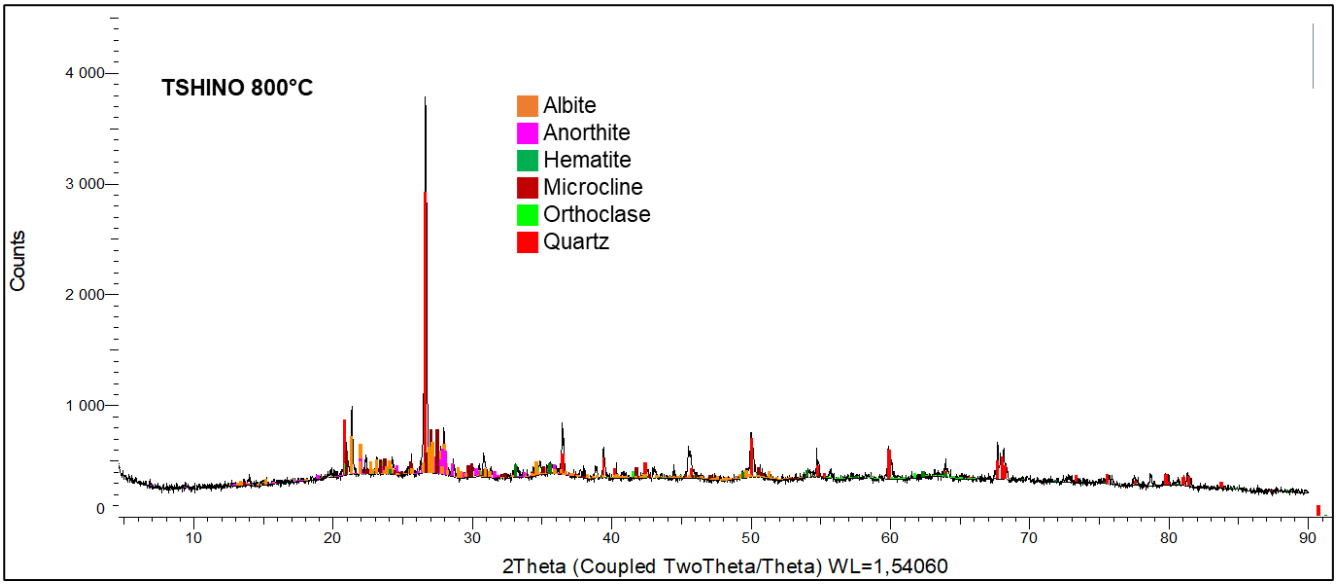

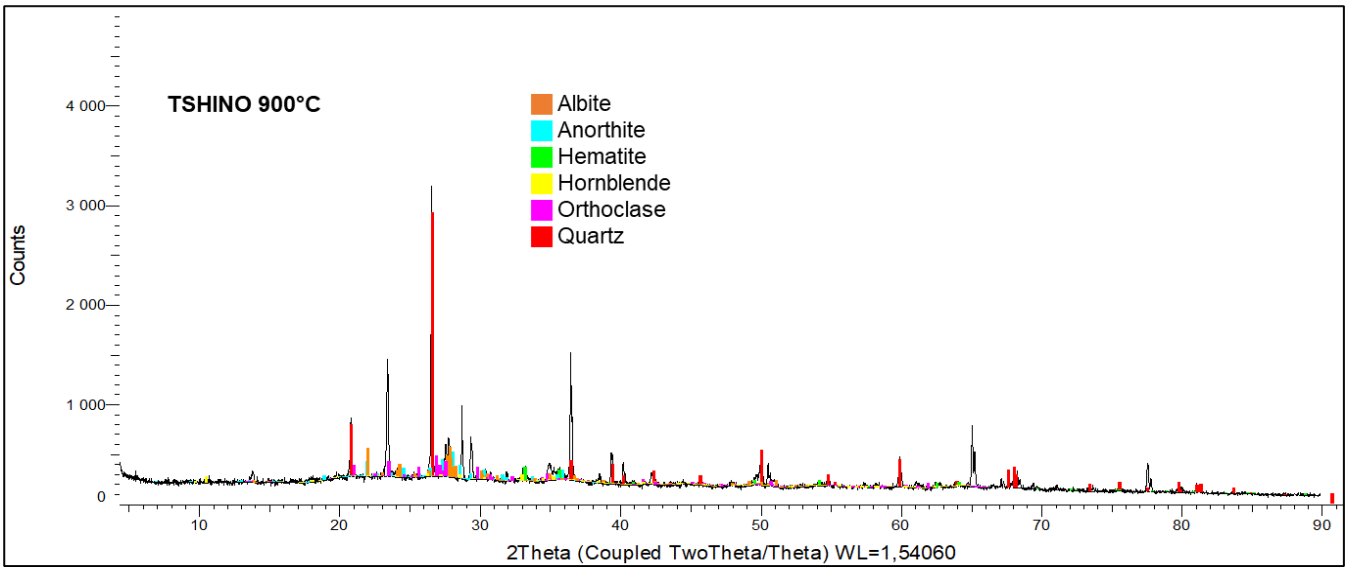

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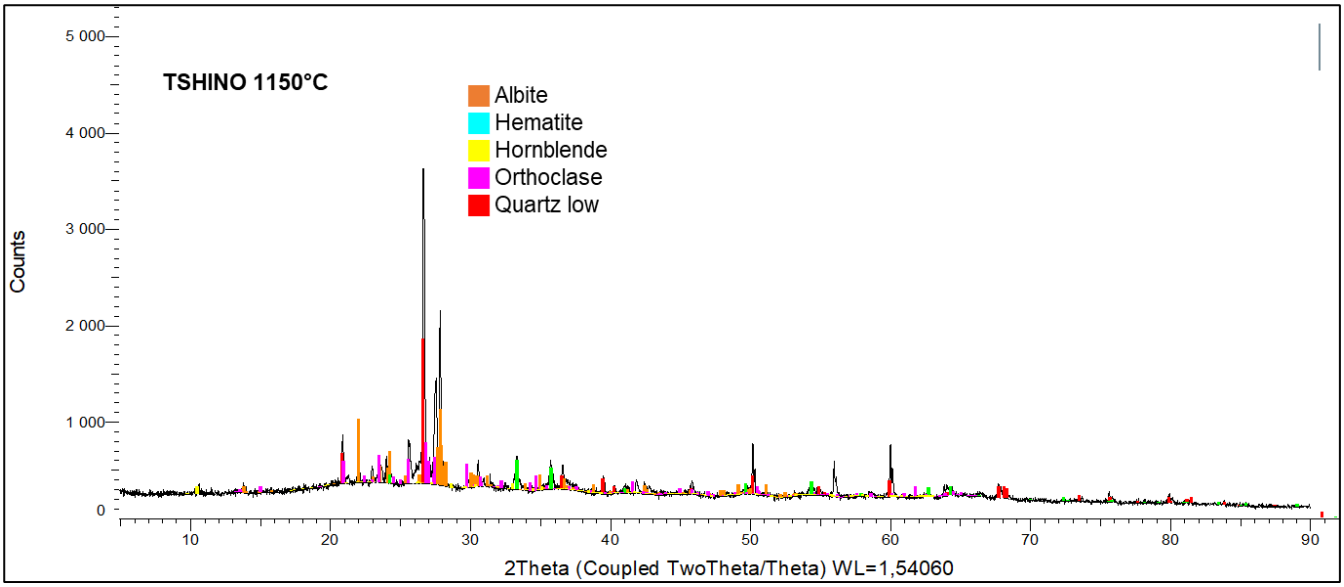

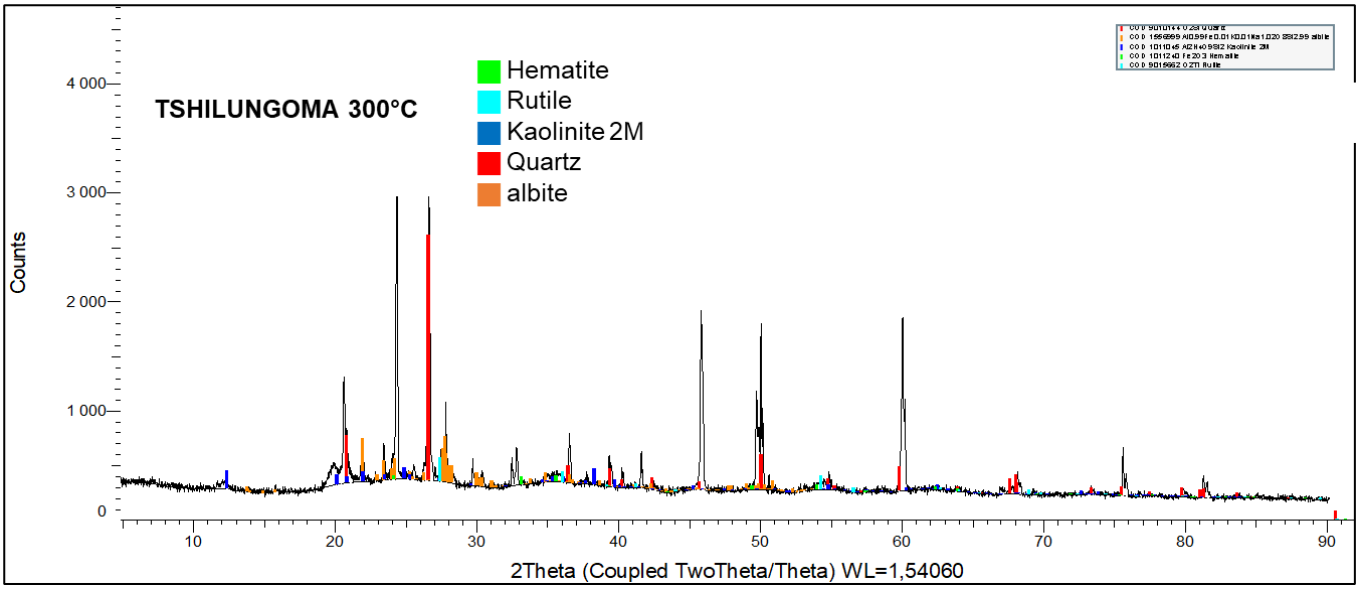

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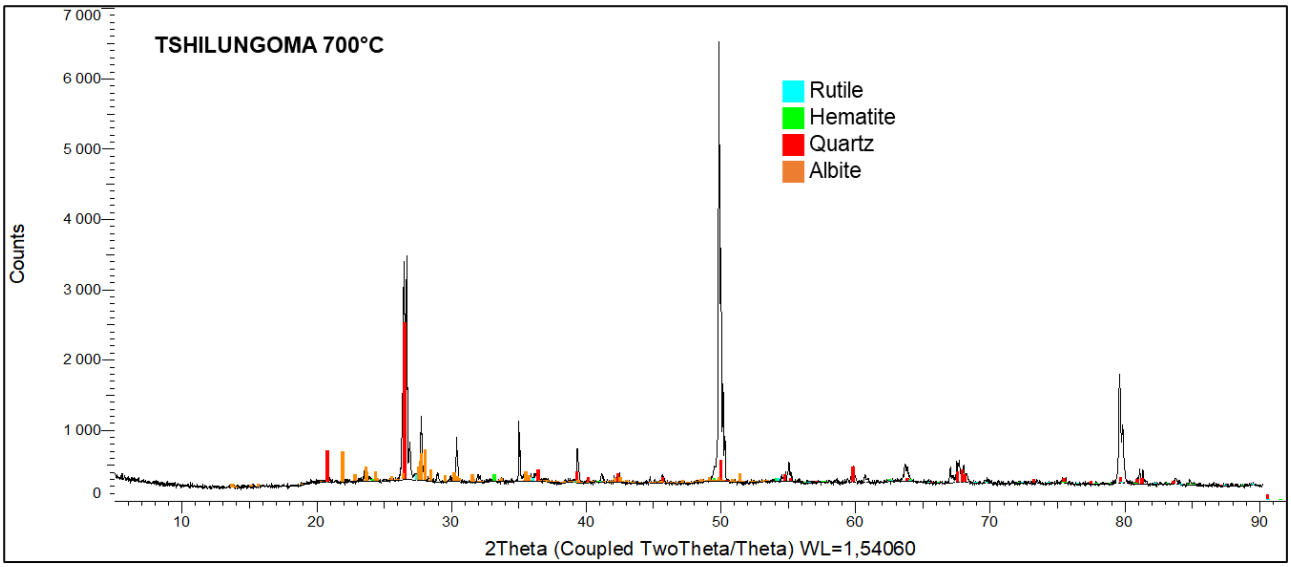

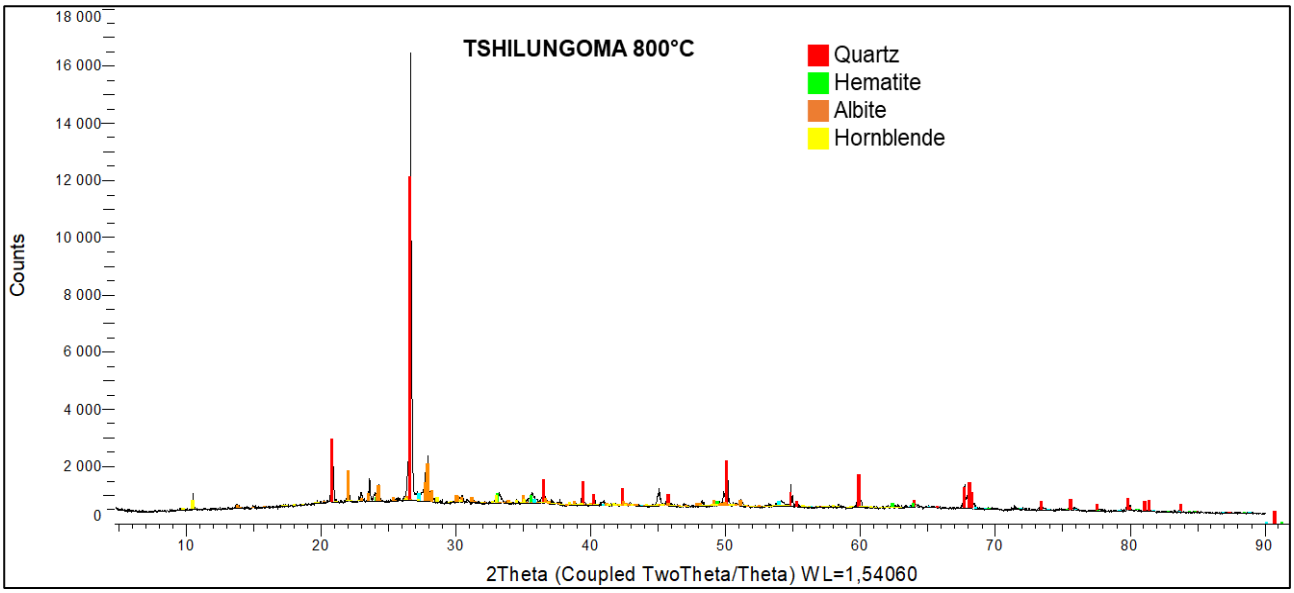

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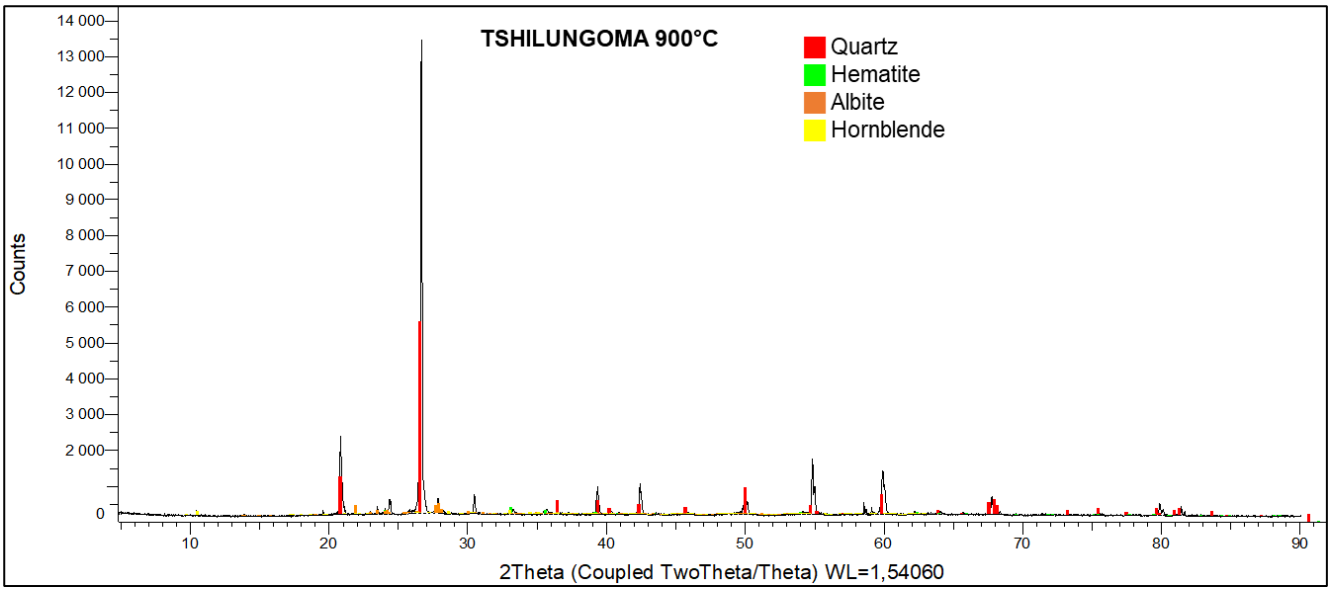

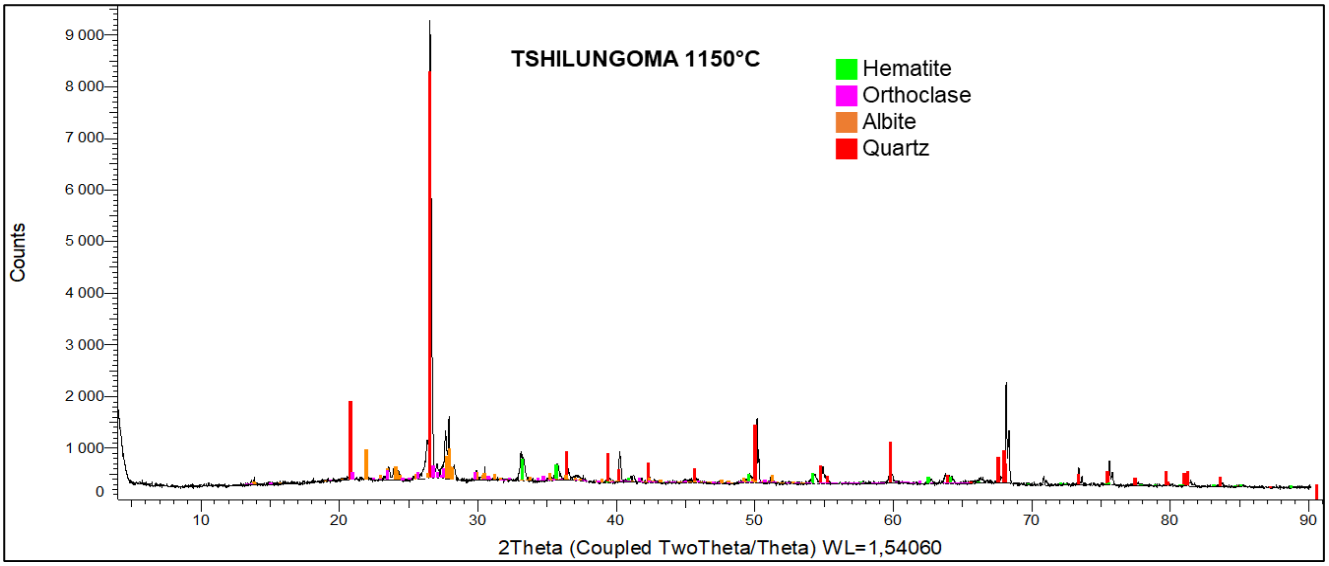

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Appendix H: Linear Shrinkage Values of Clay Samples from Different Areas at Various Temperatures

	linear shrinkage at different temperatures (°C)				
Samples	300	700	800	900	1150
Dzingahe	17.14	17.14	11.43	15.71	17.14
Ha-Matsika	15.94	15.94	15.94	15.94	15.94
Madadani	14.29	14.29	14.29	14.29	14.29
Muledane	9.09	9.09	10.61	12.12	12.12
Ngwenani	17.14	17.14	14.29	11.43	14.29
Lwamondo	11.76	11.76	14.71	14.71	13.24
Tshiulungoma	14.29	14.29	14.29	14.29	14.29
Tshino	14.71	14.71	14.71	14.71	11.76

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Appendix I: Table Showing How Clay Minerals Change at Different Temperatures

Site	Temperature °	Minerals																						
		Albite	Anorthite	anatase	Clinochlore	Clinoenstatite	chlorotoids	Epidote	Goethite	Grossite	Hornblende	Hemitite	Hematite-proto	Ilmite	kaolinite	Kaolinite 2M	Maghemite	Microline	Muscovite	Orthoclase	Rutile	Quartz	Quartz low	Talc
Dzingahe	raw	-	-	-	-	-	-	-	-	-	-	3.35	-	-	22.04	-	-	-	-	-	-	74.61	-	-
	300	-	-	-	-	-	9.04	-	-	-	-	2.06	-	-	-	-	-	-	-	-	-	-	79.64	-
	700	-	-	-	-	-	18.20	-	-	-	-	2.35	-	-	-	-	2.23	-	-	-	-	-	77.21	-
	800	-	-	-	-	-	-	-	-	-	-	6.63	-	-	-	-	-	-	28.70	-	-	-	64.67	-
	900	-	-	-	-	-	-	-	-	-	-	4.71	-	-	-	-	-	-	15.98	-	-	-	79.31	-
	1150	-	-	-	-	-	-	-	-	-	-	12.81	-	-	-	-	-	-	-	-	6.89	80.30	-	-
Ha- Matsika	raw	-	-	-	-	-	-	-	7.83		-	5.3	-	-	26.36	-	-	-	-	-	-	60.50	-	-
	300	-	-	-	-	-	25.37	-	-		-	5.35	-	-	30.42	-	-	-	-	-	-	38.85	-	-
	700	-	-	-	-	-	22.85	-	-	19.54	-	4.44	-	-	-	-	-	-	-	-	-	-	53.18	-
	800	-	-	-	-	-	27.37	-	-	15.69	-	10.84	-	-	-	-	-	-	-	-	-	-	46.11	-
	900	-	-	-	-	-	-	-	-	22.74	-	13.31	-	-	-	-	-	-	-	-	-	-	63.95	-
	1150	-	-	-	-	-	-	-	-	-	-	-	16.90	-	-	-	-	-	-	-	5.33	-	77.77	-
Lwamondo	raw	-	-	-	-	-	-	-	-	-	-	13.25	-	-	-	49.61	-	-	-	-	-	37.14	-	-
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	33.88	-	-	-	-	-	-	-	54.45	-
	700	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	69.12	-
	800	-	-	-	-	-	-	-	-	-	-	29.25	-	-	-	-	-	-	-	-	-	64.47	-	-
	900	-	-	-	-	-	-	-	-	-	-	58.02	-	-	-	-	-	-	-	-	-	41.98	-	-
	1150	-	-	-	-	-	-	-	-	-	-	29.51	-	-	-	-	-	-	-	-	-	-	70.49	-
Madadani	raw	-	-	-	-	-	-	-	-	-	-	3.14	-	-	17.61	-	-	-	-	-	-	79.245	-	-
	300	-	-	-	-	-	-	-	-	-	-	9.53	-	-	-	32.02	-	-	-	-	-	58.45	-	-
	700	-	-	4.49	-	-	-	-	-	-	-	10.20	-	-	-	-	-	-	-	-	-	85.31	-	-
	800	-	-	0.97	-	-	-	-	-	-	-	4.59	-	-	-	-	-	-	-	-	-	94.44	-	-
	900	-	-	-	-	-	-	-	-	-	-	0.84	-	-	-	-	-	-	-	-	-	-	99.16	-
	1150	-	-	-	-	-	-	-	-	-	-	5.89	-	-	-	-	-	-	-	6.54	-	87.56	-	-
Muledane	raw		-	-	<1				3.48			2.19	-	1.86	11.99	-	-	-	-	11.53	-	37.99	-	-
	300		17.52	-	-	-	-	-	-	-	-	3.74	-	-	20.41	-	-	-	-	17.04	-	41.28	-	-
	700	24.43	-	-	-	-	-	19.44				3.87	-	-	-	-	-	-	-	-	3.16	49.10	-	-
	800	19.73	-	-	-	-	-	-	-	-	26.15	4.92	-	-	-	-	-	-	-	12.67	-	36.53	-	-
	900	16.33	-	-	-	11.01	-	-	-	-		6.30	-	-	-	-	-	-	-	-	-	66.36	-	-
	1150	27.37	-	-	-	-	-	-	-	-	10.12	7.53	-	-	-	-	-	-	-	16.98	-	38.01	-	-
Ngwenani	raw	-	-	-	-	-	-	-	-	-	-	8.64	-	-	31.26	-	-	-	-	-	-	60.10	-	-
	300	-	-	-	-	-	-	-	-	-	-	6.52	-	-	26.29	-	-	-	-	-	-	67.19	-	-
	700	-	-	-	-	-	8.29	-	-	10.82	-	2.65	-	-	-	-	-	-	-	-	-	78.23	-	-
	800	-	-	-	-	-	12.49	-	-	10.65	-	6.38	-	-	-	-	-	-	-	-	-	-	70.48	-
	900	-	-	-	-	-	-	-	-	-	-	3.23	-	-	-	-	-	-	-	-	-	96.77	-	-
	1150	-	-	-	-	-	-	-	-	-	-	3.80	-	-	-	-	-	-	-	-	1.51	-	94.68	-
Tshilungoma	raw	34.96	37.73	-	-	-	-	-	-	-	-	3.84	-	-	3.89	-	-	-	-	8.59		10.95	-	-
	300	44.87	-	-	-	-	-	-	-	-	-	1.64	-	-	-	13.40	-	-	-	-	4.09		36.00	-
	700	55.97	-	-	-	-	-	-	-	-	-	2.01	-	-	-	-	-	-	-	-	1.66	40.36	-	-
	800	34.76	-	-	-	-	-	-	-	-	14.41	2.55	-	-	-	-	-	-	-	-		48.27	-	-
	900	22.92	-	-	-	-	-	-	-	-	7.10	2.37	-	-	-	-	-	-	-	-	-	67.61	-	-
	1150	29.30	-	-	-	-	-	-	-	-	-	3.48	-	-	-	-	-	-	-	10.22		57.00	-	-
Tshino	raw	-	-	-	8.58	-	-	-	-	-	4.60	-	-	33.52	7.7	-	-	-	-	16.52	-	24.53	-	4.56
	300	26.82	24.19	-	-	-	-	-	-	-	11.21	-	-	-	-	6.84	-	-	-	17.93	-	13.00	-	-
	700	16.66	21.56	-	-	-	-	-	-	-	17.62	-	-	-	8.59	-	-	-	-	13.20	-	22.37	-	-
	800	27.84	17.40	-	-	-	-	-	-	-	-	1.45	-	-	-	-	-	19.60		9.44	-	24.27	-	-
	900	23.85	25.54	-	-	-	-	-	-	-	3.81	1.84	-	-	-	-	-	-	-	13.42	-	31.53	-	-
	1150	48.39	-	-	-	-	-	-	-	-	3.87	3.95	-	-	-	-	-	-	-	25.33	-	-	-	18.46

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