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Physical-mechanical properties and thermogravimetric analysis of fired clay brick incorporating palm kernel shell for alternative raw materials

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A R T I C L E I N F O

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A B S T R A C T

This article explores the potential of incorporating palm kernel shells (PKS) from palm oil mill waste as a clay replacement for fired clay bricks. PKS, an abundant byproduct of palm oil extraction, have high cellulose content and high calorific value, making them an ideal option for clay replacement in brick making. For this purpose, clay soil was replaced with different percentages of PKS (0, 1, 5 and 10%) and subjected to a firing temperature of 1050 °C (heating rate of 1 °C/min). The physical–mechanical properties such as shape, size, colour, dry density, water absorption, thermal conductivity, porosity and compressive strength, as well as microstructural and morphological properties (XRD, SEM-EDX and digital image) and thermal analysis data (TGA-DTA) were evaluated to determine the effects of replacing PKS in fired clay bricks. The results showed that the incorporation of PKS increased firing shrinkage and porosity and decreased dry density, compressive strength, and thermal conductivity. However, incorporating more than 5% PKS resulted in lower mechanical properties (24.6 to 11.0 MPa) and higher water absorption (3 to 12%) due to increased firing shrinkage and porosity (0.3 to 0.9% and 13 to 20%, respectively). The bricks also exhibited lower density (1799 to 1645 kg/m^3) and improved thermal properties (0.54 to 0.36 W/m.K) due to the development of porosity during the firing process. While the degradation of organic components was a concern, it was determined that all organic components were completely degraded below 650 °C and the bricks matured at 950 °C. The study concluded that the use of PKS as a partial replacement for clay in brick manufacture is a viable solution for waste management.

1. Introduction

Brick is a popular building material that has been used in the construction industry for centuries due to its attractive appearance and natural appeal. Depending on the design and arrangement, brick can give a building a rustic, traditional, or even modern aesthetic. Because of its strength and durability, brick is also commonly used for a variety of construction projects, including residential, commercial, and landscape projects [1]. However, the demand for bricks has led to an increase in brick production. It is well-known that clay is a natural resource that is often used in the production of clay bricks. As the demand for brick has risen, the overexploitation and depletion of clay resources have become a concern [2]. This has become an environmental issue as the depletion of clay resources can lead to soil degradation and other negative environmental impacts [3].

The extraction of clay as a raw material for producing fired clay bricks can be energy-intensive and harmful to the environment. According to a study by Ncube et al. [3] and Issaka and Ashraf [4], this

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process can involve the removal of topsoil and the excavation of large areas of land, which can disrupt natural habitats and ecosystems, as well as affect local communities and the availability of resources, such as water. In order to minimize this impact and the depletion of clay resources, it is important to consider using alternative raw materials such as agricultural waste or recycled materials as a partial substitute for clay, and adopting sustainable production methods such as renewable energy and pollution prevention [5–7]. Agricultural waste can be readily available and cheaper than traditional raw materials, resulting in lower brick production costs [6,8]. Some agricultural waste materials such as crop residues, food processing by-product, livestock bedding and other agricultural waste can improve the physical and mechanical performance of bricks, nevertheless it is important to determine the suitability of a particular agricultural waste material for use in brick production [6]. Using agricultural residues in bricks can also reduce the demand for finite resources like clay and promote sustainable resource use. Additionally, incorporating agricultural waste in brick production can divert these materials from landfills and reduce environmental impact.

However, the use of agricultural waste in bricks can also have disadvantages, depending on the materials used and the goals of the brick manufacturing process. A possible disadvantage is lowering brick strength and durability. Some agricultural wastes, such as tea waste, sawdust, and rice husks may have poorer mechanical properties than conventional brick raw materials, resulting in bricks with lower strength and durability due to the formation of porosity in the brick [9,10]. These may be unsuitable for certain applications or have a shorter life span. Therefore, it is important to carefully consider some factors such as physical and mechanical properties of bricks, availability of waste, cost of using waste, environmental impact, and production methods when deciding to incorporate a certain type of agricultural waste in brick production [3,6].

More recently, there has been a growing interest in incorporating different types of agricultural wastes to produce low-cost, environmentally friendly fired clay bricks [11,12]. Incorporating waste in building materials is a practical way to address the problem of environmental pollution. It is well known that agriculture industry generates large amounts of solid waste that can damage ecosystems, soils, and the environment. Agricultural wastes, as defined by the United Nations, include a range of materials such as manure and other wastes from farms, poultry houses, and slaughterhouses; crop wastes; fertilizers runoff from fields; pesticides that enter water, air, or soil; and salt and silt drained from fields [13]. Recycling these wastes in the manufacture of bricks can reduce the negative impact on the environment. According to Obi et al. [14], agricultural waste can come in a variety of forms, including ash, solid waste, and sludge, which vary in composition depending on the agricultural system or activity. Olive biomass fly ash, sugarcane bagasse ash, rice husk ash, ground coffee ash, and washed olive pomace ash are examples of agricultural waste in ash form produced as a by-product of combustion, e.g., in boilers [15–18]. During the combustion process, most of the moisture in the waste evaporates and organic materials are burned, producing a by-product rich in silica and minerals [15–18]. These by-products, also known as pozzolanic waste, contain siliceous or aluminosiliceous materials that can form calcium silicate hydrate or other cementitious compounds that improve the bonding properties of bricks [19].

Agricultural wastes, which often contain a high percentage of lignocellulose in solid form, can be degraded by microorganisms through the production of enzymes that decompose cellulose, hemicellulose, and lignin under natural conditions [20]. When agricultural wastes are exposed to high temperatures, the organic material can easily burn and release pollutants such as CO_2, CO, and SO_2 into the atmosphere [21]. Besides, this waste also has a very high calorific value and can be a good fuel source for electricity generation [22]. Examples of agricultural wastes in solid form include tea waste, sawdust, sugarcane bagasse, and rice husks [9,10]. Sawdust is a by-product of the wood industry, while sugarcane bagasse and rice husks are generated during the processing of sugar and rice in mills.

Ozturk et al. [9] investigated the potential of using tea waste as a clay replacement and found that the incorporation of up to 10% tea waste significantly improved various physical and mechanical properties such as density, porosity, and thermal conductivity by forming pores after exposure to high temperatures. The incorporation of tea waste resulted in reduced compressive strength due to increased porosity. However, tea waste can still be used as an alternative pore-forming material in fired lightweight bricks while improving physical and mechanical properties. Also, Luna-Cañas et al. [10] reported that organic materials contained in sawdust, sugarcane bagasse, and rice husks could be completely burned during the brick manufacturing process, leaving numerous pores in the brick and affecting the physical and mechanical properties. Agricultural waste can also be in the form of sludge. In a study by Adazabra et al. [23], it was found that incorporating spent shea into fired clay bricks is a beneficial process because the minerals contained in the spent shea can improve fluxing properties, increase porosity, provide a secondary fuel, and increase compressive strength.

Meanwhile, there is now a growing awareness of the need to reduce waste and its negative impact on the environment, as well as the high cost of waste disposal through sustainable resource recovery practices [24,25]. This has led to increased interest in using products made from waste materials, which can diversify the range of available products and reduce final costs. The use of waste materials can also provide some industries with an alternative source of raw materials. In Malaysia, the agricultural sector has been an important contributor to the country's economy and has helped reduce dependence on imports, but producers still need to address the various issues associated with biomass waste from agriculture. This is a significant problem because the production and processing of agricultural products often generates a large amount of biomass waste such as solid, liquid, and gasses substances that can be toxic and harmful to humans and the environment [26].

Since oil palm is recognized as the most valuable agricultural commodity and brings significant economic benefits to the country, several agencies have been established to support the palm oil industry. However, efforts to optimize palm oil production have led to problems with biomass waste disposal [27]. Reportedly, there are 448 palm oil mills in Malaysia and many of them have been certified as sustainable and ethical by organizations such as the Malaysian Sustainable Palm Oil (MSPO) and the Roundtable for Sustainable Palm Oil (RSPO) [28,29]. These certifications demonstrate a commitment to sustainability and can provide immediate benefits, but they also help companies be good corporate citizens and gain market share [29]. However, only companies registered and licensed with the Malaysian Palm Oil Board (MPOB) are fully committed to implementing sustainable practices such as zero-burn policies and palm oil biomass recycling programs, as well as supporting ethical and sustainable agriculture and taking action on climate change [30,31]. Palm oil mills that operate illegally and do not follow good agricultural practices or consider environmental conservation or social rights often face problems with land ownership and poor management, including a lack of clear land use permits and overplanting without consulting the rightful owner [29]. These mills also often lack environmental impact assessments and have inadequate solid waste management systems [32].

Palm oil waste is becoming a significant environmental problem because of its large annual production. It is generated during palm oil processing and is composed of empty fruit bunches (EFB), palm kernel shells (PKS), palm fibers (PF), and palm oil fuel ash (POFA), which make up 90% of total palm oil waste [33]. EFB account for 22% of the waste, PKS 5.5%, PF 13.5%, and POFA 5% [34,35]. Recent studies have shown that palm oil production in Malaysia generates a large amount of biomass waste in the form of PKS (0.94 tons per hectare), PF (2.32 tons per hectare), and POFA (3.00 tons per hectare) [36,37]. These waste products are generated during the palm oil processing and are considered biomass wastes. According to Ab Manan et al. [38] and Azura et al. [39], studies have shown that heavy metals can accumulate in palm oil