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Performance Evaluation of Sludge – Added Clay Bricks

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Abstract

The papermaking industry produces a large amount of sludge through wastewater treatment processes, which has a significant impact on the environment if not managed properly. Conventional disposal methods such as landfilling and incineration are expensive and contribute to pollution and loss of valuable resources. Therefore, a sustainable approach is needed to manage this industrial waste. This study focuses on the potential reuse of paper industry sludge to produce clay bricks. The main objective of the study was to evaluate the suitability of sludge as an additive in bricks in terms of physical stability and environmental impact. The study included three main methods, characterization of sludge content in terms of moisture content and chemical composition, production of brick samples with 5%, 10%, 15%, and 20% sludge mixtures, and analysis of the mechanical performance and water absorption of the resulting bricks. The study showed that bricks with sludge content up to 5% met the MS 76:1972 standard regarding water absorption rate but not on compressive strength. SEM-EDX and additional colour tests also showed safe performance regarding structure and chemical effects. In conclusion, although the compressive strength did not meet structural standards, the use of paper industry sludge in clay bricks remains a sustainable option for managing industrial waste and can be suitable for non-structural applications. With proper treatment and optimized processing conditions, sludge-amended bricks may serve as an environmentally friendly alternative for non-load-bearing or secondary construction purposes.

1. Introduction

Sludge production from the paper industry is a concern for environmental issues. The amount of waste from paper and paperboard produced worldwide is estimated to be approximately 417.3 million metric tons in 2021 [1]. The ability to recycle or reuse industrial waste has gained popularity as environmental sustainability has become a priority. To elaborate, reusing paper industry sludge for bricks in construction is one possible solution. The increase in paper consumption worldwide has also led to an increase in sludge production. The increase in paper consumption worldwide has led to an increase in sludge production. In the era of sustainable development, the issue of industrial waste disposal is receiving increasing attention, especially sludge produced by the paper industry. This sludge, which is a by-product of wastewater treatment, often contains organic and inorganic substances that have the potential to pollute the environment if not managed properly. Therefore, innovative approaches are needed to reduce environmental impacts while at the same time utilizing this waste productively.

Industrial waste is categorized into solid, liquid, or gaseous forms, each necessitating a specific treatment and disposal approach. The United States of America is thought to generate as much industrial waste annually as 7.6 billion tonnes [2]. In 2021, China produced around 3.8 billion tons of general industrial solid waste [3]. The increase in paper consumption worldwide has led to increased sludge production. The deinking sludge, a waste product of paper recycling that is unsuitable for manufacture of new paper, is found among the sewage sludge [4]. Scrap wood, oil, solvents, scrap metals, plastic, gravel dirt, bagasse, chemicals, and even food scraps from dining establishments are among the many industrial wastes generated [5]. This sludge, which is a by-product of wastewater treatment, often contains organic and inorganic substances that have the potential to pollute the environment if not managed properly. Therefore, innovative approaches are needed to reduce environmental impacts while utilizing this waste productively. It can be recycled by using it in bituminous mixtures, cement clinker, mortars, bricks, ceramics, and other product formations, which lowers the cost of the finished product and improves environmental protection [6].

Sludge management from the paper industry is a major challenge in the context of environmental sustainability. About 40–50 kg of dry sludge are produced by the paper industry for each tonne of paper produced. It is composed of 30% secondary (biological) sludge and 70% primary sludge [7,8]. This sludge, which is rich in organic matter, heavy metals, and industrial chemicals, is often traditionally disposed of through landfilling or incineration. Although landfilling has also been a popular way to dispose of sludge, researchers are now forced to look for new uses for sludge due to the limited landfill area, high expense, and stringent environmental regulations [9]. These disposal methods are not only costly, but also contribute to soil, groundwater, and greenhouse gas emissions. In an effort to minimize environmental impacts, approaches to recycling and reusing industrial waste such as sludge are gaining increasing attention. A few researchers created lightweight, charred clay bricks with paper sludge [10]. However, studies that in-depth evaluate the potential of sludge use in the production of local building materials such as clay bricks are still very limited, especially in Malaysia. Fig 1, there is an increase in waste every 2 years. In 2020, 36,138 tonnes of waste were produced, which increased in 2024 to 39,403 tonnes/day.

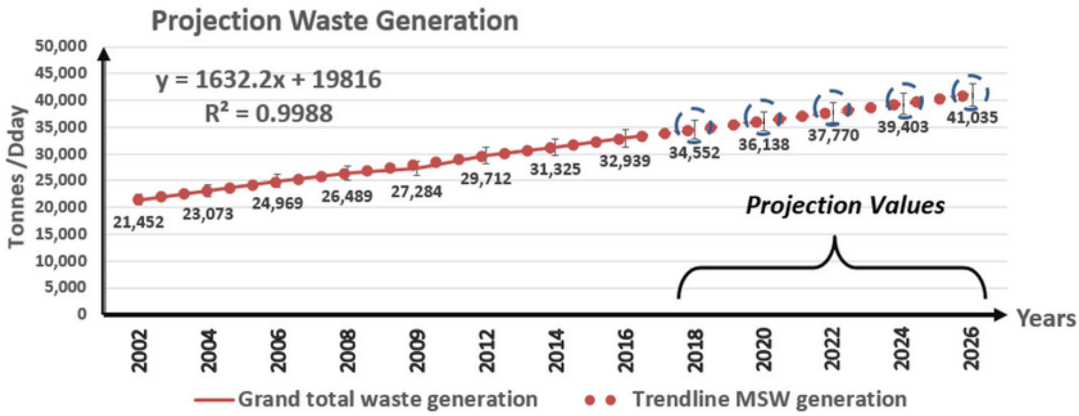

Fig. 1: Projection of waste generation from Malaysia [11].

The main gap in existing studies is the lack of scientific data and performance evidence on the suitability of sludge as an additive in bricks, especially in terms of compressive strength, water absorption rate, and potential pollutant release [12]. In addition, aspects of environmental safety monitoring, such as studies on the solubility of heavy metals after bricks are used, have also not been fully explored. If this study is not conducted, the opportunity to manage sludge waste more sustainably will be missed [13]. It will continue to be disposed of using old methods that have a negative impact on the environment and involve high operating costs for the industry. On the other hand, if this study is conducted, it has the potential to form the basis for a green innovation in the construction sector by introducing alternative sustainable building materials [14]. In fact, if proven successful, it can reduce dependence on natural raw material sources, save costs, and reduce pollution, in line with the country's sustainable development goals [15].

Disposal of sludge from the pulp and paper industry poses serious environmental challenges when not adequately managed. Sludge contains toxic constituents such heavy metals (Pb, Fe, Cu, Ni, Cd, Cr, Zn, As), hazardous organic chemicals (di-butyl phthalate, di-n-octyl phthalate, 2-hydroxysocaproic acid, benzenepropanoic acid), and increased quantities of phenolic compounds [16]. Sludge often contains residual chemicals such as lignin, chlorine from the bleaching process, and heavy metals that can leach into soil and waterways, leading to pollution [17]. Its organic content promotes anaerobic decomposition in landfills, releasing the greenhouse gas methane more than 25 times more potent than CO_2, thus contributing to climate change [18]. The persistent inclusion of organic pollutants and potentially toxic metals in untreated sludge increases long-term ecological and health risks. These heavy metals have the potential to leak into surface and groundwater and contribute to water contamination if improperly managed [19]. Recognizing these dangers, researchers have begun to explore sustainable reuse options, such as incorporating paper sludge into fired clay bricks, which offer the benefits of resource conservation and pollution reduction [20].

Recycled paper mill sludge exhibits a complex combination of organic fibers, inorganic minerals, additives, and trace contaminants, defining its potential for reuse and the need for careful characterization. In addition to cellulose fibers (23%), minerals (ash content) (63.5%), and metals, the DPS is composed of 46.4% water. DPS powder's mineralogy analysis revealed that it is made up of inorganic fillers, primarily talc, kaolinite, and calcite, and carbon in the form of organic fibers [21]. Composed of more than 50% cellulosic materials such as lignin and cellulose, it also contains significant levels of calcium carbonate, silicates, and clays such as kaolinite [22]. Typically, it contains cellulose fibers, lignin, ash, calcium carbonate, and residual chemicals from the deinking and bleaching processes [23]. Furthermore, recycled paper sludge may carry trace levels of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn), which originate from the printing inks and dyes used in the original paper [24]. These characteristics raise concerns about environmental safety, especially in reuse applications such as construction or agriculture. By classifying the bricks according to the leaching of certain metals, studies [23] have conducted the leaching test on the final product, which is the bricks. However, due to its high organic content and mineral-rich composition, paper sludge has shown promising potential in producing building materials such as bricks, where it can improve thermal insulation while supporting residual reinforcement [22].

A study looked at using paper sludge as an environmentally friendly substitute for cement in cement-based goods for civil construction in order to produce eco-efficient cement [25]. One potential initiative to address the global challenges of waste management and sustainability is to incorporate clay and sludge from the paper industry into brick production. Previous studies have shown that waste from the paper industry when mixed into building materials such as cement, can meet the requirements of construction standards [26]. However, using clay as the base material for bricks is still considered a more environmentally friendly approach, mainly when local clay sources are used [27]. Furthermore, using waste materials in brick production can reduce the dependence on clay and thus reduce the pollution load due to solid waste dumping [4]. Therefore, the production of bricks based on a mixture of clay and sludge from the paper industry should be studied in more depth so that it can provide tangible benefits to the environment and sustainable development at the global level.

This study was guided by three main objectives. First, to identify the optimal proportion of paper sludge in clay brick samples by varying sludge content of 5%, 10%, 15%, and 20% w/w and assessing performance based on physical and mechanical standards. Second, to determine the moisture content of paper industry sludge and to analyze the colour and surface morphology of the sludge-incorporated bricks using Scanning Electron Microscopy (SEM) under standard laboratory conditions. Last, to evaluate clay bricks' compressive strength and water absorption rate with optimized sludge content according to MS 76:1972 specifications. All three objectives must be met to ensure that the products produced are safe and protect the environment. Prolonged exposure to these substances has been linked to various health problems, including cancer, neurological disorders, and reproductive toxicity [28].

2. Methodology

In this study, five brick ratios will be produced and involve six sample for each ratio, three sample for compressive strength and three sample for water absorption. To ensure that the bricks produced can be compared with MS76:1972, a control brick or brick without a mixture of sludge must be made and considered as the first ratio brick. Then, it is followed by adding sludge to the brick by 5%, 10%, 15% and 20%. To achieve the objectives, this study must be carried out according to the methodology that was made. It begins with the collection of industrial waste sludge samples and then the production of the clay bricks themselves. To meet the objectives, mechanical and parameter tests must be carried out to obtain final results that can be improved for the future.

2.1 Sludge Sampling

Sludge sampling was one of the essential steps in identifying the potential of industrial waste that can be reused in construction applications, especially in the production of sustainable building materials such as bricks. This sampling procedure followed MS 1756-3:2005 [36], which provides guidance on proper sludge sampling and characterisation. This activity involved a site visit to the factory to understand the sludge production process generated from recycling operations and wastewater treatment. Sludge samples were systematically taken from the waste storage area and collected in special containers to avoid cross-contamination. This sampling procedure also complied with the established occupational safety and health standards to prevent any risks to operators. The samples obtained were then taken to the laboratory for analysis in terms of physical and chemical content. The information obtained from this analysis will be used to study the effectiveness of sludge as an additive in the production of clay bricks, thus contributing to the development of more environmentally friendly and sustainable building materials.

2.2 Preparation of Sample

Two primary raw materials from the paper industry were used to produce clay bricks mixed with sludge, namely clay and sludge. These materials were used directly without going through a drying or filtration process to obtain fine clay. This decision was taken due to the time constraints faced throughout the study process and the method of preparing the materials, which were not too specific or detailed at the initial stage. However, the available raw materials were still used according to the basic procedures set to ensure continuity in the production of brick samples.

The selection of ratios was made based on previous studies which stated that the ratios used ranged from 0%-30% [28,29]. However, this study only selected 5 ratios as a trial. The sludge was prepared in five different percentages, which are 0%, 5%, 10%, 15%, and 20%, to account for experimental variations. The mixing process was carried out after the raw materials were prepared based on a specific mixing ratio determined in advance. This process referred to common industrial practice and was aligned with general guidelines outlined in **BS 3921: Specification for Clay Bricks**, which emphasizes the importance of consistent quality and proper workability of clay mixtures. Water was added gradually and carefully to avoid making the mixture too soft or 'stretchy,' which could affect the molding process. Excessive water content can lead to deformation during shaping and drying. Therefore, this step must be carried out with strict control. Table 1 in this report shows the details of the quantity and mixing ratio used for each sample produced, and this table serves as the primary reference throughout the brick production process

Table 1: Final Material Quantities for Each Mix

Sludge (%)	Clay (g)	Sludge (g)	Water (ml)	Sample
0	2550	0	300ml each brick	6 samples each ratio
5	2400	150		
10	2330	220		
15	2225	325		
20	2140	410		

Once the mixing process is complete and the texture reaches the appropriate level, the mixture is placed in a special mold measuring 215 mm long, 100 mm wide, and 65 mm high. The mold used in this study is designed to be open at the top and bottom to facilitate the demoulding process; the bricks can be removed immediately after the mixture is fully compacted. This approach ensures the formation of uniform bricks in size and shape before curing and firing.

To ensure the strength and durability of the produced bricks are at an optimum level, the curing process is one of the important stages in the production of clay bricks mixed with paper industry sludge [15,29]. Generally, the curing process can be carried out for several periods, namely seven days, 14 days, 21 days, or 28 days, depending on the study's needs and the test's objectives [30]. Previous studies have shown that a more extended curing period will increase the bricks' compressive strength due to forming a more stable and dense internal structure [15,29]. In this study, a curing period of 21 days was chosen as the appropriate period for each brick sample. This selection was made due to time constraints in completing the project, and 21 days was considered a practical midpoint between 14 days and 28 days, commonly used in materials engineering studies. The curing process is done immediately after the bricks are removed from the mold. The bricks are then placed at room temperature and stored in a protected open space or a manufacturing laboratory with a stable ambient temperature. During this curing period, the bricks are left damp or not too dry to ensure that the hydration reaction between the active ingredients can occur effectively, thus helping to form a strong internal bond in the brick structure.

A clay brick must cure at least 21 days to ensure that the brick is strong [31]. After the 21-day curing period, the bricks will undergo the final process of firing, which is an important stage in increasing strength, shape stability, and weather resistance. Ideally, the bricks should be fired at temperatures between 800°C and 1000°C to achieve optimal material maturity and completely decompose all unstable chemical elements. However, constraints regarding concrete laboratory equipment and facilities at Universiti Tun Hussein Onn Malaysia (UTHM) have limited the firing temperature to only 200°C, and the bricks were fired for 48 hours using the available laboratory oven. Figure 2 shows the entire sample of the mixture brick after firing.

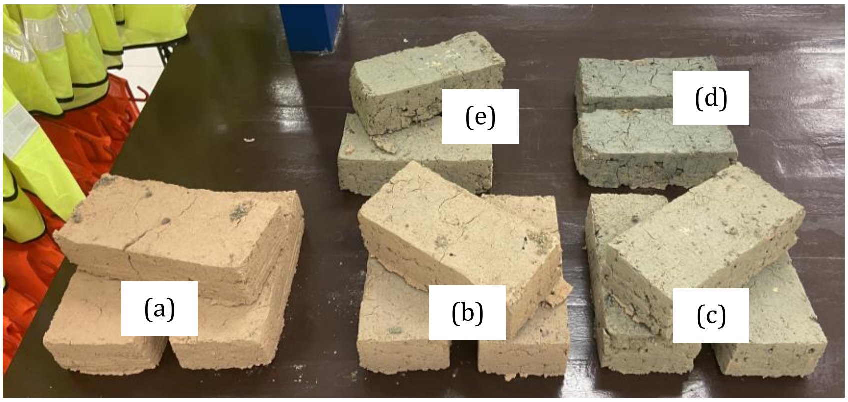

Fig. 2: The sludge added clay brick after firing process: (a) control, (b) 5%, (c) 10%, (d) 15%, (e) 20%

Once the firing process is complete, the bricks will be removed from the oven and allowed to cool at room temperature for 24 hours to stabilize the internal structure and prevent any cracks due to thermal shock. After the cooling process, the bricks are ready to undergo physical and mechanical tests such as compressive strength, water absorption, and density tests to assess the overall performance of the brick product produced from this industrial waste material.

2.3 Sample Analysis

To achieve all the objectives of the study, several tests need to be carried out. Once the sludge sample is obtained, a moisture content test needs to be carried out to determine the amount of water contained in the sludge. This process begins with the initial weighing of the sludge sample (Wet), followed by combustion at 105°C for 24 hours. After combustion, the dried sample is reweighed to obtain the final weight (Dry). The moisture content value is then calculated in percent (%) using the equation (1) or formula given below.

$$\text{Moisture Content (\%)} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Wet Weight}} \times 100 \quad (1)$$

According to the MS 76:1972 standard, there are two main tests specified in the Malaysian Standard for the evaluation of bricks: the water absorption test and the compressive strength test. Based on the Standard, the water absorption rate should be less than 20%, while the compressive strength should exceed 5 MPa if the brick is used for construction purposes.

After the firing process, the water absorption test is carried out as soon as the brick is cooled. Each brick is weighed first before being immersed in water for 24 hours and recorded as W1. This procedure is carried out according to the sludge added clay brick ratio: control (0%), 5%, 10%, 15% and 20%. After 24 hours, the brick surface is wiped with a damp cloth to remove excess water on the surface and then re-weighed to obtain the W2 value. The equation (2) or formula below calculates the water absorption value using percentage (%).

$$\text{Water Absorption (\%)} = \frac{W1 - W2}{W1} \times 100 \quad (2)$$

Throughout the immersion process, it was found that there was a change in color and water impurity for each mixture ratio. Therefore, the soaking water from each sample was taken and stored to be tested for turbidity using a UV-VIS Spectrophotometer DR6000 with a PtCo reading unit (50 mm path length).

At the same time, a compressive strength test was also conducted to assess the strength of the brick structure and ensure that it complies with the requirements of the Malaysian Standard. This test was performed using a Universal Testing Machine (UTM) available at the Materials Laboratory, UTHM, and the compressive strength data was recorded directly during the test.

Finally, the brick mixture ratio that showed the best performance regarding water absorption rate and compressive strength will be analyzed using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX). This test aims to evaluate the porosity structure of the brick as well as detect the presence of heavy metal elements that may be released from the sludge mixture.

3. Results and Discussion

In the Results and Discussion section, the discussion is divided into three main components. The characteristics of sludge include moisture content testing. The mechanical performance of sludge added clay brick, which includes compressive strength and water absorption testing. Physical characteristics of sludge added clay brick, which involves two tests, namely Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX) and brick immersion turbidity analysis.

3.1 Characteristics of Sludge

Moisture content is one of the important parameters in determining the physical properties of raw materials, especially sludge from the paper industry, before it is used in brick production. Once the sludge sample is taken and brought to the laboratory for storage, the moisture content test is carried out immediately. Figure 3 shows a wet sludge sample from recycling paper used in this project.

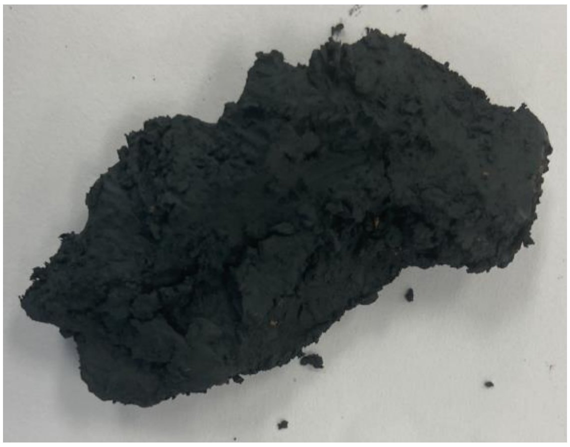

Fig. 3: Sludge of the recycling paper industry

A small portion of the sample is taken, weighed, and then dried in an oven at 105°C for 24 hours. After the drying process is complete, the sample is removed and reweighed to obtain the dry weight. Based on the calculations carried out, this study found that the moisture content in the sludge is 30%, as shown in Table 2.

Table 2: Result of the moisture content of sludge

Sample	Aluminum tin (g)	Volume of sludge (g)	Wet Weight (g)	Dry Weight (g)	Moisture Content (%)
1	27.45	13.8	41.25	29.96	27.4
2	27.63	23.51	51.22	33.25	35.1
3	27.31	15.80	43.11	31.12	27.8
			Average		30.1

3.2 Mechanical Performance of sludge added clay brick

3.2.1 Water Absorption

According to the MS 76:1972 standard, the water absorption rate of a brick must be below 20% to ensure that it is suitable for use in construction. Based on the study conducted, it was found that all the brick samples tested had a water absorption rate of less than 20%, as shown in Table 3. Water absorption tests conducted on clay brick samples mixed with sludge at 0% (as control), 5%, 10%, 15%, and 20% showed the influence of sludge content on the air absorption capacity of the brick. Figure 4 shows the brick of 10% being soaked for 24 hours. These results provide a clear picture that the addition of sludge in the ratio studied does not affect the set air absorption standards. This test should be conducted separately for each mix ratio to observe the difference in the color of the water resulting from the soaking. A total of 7 liters of water was used for each container to ensure the bricks were fully soaked to obtain consistent and accurate results.

Fig. 4: One of the ratios (10%) that are being soaked.

Table 3: Average result of water absorption for each ratio

	Control	5%	10%	15%	20%
Water absorption (%)	14.82	10.77	11.84	16.06	14.13

From the results obtained, the control brick, which is without sludge, recorded the highest water absorption rate with an average of 14.82%. This may be due to the naturally porous structure of pure clay and the effect of non-uniform shrinkage during firing. On the other hand, bricks with 5% sludge showed the lowest absorption rate, with an average of only 10.77%, making it the most stable sample in terms of density and ability to resist water ingress.

However, when the percentage of sludge was increased to 10%, the water absorption rate rose again to an average of 11.84%. Although this value remains within acceptable limits based on BS 3921, it suggests that the internal structure of the brick begins to exhibit increased porosity, potentially caused by the introduction of air voids. This trend became more evident at 15% and 20% sludge incorporation, with water absorption levels recorded at 16.06% and 14.13%, respectively. These higher values indicate that sludge, particularly due to its organic content, low density, and light composition, can reduce the brick's compactness and water-holding resistance, leading to higher porosity and moisture permeability.

Based on the tests conducted on the brick samples, namely water absorption, it was found that the 5% sludge added clay brick ratio showed the best performance compared to the 10%, 15%, and 20% ratios. If examined in detail, the water absorption test results for bricks with a ratio of 5% recorded a low absorption rate of only 10.77%, which is far below the maximum limit of 20% set by the MS 76:1972 standard. This shows the sludge added clay brick ability to reduce porosity and maintain the brick's stability when exposed to moisture.

3.2.2 Compressive Strength

Table 4 shows the compressive strength values for each sample tested. Three samples were taken for each mix ratio, making a total of 15 samples for this test only. Based on the data obtained, it was found that none of the mix ratios reached the minimum level of compressive strength specified by the MS 76:1972 standard, which is at least 5 MPa for bricks used in construction. This result indicates that the addition of sludge in the range studied has a negative effect on the strength of the brick structure.

Table 4: Average result of compressive Strength for each ratio

	Control	5%	10%	15%	20%
Compressive Strength (MPa)	0.803	0.440	0.370	0.210	0.077

According to MS 76:1972 (Standard for Burnt Clay Bricks in Malaysia), the minimum compressive strength for common burnt clay bricks is 5 MPa. This requirement ensures that bricks are suitable for general construction and can bear moderate loads safely. None of the brick samples produced in this study met this requirement, primarily due to the firing limitations, as bricks were only heated at 200°C, far below the standard industrial firing range of 900°C–1000°C [33].

If observed in detail, the strength of the bricks shows a decreasing trend as the percentage of sludge content is added to the clay mixture. This result proves that the addition of sludge has a negative effect on the compressive strength of the bricks, thus affecting the stability of their structure. The reduction in compressive strength was observed after incorporating sludge in clay body [38].

Meanwhile, for the compressive strength test, although the value obtained did not reach the minimum level set by the standard and was still below the strength of the control brick (without sludge), the brick with a mixture of 5% still recorded the highest value among all the mixture ratios tested. This shows a strong potential that, if the brick production process is carried out more carefully and according to optimal procedures [38]. The compressive strength of bricks at this ratio can likely be increased to exceed the minimum limit required in MS 76:1972.

3.3 Characteristics of sludge added clay brick

3.3.1 Brick Immersion Turbidity (Colour)

During the water absorption test, it was found that the brick-soaking water experienced a significant color change. This change occurred because the materials from the brick, especially pigments and fine particles, dissolved and dispersed into the soaking water. This situation indicated that the brick mixture, especially those containing sludge, could release dissolved materials into the aqueous environment. Figure 5 shows The color produced from each brick immersion according to the ratio. Each sample of the soaking water was taken and tested for turbidity using a DR6000 UV-Vis Spectrophotometer, following the APHA Standard Methods 2120C for True Color Measurement [37].

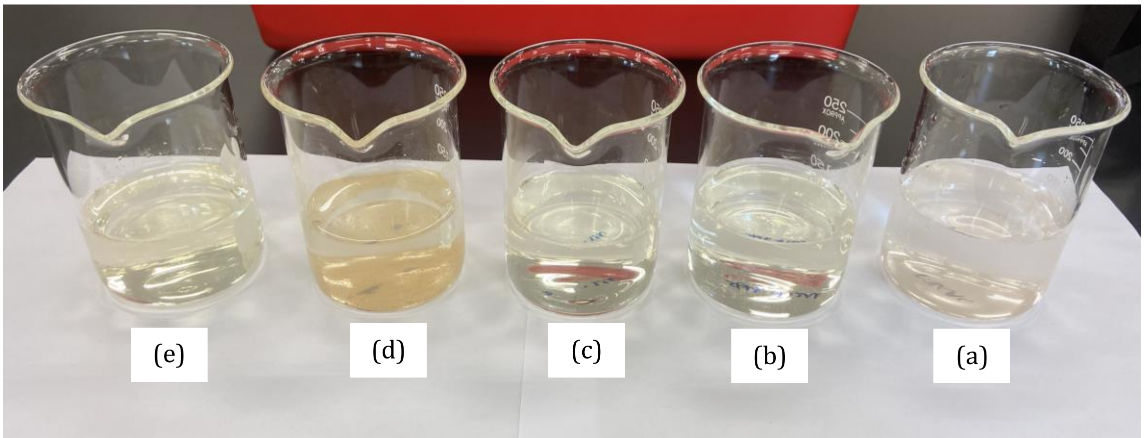

Fig. 5: Turbidity each ratio: (a) control, (b) 5%, (c) 10%, (d) 15%, (e) 20%

Table 5 shows the color intensity readings for each mixture ratio, with units measured in Platinum-Cobalt units (Pt-Co). The brick with a 15% sludge mixture generally recorded the highest color intensity level of 85 Pt-Co, indicating a higher concentration of dissolved materials than other ratios. These results suggest that adding sludge at a specific rate can increase the potential for releasing dissolved materials into the water.

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Table 5: The result of turbidity

	Control	5%	10%	15%	20%
Colour Intensity (Ph-Co)	15	30	31	82	63

In detail, each brick produced releases color when exposed to water. This high value suggests the significant release of soluble compounds, including organic matter, paper dyes, suspended solids, and perhaps heavy metals, into the soaking water. The turbid appearance of the water further supports the presence of fine particles unbound in the brick matrix, which have been mobilized during soaking. This behavior reflects the known chemical characteristics of paper sludge, which often contains residues such as lignin, cellulose fibers, printing inks, and surfactants [34].

3.3.2 SEM-EDX

The 5% sludge ratio was selected as the best mixture in this study for further analysis through SEM-EDX testing. This selection also considered technical and logistical constraints, where only three samples could be sent to the laboratory for additional testing. SEM-EDX analysis will provide a clearer picture of the bricks' microscopic structure and detect heavy metal elements that may be present due to the use of sludge in the mixture.

Surface morphology and elemental composition were analyzed on clay brick samples containing 5% paper industry sludge using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) methods. The brick samples were cut into small pieces and dried in an oven at 105°C for 24 hours until reaching a stable mass. Next, the samples were attached to a stub and coated with a layer of gold (Au) using a Quorum Q150R S sputter coater for 1–3 minutes to increase surface conductivity.

From the process, the image produced in Figure 6 shows a zoomed image of 1000x. SEM observations at 1000x magnification showed a dense, uniform brick surface structure with few pores. This is in line with the low water absorption test results, proving that at a rate of 5% sludge addition, the material functions as a micro-filler that reduces porosity in the brick matrix.

EDX tests were also conducted in the same area to identify the chemical element composition in the brick. The results, as shown in Figure 7 and Table 6, indicate the presence of carbon (C) elements at 57.90%, oxygen (O) at 30.14%, silicon (Si) at 6.08%, and aluminum (Al) at 4.48%, which are the main components of organic matter and clay. Heavy metal elements such as lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) were also detected in small amounts, 1.03%, 0.21%, 0.12%, and 0.05%, respectively. The presence of these toxic elements indicates a potential risk to the environment. Hence, further tests, such as the Toxicity Characteristic Leaching Procedure (TCLP), are recommended to ensure that heavy metals do not dissolve in humid or wet environments.

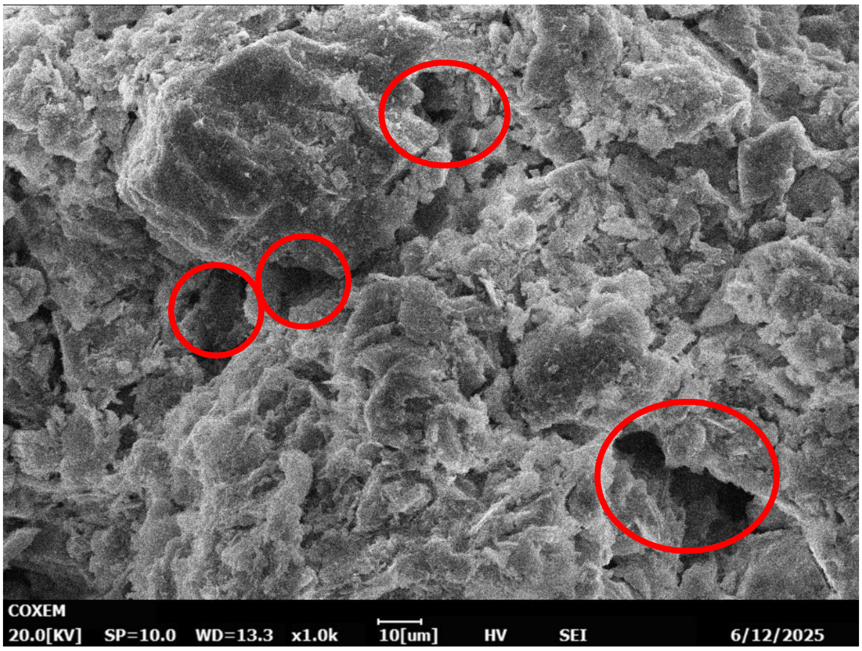

Fig. 6: SEM image of the sample

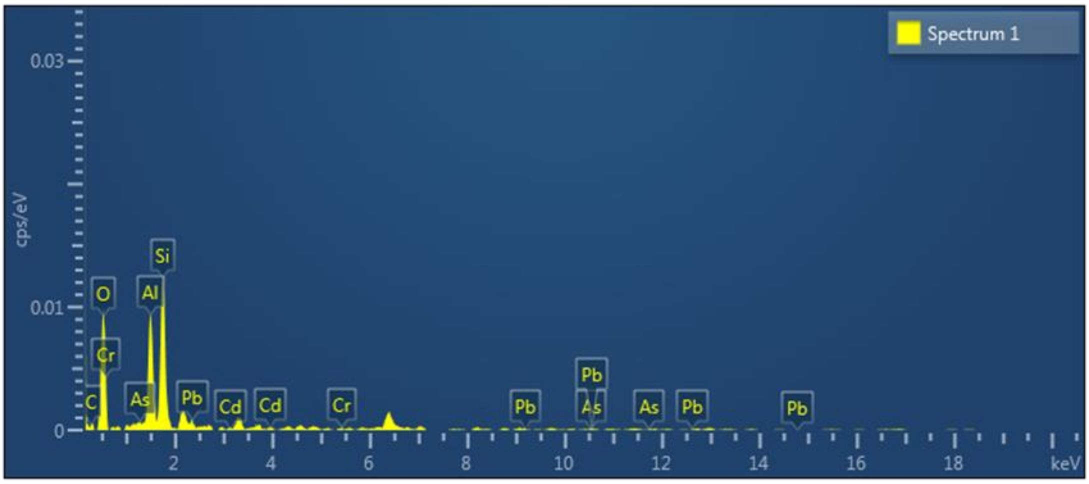

Fig. 7: Graph element on sample

Table 6: The results of the Energy Dispersive X-ray (EDX)

Spectrum 1				
Element	**Line Type**	**Weight %**	**Weight % Sigma**	**Atomic %**
Si	K series	6.08	0.90	3.05
O	K series	30.14	5.67	26.55
Al	K series	4.48	0.83	2.34
C	K series	57.90	4.85	67.93
Cd	L series	0.21	0.52	0.03
Cr	K series	0.12	0.31	0.03
Pb	M series	1.03	1.12	0.07
As	L series	0.05	0.68	0.01
Total		100		100

4. Conclusion

This study evaluated the potential use of paper industry sludge as an additive in clay brick production. As a by-product of wastewater treatment, sludge contains organic matter, fine particles, and heavy metals that can harm the environment if not managed properly. In line with sustainable development goals, this study assessed its reuse potential in brickmaking, focusing on physical, mechanical, and environmental safety aspects.

The moisture content in the sludge was analyzed and found to have an average rate of 30%, an essential value in planning the raw material mix ratio. Five brick mix ratios were produced: 0% (control), 5%, 10%, 15%, and 20% sludge, and tested regarding water absorption rate and compressive strength. The results showed that all samples met the water absorption standards according to MS 76:1972 (less than 20%), with the 5% ratio recording the lowest absorption of 10.77%. Regarding compressive strength, no sample exceeded the minimum value of 5 MPa set by the standard, but the 5% ratio still showed the highest performance among the samples tested. The failure to achieve this strength standard is believed to be due to the constraints of the combustion temperature, which only reached 200°C compared to the usual industrial range of 800–1000°C.

Further tests using the SEM-EDX method were carried out on bricks with a ratio of 5%, which was identified as the best mixture. The SEM results showed a dense and uniform brick surface structure with few pores, proving the role of sludge as a micro-filler that helps reduce the porosity of the brick. Meanwhile, the EDX test identified significant elements such as carbon, oxygen, silicon, and aluminum derived from natural raw materials and sludge organic matter. However, heavy metal elements such as lead, cadmium, chromium, and arsenic were also detected in low concentrations, thus raising the need for further studies regarding the potential for leaching toxic substances in humid environments.

The findings indicate that paper industry sludge can be effectively utilized as an additive in clay brick production, especially for lowering water absorption and possibly improving thermal performance, as long as the firing process is conducted within the optimal temperature range of 900°C to 1100°C. However, several constraints that affect the study's results have been identified, especially in the combustion process, which does not reach industry-standard temperatures. Therefore, for future studies, it is recommended that the brick production process be carried out using high-temperature furnaces to ensure that the bricks reach full maturity and strength that complies with construction standards. In addition, environmental safety aspects need to be paid attention to by implementing the Toxicity Characteristic Leaching Procedure (TCLP) test to ensure that heavy metals do not dissolve and pollute water resources if the bricks are used in humid or wet environments.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

This journal requires that all authors take public responsibility for the content of the work submitted for review

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