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Review

Suitability of Reusing the Spent Diatomaceous Earth in Brick Production: A Review

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Abstract
Diatomaceous Earth (DE) is commonly used as a filter material in the brewery industry. Spent Diatomaceous Earth (SDE) is an industrial waste generated after filling DE pores with impurities from brewing industries during filtration. After the final filtering process, this SDE is disposed into dumping areas, causing numerous environmental concerns. SDE has been recently reported as a substitute for clay in brick production. Incorporating SDE with clay in brick production can reduce the amount of clay added to the brick and the SDE waste discharged into the environment. However, only limited literature is available on SDE utilization in brick production. This paper reviews the recent research on reusing SDE in brick production. Moreover, the manufacturing process of bricks, including essential chemical reactions accompanying the firing of brick, properties of SDE and clay, factors maintained in brick, and affecting the quality of brick, have also been discussed in this review.

Keywords: Bricks, clay, diatomaceous earth (DE), spent diatomaceous earth (SDE), recycling

Introduction

The generation of waste materials and by-products from the various industries, including food and breweries, textile, paint, and agriculture, has become a significant issue for the environment and society. For instance, according to the United States Environment Protection Agency (EPA) Guide for Industrial Waste Management 2021, approximately 7.6 billion tons of industrial solid waste are discharged from many American industrial facilities annually [1]. Moreover, industrial waste management guidelines are also released every year to industries by the international environmental and health regulatory agencies and local governments to ensure proper management of waste. As a result, many investigations are underway worldwide to reduce, reuse or recycle industrial solid waste [2].

Diatomaceous earth (DE) is obtained from deposits formed by sedimentation of the fossilized skeletons of unicellular marine algae called diatoms with siliceous skeletons associated with clay minerals and quartz [3,4]. DE typically consists of over 85% silicon dioxide (SiO_2), with a considerable amount of alumina (Al_2O_3) [5]. Among the several reserves of diatomites, the world's largest reserves are in the United States and China. World production of DE in 2013 was 2.3 Mt where the United States accounted for 33%, China for 18%, Denmark for 14%, and Peru for 5.3%. In addition, small amounts of diatomaceous earth are obtained in twenty-five other countries [6]. Diatomaceous earth, known as Kieselguhr, is a non-metallic, soft, brittle, fine-grained, and siliceous sedimentary rock. DE has been widely employed as filler, adsorbent, packing material, catalyst, thickener, extender, and natural insecticide [7]. It is also broadly used as a filter medium to separate fine particles. For instance, DE is

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mainly used for filtering water, juice, beer, wine, spirits, syrups, and gelatin in food processing and brewery industries [8]. Diatom structure is quite complex as it contains many fine pores and channels that help the material maintain a low specific weight, low heat conduction, high specific surface area, and high absorption capacity [3]. In addition, DE is also a good insulator as it contains silica-rich small particles with a highly porous structure [9,10].

Spent DE (SDE) is an industrial waste generated mainly from the food processing and brewery industries [11,12]. Breweries produce approximately 378.1 million kilograms of SDE annually [13,14]. Due to high energy, cost, and labor requirements, Regeneration DE from SDE is not practically a viable option. Therefore, most SDE is typically landfilled or discarded in the environment without any further pretreatment. Disposing SDE into the environment has several adverse effects, including land degradation, inland water pollution, loss of agricultural lands, deforestation, air pollution, and loss of biodiversity [3]. Recently, the use of SDE in agricultural, construction, and brick production industries has merged as a feasible, environmentally friendly, and economically feasible approach. Therefore, there is significant interest in utilizing SDE for other applications.

Over the past few years, SDE has been considered in the construction industry, including the bricks manufacturing process [15], owing to its unique properties. Interestingly, diatoms were used in the construction of the building by the ancient Egyptians [16]. Clay mixed with SDE help to reduce the fuel consumption during the firing processing by reducing the vitrification temperature and by adding additional calorific value from organic matter in SDE. [17,18] The vitrification temperature is lowered due to the transformation of silica aluminate into different crystal and glass phases, acting as fluxes [2]. SDE also decreases the weight of the brick by increasing the porosity inside the brick. Therefore, SDE can be used to make lightweight calcium silicate bricks with good thermal insulating properties [10]. In addition, the high-water content in SDE saves the amount of water required for the brick production process. Moreover, instead of using the typical synthetic pore-forming material such as expanded polystyrene, which has regulatory limits on gaseous effluent emission, SDE offers a practical and affordable option to reduce the bulk density of ceramic bricks [3]. SDE also reduces the amount of clay required during brick manufacturing. Most importantly, using SDE to manufacture bricks help reduce waste disposal and protect the environment [3,15].

Although there is an increasing interest in utilizing SDE in brick manufacturing production, there is scarce literature. Therefore, this review paper focuses on the use of SDE in the brick manufacturing process. Moreover, this paper also discusses the basic brick production process, properties of clay, SDE, and bricks, factors affecting the quality of a brick, and a comparison of basic properties of a brick with SDE present. To the best of our knowledge, this is the first attempt to review the application of SDE in the brick manufacturing process.

Manufacturing Process of Bricks

The main processes of brick manufacturing include:

- Evaporation water
- Mineral decomposition
- Carbon burnout
- Quartz inversion
- Vitrification

Evaporation Water

Water evaporates in two stages during the burning of bricks. First, surface-bound water evaporates from surface pores and spaces at 100–150°C as an exothermic process. Then, at 600 –900°C, chemically-bound water or hydroxyl water evaporates from the bricks in the second step. Generally, the clay type and mixing composition directly impact the water evaporation rate [19].

Mineral Decomposition

The qualities of bricks are determined by the mineral transformations that occur during the fire of raw materials [20]. Despite the extensive production of bricks, the mineralogical decomposition, and dynamic interactions between different mineral phases during the brick firing process have yet to be extensively investigated. The factors that influence the mineral decomposition include the type of raw material and its composition, the presence or absence of additives, firing temperatures, and oxidation or reduction conditions inside the kiln [21,22].

Carbon Burnout

The black color core generally found at the center of the fired clay body is caused directly by unburnt/unoxidized carbon. Therefore, the burnout of carbonaceous material is also vital during the firing process because carbon burnout eliminates the carbon black core [23] due to the water-gas interaction [24]. There are two steps to the oxidation of carbon in brick clay. The first stage is governed by gas diffusion, while the second is governed by the porosity of the material [25].

Quartz Inversion

Brick-making soil mainly consists of silica with an alpha (α)-quartz crystal structure. During the firing of bricks, the α-quartz structure changes into beta (β) quartz crystal structure at 573°C and 1 atm pressure, a reversible reaction known as the quartz inversion [26,27]. Due to this transformation, volume is expanded by about 2%. Furthermore, the transformation of α to β quartz crystal structure during the heating process is endothermic. In contrast, the cooling process of bricks is exothermic [26,28]. Therefore, the heating and cooling rates near the quartz inversion temperature must be carefully controlled to achieve a uniform temperature. This inversion may lead to the cracking of brick if the cooling process occurs abruptly through the inversion temperature [27]. Generally, the thermal cracking can be avoided by maintaining a cooling rate below 50 °C/hour as recommended.

Vitrification

Vitrification is the process of partial fusion of clay particles during the firing process. As vitrification occurs, the proportion of glassy bond increases, and it ties the entire mass together, providing strength to the brick [6,27,29]. The vitrification also lowers the porosity of the fired product. The amount of clay melted during firing is determined by the temperature and time of the heat treatment. Clay begins to vitrify at around 900°C. The vitrification temperature is determined by the types of minerals present in the clay, their proportions, and fluxing oxides such as ferrous oxide, lime, magnesia, and potash. Fluxing oxides tend to lower the vitrification temperature [27].

Chemical Reactions Accompanying the Firing of Brick

During the initial firing stage, loosely attached water evaporates at around 100 °C [30].

The combustion of organic matter present in clay occurs between 200 °C and 500 °C [2]. As the temperature rises further, chemically bound water evaporates, called dehydroxylation. For instance, the dihydroxylation of kaolin minerals in clay occurs at 400-700 °C [28], see equation (1).

$$Al_2O_3.2SiO_2.2H_2O \rightarrow Al_2O_3.2SiO_2 + 2H_2O \qquad \text{Equation (1)}$$

Dehydroxylation of montmorillonite mineral present in two steps at 600-800 and 850-925 °C. The dihydroxylation reaction of montmorillonite mineral is given in equation (2).

$$Al_2O_3.4SiO_2.H_2O \rightarrow Al_2O_3.4SiO_2 + H_2O \qquad \text{Equation (2)}$$

Muscovite mica can be found as a mineral in clay. Some clay types contain minerals like pyrite (FeS_2) and calcium limestone ($CaCO_3$) [31,32]. The red color of the bricks is caused by the oxidized iron, which is given by the two-stage decomposition of pyrite at 380 and 412 °C, see equations (3) and (4) [28,29].

$$FeS_2 + O_2 \rightarrow FeS + SO_2 \qquad \text{Equation (3)}$$

$$FeS + 7O_2 \rightarrow 2Fe_2O_3 + SO_2 \qquad \text{Equation (4)}$$

As given in equation (5), $CaCO_3$ decomposes at 800 °C into CaO (lime) and CO_2, which helps to increase the porosity of the brick [33,34].

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{Equation (5)}$$

In the presence of water, CaO is converted into $Ca(OH)_2$, see equation (6). Finally, $Ca(OH)_2$ is converted to $CaCO_3$ in the presence of atmospheric CO_2, see equation (7).

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad \text{Equation (6)}$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad \text{Equation (7)}$$

As a result of these reactions, volume increases, causing the formation of fissures called lime blowing [35]. Lime blowing could increase the porosity. Lime (CaO) and periclase (MgO), which are decomposition products of dolomite, transform into portlandite ($Ca(OH)_2$) and brucite ($Mg(OH)_2$) in the presence of water, increasing the porosity of brick. Then later in the presence of carbon dioxide, brucite is converted to hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) [36].

Properties of SDE and Clay

Characteristics of Spent Diatomaceous Earth (SDE)

Diatomaceous earth (DE) is the skeleton remains of diatoms that existed in large numbers over 5-15 million years ago [37] and it is a naturally occurring clay material. It has highly porous fossilized remains and each granule consists of millions of microscopic, hollow, perforated cylindrical shells. Those characteristics result in a lightweight, high porosity, and thermally resistant adsorbent material [38]. Figure 1 shows the microscopic structure of DE.

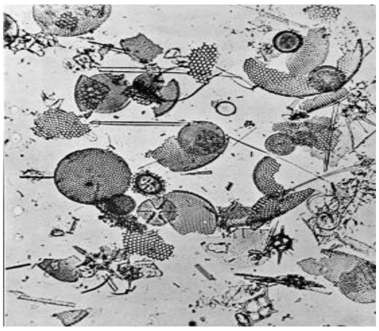

Figure 1. Microscopic structure of DE. Reprinted with permission obtained from ref [5].

DE uses as a filter medium because of its porous nature [39]. Figure 2 depicts the particle size distribution of DE. As shown in Figure 2, the particle size of DE varies from 6 to 200 μm and the average particle size is around 47 μm [39]. Due to the lightweight, porous, and thermal resistant properties, SDE has been considered for building, humidity regulation, and adsorbent materials [38,39,40]. Diatomaceous bricks can withstand high temperatures and insulate high-temperature furnaces like asbestos [5]. Due to its microporous structure, DE decreases the convection heat transfer by decreasing the air circulation. Moreover, the DE also reduces the heat transfer by radiation because of the various reflecting surfaces that bound the pores in diatomaceous earth [5]. In addition, SDE contains fluxing oxides (K_2O, Na_2O) and auxiliary fluxing oxides (CaO, MgO, Fe_2O_3) that also contribute to reducing the firing temperature during the brick formation process [2].

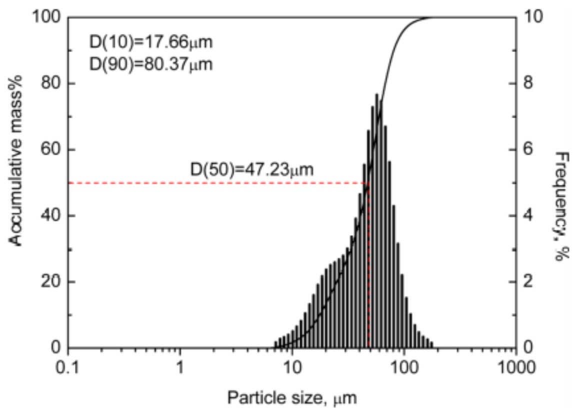

Figure 2. Particle size distribution of DE earth. Reprinted with permission obtained from ref. [39].

Characteristics of Clay

There are three main types of clay found in the environment: black, yellow, and red clay. The chemical compositions of the three clay types are summarized in Table1. Yellow clay contains the highest silica content, whereas Black clay contains the highest alumina content. Black clay shows a higher weight loss of 13.42% during the firing since it has the highest organic matter and carbonate content. During the firing, weight loss occurs due to the combustion of organic matter and decomposition of carbonates. Red clay has the lowest weight loss of 8.47% due to the lower carbonate content [2]. However, the moderate amount of carbonate present leads to increased compressive strength and reduces shrinkage and anisotropic behavior. Also, carbonates can act as a flux [41]. In red clay, carbonates are commonly found as dolomite than calcite. Therefore, decomposition of carbonates in the red clay occurs at a lower temperature (700 °C) than in yellow clay (720 °C) [2].

Chemical and Mineralogical Composition of SDE and Clay

Tables 1 and 2 summarize the chemical and mineralogical composition of SDE and clay. As shown in Table 1, SiO_2 (74.61 %) is the main constituent in SDE and Al_2O_3 (aluminum oxide) (5.48%) is the second common constituent. In addition, fluxing oxides (K_2O) and auxiliary fluxing oxides (CaO +Fe_2O_3) [2] are also present in SDE. Due to the presence of fluxing and auxiliary fluxing oxides, the firing temperature of the bricks decreases, making SDE a suitable additive for brick production. Clay is crystalline in nature, and quartz is the major mineral found in clay, see Table 2. In contrast, the amorphous phase predominates in SDE, while the crystalline phase contains only quartz and cristobalite, see Table 2.

Table 1. Chemical composition of SDE and clay [2,15].

Oxide content	Clay (%)	SDE (%)	Yellow Clay (%)	Red Clay (%)	Black Clay (%)
SiO_2	55.28	74.61	60.40	50.15	42.49
Al_2O_3	12.12	5.48	11.46	19.67	8.56
Fe_2O_3	4.83	0.73	4.02	8.21	3.72
CaO	9.21	0.48	8.73	2.80	11.26
MgO	1.49	0.12	1.39	3.57	2.55
MnO	0.03	-	0.03	0.12	0.03
Na_2O	0.49	1.32	0.38	0.02	0.21
K_2O	2.78	1.45	2.73	6.37	2.57
TiO_2	0.83	0.30	0.64	0.83	0.61
P_2O_5	0.12	0.39	0.10	0.16	0.11
ZnO	-	0.1	-	-	-
V_2O_5	-	0.05	-	-	-
Zn (ppm)	279.3	-	-	-	-
LOI	10.55	13.40	9.54	7.86	9.80

*LOI: Loss of Ignition

Table 2. Mineralogical composition of SDE and clay [4]

Oxide content (%)	Clay	SDE
Quartz	40	15
Cristobalite	n.d.	30
Feldspars	7	n.d.
Calcite	8	n.d.
Dolomite	4	n.d.
Magnesium Silicate	n.d.	n.d.
Phyllosilicates	39	n.d.
Amorphous	n.d.	55

*n.d.: Not detected

Factors Maintained in a Brick

When a brick is used for construction purposes, it should meet specific specifications. Table 3 summarizes the categorization of different brick types according to American Society for Testing and Materials (ASTM) standards based on water absorption and compressive strength. Those two factors mainly affect the durability of the brick. As seen in Table 3, engineering bricks are divided into A and B, which require the highest compressive strength and the lowest water absorption percentage compared to other brick types. Building bricks are mainly divided into three categories as severe weather (SW), moderate weather (MW) and no weather (NW). NW bricks need the lowest compressive strength since those are not used in load-bearing walls, while SW bricks require much higher compressive strength because those are employed in walls exposed to severe weather conditions.

Table 3. Brick categorization according to ASTM standards (Adapted with permission obtained from ref. [42]).

Brick Type		Cold water Absorption (%)	Compressive Strength (MPa)
Building Brick	SW	16	20.7
	MW	22.5	17.2
	NW	-	10.3
Facing Brick	MW	22.5	17.2
	NW	-	10.3
Engineering Brick	A	4.5	69.0
	B	7.0	48.5

[a]SW – Severe Weather; [b]MW – Moderate Weather; [c]NW – No Weather

The application of each bricks type depends on the location, weather resisting capability and purpose of use. Table 4 shows different types of bricks, their specifications and usage based on location, weather resisting ability and purpose of use.

Table 4. Bricks classification (adapted with permission obtained from ref. [43]).

Basis	Type	Specifications and Usage
location	Facing brick	● Used on the exterior wall of buildings ● weather resistant ● stronger than other bricks and have better durability
	Backing brick	● Used behind the facing bricks to provide support
weather resisting capability	Severe Weather	● Used in the countries which are covered in snow most of the time of year ● Resistant to any kind of freeze-thaw actions
	Moderate Weather	● Used in the tropical countries ● They can withstand any high temperature
	No Weather	● Do not have any weather resisting capabilities ● Used on the inside walls
Purpose of use	Common bricks	● Low quality, low compressive strength. used on the interior walls
	Engineering bricks	● High compressive strength and low absorption capacity ● Strong and dense

Compressive Strength

Compressive strength is the most relevant mechanical index for building material. According to European and ASTM standards, the minimum average compressive strength for moderate weathering bricks is 17.2 MPa and for severe weathering bricks is 20.7 Mpa [44]. Typically, the compressive stress of a brick decreases with increasing the open porosity because irregular-shaped elongated pores and other microscopic imperfections act as stress concentrator notches [2]. Carbonate content in clay generally leads to an increase the compressive strength. Moreover, textural and microstructural characteristics are correlated with the bricks' compressive strength, including increasing vitrification [45]. Figure 3 shows the change in the comprehensive strength upon firing of calcareous (Viznar) and non-calcareous (Guadix) bricks [45]. Viznar is the clay that contains significant amounts of calcite and dolomite, while Guadix contains no carbonates.

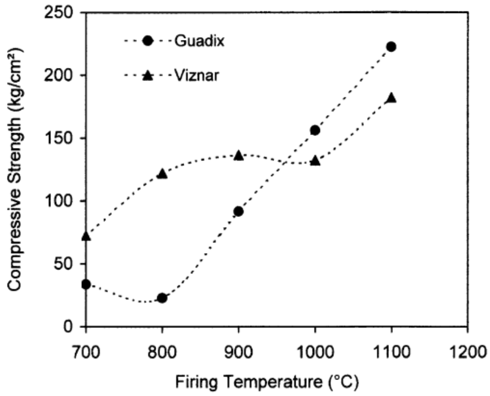

Figure 3. Compressive strength evolution upon firing of calcareous (Viznar) and non-calcareous (Guadix) clay. Reprinted with permission obtained from ref [45].

Tensile Strength

The tensile strength of a brick is negligible compared to its compressive strength. Therefore, bricks perform well under high compressive forces. However, a negligible tensile strength can make the structure more vulnerable during earthquake situations [46]. The cracking of brick happens due to stress depending on external loadings, temperature, humidity, deformation properties, and low tensile and shear strengths [47]. Also, the tensile strength of brick is more vital when the reinforcement is not considered in the structure. This type of construction is required in corrosion zones such as coastal areas and splash zones [46].

Water Absorption Capacity

Water absorption capacity directly affects the quality and durability of a brick [2]. It also affects the surface finishing of the brick-laid wall [48]. The durability of the brick increases with decreasing water absorption capacity, increasing the resistance towards natural environmental factors [2]. Typically, the water absorption capacity, which is expressed as a percentage of the dry brick weight, can indicate available pore space in brick. The water absorption capacity of a brick generally changes with the properties of clay, degree of firing, and method of manufacturing [48].

Bending Strength

The bending strength of bricks is essential when walls resist lateral loads such as wind and earth pressure. In addition, the bending strength is crucial for loaded or lightly loaded components such as cellar walls beneath patios, veneer, non-loading, and freestanding walls [49]. Also, bending strength is an important design consideration for unreinforced masonry to avoid cracking unreinforced brick or structural failures [2].

Factors Affecting the Quality of Brick

The quality of a brick varies with many parameters. Therefore, it is difficult to compare the results concerning all parameters individually because many studies were conducted with only a few varying parameters. The following section provides how the quality of brick varies with changing SDE amount present in the clay.

Firing Temperature

Compressive strength is highly affected by firing temperature. Therefore, decreasing firing temperature and firing time reduces the cost of production and increases productivity. Since the quartz invasion temperature of silica is at 573 °C, the minimum temperature of brick firing should maintain above that temperature [48]. The firing defect is, known as the black core, occurs if carbon is not entirely removed by oxidation during the firing process. That could cause by high organic matter in clay and diatomaceous earth [35]. However, at higher temperatures (1000-1100 °C), total pore size and water absorption decreased sharply due to the vitrification and introduced difficulties in holding mortar to the brick [48].

Generally, smaller pores between clay particles begin to disappear at higher temperatures due to the melting and coalescence of particles. However, the larger pores are formed due to gas release caused by the loss of OH- groups in phyllosilicates [45]. The red color occurs due to the high iron oxides [15]. Also, water absorption significantly decreases when increasing the temperature due to the formation of the amorphous phase at high firing temperatures [48]. In contrast, bulk density increases with increasing the firing temperature, and the maximum density occurs at 1000 °C. This is due to the dense microstructure at the beginning of the sintering stage [50]. When the sintering temperature increases from 850 °C to 950 °C, the thermal conductivity of the materials containing diatomaceous waste decreases due to increased porosity [4].

Firing temperature also affects the shrinkage of the bricks during the firing process. High shrinkage causes the destruction of bricks in the firing and drying stages of the production. Shrinkages in bricks occur chemically, and mechanically bound water is lost. In general, weight loss is attributed to the loss of organic matter in clay [48]. The decomposition of organic matter takes place in two distinct stages. The first stage begins at 200 °C with the decomposition of dead bacteria, biodegradable material, undigested organics, and semi-volatile compounds. During the second stage, oxidation of non-volatile components occurs between 400 °C and 550 °C. Also, at the beginning of the firing process, weight loss occurs due to the release of hygroscopic water [2]. Furthermore, brick weight loss also depends on the inorganic substances in clay being burnt off during the firing process [48].

Firing Time

Figures 4 and 5 show the variation of compressive strength and bending strength with firing time. As shown in Figures 5 and 6, there is no significant variation in the mechanical properties with the firing time. The temperature increase should maintain at an adequate rate to avoid rapid firing. The rapid firing may cause the bloating of clay due to the formation of an impermeable vitrified outer skin, preventing the loss of gases such as water vapor and CO_2 from the interior of clay. Therefore, the rate of the firing process is a crucial factor since it affects the final properties of the brick; hence the furnace temperature should gradually increase to the final firing temperature. However, increasing firing time has no significant impact on firing shrinkages and weight loss. The weight loss occurs due to carbonaceous matter combustion and dihydroxylation, which are not time-dependent processes [48]. Therefore, increasing the firing time of bricks may create a waste of energy and time with no improvement to the quality of the bricks.

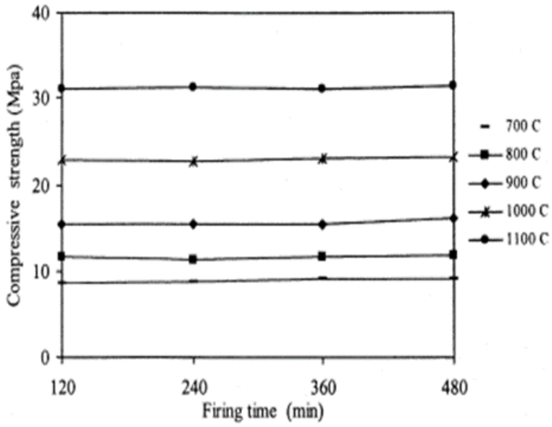

Figure 4. Variation of compressive strength with firing time. Reprinted with permission obtained from ref. [48]

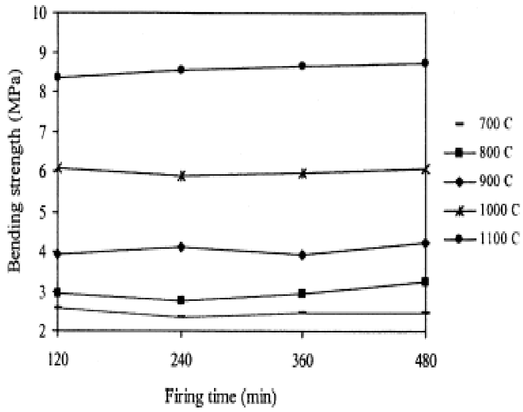

Figure 5. Variation of bending strength with firing time. Reprinted with permission obtained from ref. [48].

SDE Mixing Percentage

Studies have been conducted by varying the SDE mixing ratios from 1 wt% to 15 wt%. Generally, with high SDE mixing percentages, the compressive strength of brick decreases. But with 3 wt% of SDE compressive strength of brick was increased up to 45 MPa when the compressive strength of a control brick was 34 MPa [2]. Also, the bending strength of the bricks is gradually decreasing with increasing the SDE weight percentage. The closest value to the SDE-free brick is obtained by brick with 3 wt% SDE [3]. Figure 6 shows the variation of compressive strength with SDE wt%. As shown in Figure 6, a standard brick with a compressive strength of 25.5 MPa decreases its compressive strength with increasing SDE mixing percentage. Compressive strength with 22.5 MPa was obtained with 4 wt% SDE, the closest to the standard value [15].

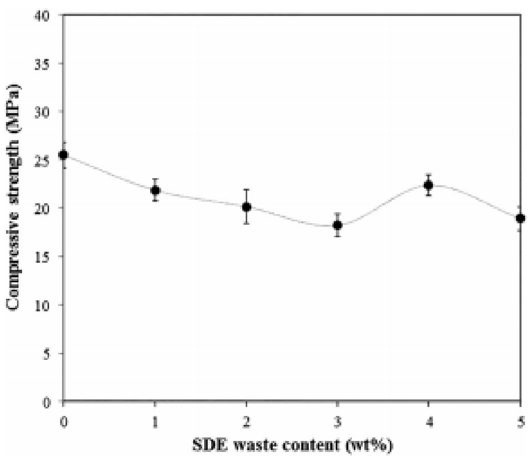

Figure 6. Variation of compressive strength with SDE wt% Reprinted with permission obtained from ref. [15].

In addition to weight loss due to dehydroxylation reaction, carbonate decomposition, loss of humidity, and organic matter combustion in clay increase with increasing SDE mixing percentage. This is due to the contribution of the organic and inorganic matter of SDE [2].

Figure 7 shows the effect of waste concentration on water absorption (%), open porosity (%) and bulk density (kg/m^3) of the fired bricks at different SDE wt% [2]. As shown in Figure 7, water absorption capacity increases with increasing SDE. This is due to the increased interconnected surface porosity with growing pores size and number. Organic waste also increases with increasing the SDE mixing percentage. The minimum water absorption rate shows as 3.31 kg/m^2.min, when the SDE mixing percentage is 3 wt%, which is lower than the maximum acceptable water suction rate of 4.5 kg/m^2.min [2].

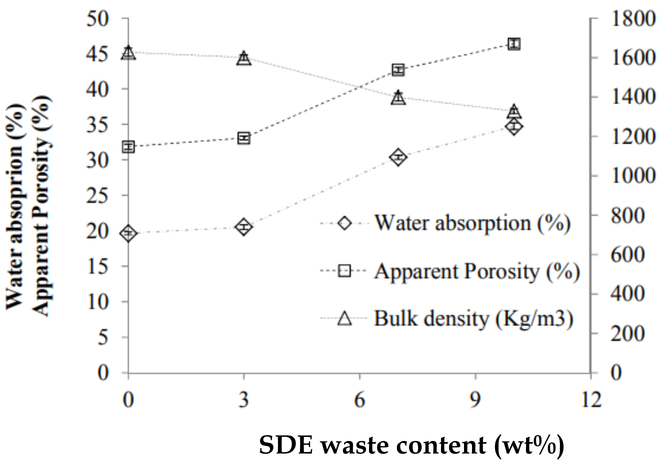

Figure 7. Effect of waste concentration on water absorption (%), open porosity (%) and bulk density (kg/m^3) of the fired bricks. Reprinted with permission obtained from ref. [2].

Cotes-Palomino et al. showed the highest density of the brick for the sample with 3% SDE (wt%). This is due to the low porosity of 3% SDE (wt%) [2]. Therefore, as the SDE Wt% increases, the bulk density of the brick decreases [2,3]. Furthermore, an increase in SDE wt% leads to more irregular pores. Moreover, the compressive strength of fired brick decreases significantly due to insufficient densification [2], angular pores, and fissuring at pore edges with increasing SDE wt% [15].

SDE contributes to the thermal conductivity due to the presence of quartz. However, increasing the SDE wt% decreases the thermal conductivity as the porosity increases. For example, Galán-Arboledas et al. reported the least thermal conductivity (0.58 W/m.K) of the brick when 7 wt% of SDE was mixed with soil and treated at 950 °C [4].

Drying Process

When the moisture content is higher in the brick, swelling and bloating occur during the firing process, caused by the expansion of entrapped water. Therefore, the excess moisture is removed at relatively low temperatures [48]. The following equation, equation (8), is used to calculate the Nosova index (Ks), which determines the degree of sensitivity of the clay to drying. This parameter shows the sensibility of a clay mixture to the dying process [4].

$$K_s = \frac{V}{V_1\left[\frac{W_1 - W}{V_1 - V}\right]} \qquad \text{Equation(8)}$$

Where,

V = Volume of clay body after air-drying

V_1 = Initial volume of the wet clay

W_1 = Moisture in the wet sample of clay

W = Moisture content in clay body after air drying

If K_s is lower than 1, the clay bodies are insensitive to the drying. If K_s is greater than 2, the clay bodies are very sensitive to drying and they can be cracked easily [51,52].

Comparison Studies

Table 5 compares the firing temperature, compressive strength, water absorption, and bending strength reported in the literature for different clay types after adding SDE. The bricks made of ceramic paste and 3% SDE showed the highest bending strength of 17.9 MPa and the lowest water absorption percentage at 1000 ° C firing temperature. Furthermore, the bending strength of bricks made using the ceramic paste increased with increasing temperature while the water absorption percentage decreased for a certain SDE mixing percentage. For example, brick made with a clay mixture of 10% red, 40% yellow, and 30% black clay by incorporating 3% SDE and fired at 950 °C showed the highest compressive strength of 45 MPa. As shown in Table 3, both the compressive strength and bending strength showed higher values when the water absorption capacity is at lower.

According to Table 3, a severe weather brick's maximum water absorption capacity is 16%, whereas a moderate weather brick is 22.5%. All the bricks tested with industrial ceramic paste show a lower water absorption percentage than the recommended value for severe weathering bricks, see Tables 3 and 5. The water absorption percentages for moderate weather bricks are made with a mixture of red, yellow, and black clay with 1% and 3% SDE and made by mixing 3% SDE with 10% red, 40% yellow, and 30% black clay and fired at 950 °C are in agreement with the standard values reported, see Tables 3 and 5. According to the literature values reported, all bricks except the compressive strength of the brick made by incorporating 10% SDE into a clay mixture including 10% red, 40% yellow, and 30% black clay and firing at 950°C deviates from the recommended range of compressive strength, see Tables 3, and 5. Bricks with 1 wt%, 3 wt%, and 4 wt% SDE display high compressive strength and can be classified as severe weathering bricks. Brick with 7 wt% SDE has the compressive strength required for no weathering bricks which are used for inner walls and non-load bearing walls.

Table 5. Summary of mechanical parameters obtained from SDE incorporated bricks

Clay type	SDE, %	Size	Firing Temperature, ℃	Compressive Strength, MPa	Water Absorption, %	Bending Strength, MPa	Ref.
The ceramic paste used in the brick industry	3	12 cm × 3 cm × 1 cm	900	-	11.7	15.7	[2]
			950	-	11.5	16.6	
			1000	-	9.6	17.9	
	9		900	-	12.9	14.5	
			950	-	12.7	16	
			1000	-	10.8	17.7	
	15		900	-	15.1	12.7	
			950	-	14.9	14	
			1000	-	12.4	16.1	
Mixture of Red, Yellow, black	1	3 cm × 1 cm × 6 cm	950	22	22	-	[14]
	2			20	24	-	
	3			18	25	-	
	4			22.4	20	-	
	5			19	25	-	
10% Red, 40%Yellow, 30% Black	3	3 cm × 1 cm × 6 cm	950	45	20.5	-	[1]
	7			11	30.4	-	
	10			8	34.8	-	
The ceramic paste used in the brick industry	3	12 cm × 2.8 cm × 1.8 cm	850	-	-	13	[3]
			950	-	-	12.5	
			1050	-	-	14	
	7		850	-	-	13	
			950	-	-	12.5	
			1050	-	-	15.5	
	10		850	-	-	11	
			950	-	-	10.5	
			1050	-	-	13	

Conclusion

The spent diatomaceous earth (SDE) from the brewery industry has been considered in construction materials, including bricks. SDE exhibits intriguing properties, including silica-rich particles, high porosity, lightweight, and thermal insulation. SDE has recently attracted attention as a substitute for the clay traditionally used for manufacturing brick. This review summarized the recent literature on utilizing waste SDE from the brewery in brick manufacturing. Moreover, this review further discussed the brick production process, properties of SDE, clay, and brick, and the key factors affecting brick quality. According to previous studies, the reuse of SDE in bricks does not affect the inert classification of these construction products, contributing to sustainable construction. However, the commercial production of bricks from SDE encounters several setbacks. The possible reasons are the lack of standard methods for producing bricks from SDE, the potential contamination from the SDE, the absence of relevant standards, and the limited acceptance of SDE-based bricks by industry and the public. Overall, the reusing of SDE as secondary raw material in bricks production shows economic and technological potential.

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Conflicts of Interest

The authors declare no conflict of interest.

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