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Light-weight bricks from clay combined with cement kiln dust and sludge wastes

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Abstract

Physical and mechanical properties of the prepared light weight building bricks made from clay, cement kiln dust waste and sewage sludge that fired at 900, 950 and 1000 ˚C were evaluated and studied. Results showed that the water absorption and apparent porosity were diminished and decreased with the replacing of cement kiln dust waste at the expense of sewage sludge till 12 wt. % cement kiln dust waste content, while the bulk density, flexural and compressive strengths were improved and enhanced. Any further increase of cement kiln dust waste content more than 12 wt. %, both physical and mechanical characteristics were adversely affected. All these characteristics were more improved with the increase of firing temperature. Therefore, the optimum brick batch was that containing 12 wt. % cement kiln dust waste at 1000 ˚C.

Keywords: clay, cement kiln dust waste, sewage sludge, absorption, density, porosity, strength

Introduction

Scope of the problem

The continuous increase in the industry of building materials is regarded as one of the main factor for the consumption of naturally occurring resources. Hence, the increasing need of building materials results in a global warming potential increment, which strongly reflects negatively on the climatic changes and the increase of the Earth's surface temperature [1]. This is often due to the very high clinkering temperature (1450 ˚C) to produce clinker which is the main component of Portland cement. Moreover, the fuel combustion and the calcination of limestone are two factors responsible for CO_2 emission during Portland cement production [2], in addition to the emissions of other gasses. Also, considerable amounts of the very light weight cement kiln dust waste (CKDW) are produced from this industry. The global cement production reached to about 4.20 billion tons in 2019 [3], where each ton of Portland cement generates 54-200 kg of CKDW [4]. This CKDW was removed from rotary kiln to avoid its undesirable increase in the resulted clinker. The composition of CKDW usually comprises alkali oxides as CaO, Na_2O, and K_2O and sulfate, chloride, and volatile materials [5-7]. The accumulation of CKDW always accompanied with several environmental problems, particularly its hazardous effect on the plant and human health [8]. The leaching of heavy metals from CKDW into the ground water and landfill consumption are the two main environmental problems caused by CKD-accumulation [9]. Additionally, the low specific gravity of this dust enhances the probability of its bearing by wind, resulting in serious problems for human health including respiratory symptoms, chronic impairment of lung function, eyes problems, skin irritation, and asthma [10]. As a result, the industry of building materials is now facing large challenges affiliating to the conservation of naturally-occurring resources, energy saving, and the mitigation of pollutants resulted from their manufacturing. So, there is a great desire to implement the concept of sustainable construction to achieve these challenges. This could be done by using of wastes as substituents in construction industry, which strongly reflected positively on the conservation of naturally-occurring resources and the reduction of energy. The use of supplementary cementitious materials as: high pulverized fly ash (HPFA), granulated blast-furnace slag (GBFS) and silica fume (SF), etc. as a partial substitution to Portland cement or generally building construction is regarded as one of the suggested solutions to mitigate the CO_2 emission generated during cement industry [11]. The production of low energy cements, such as alkali activated aluminosilicate, limestone cement and magnesium silicate cements or generally blended cements [6, 7, 12], is another favorable solution for resolving the environmental problems resulted from traditional cement production. The replacement of cement by CKDW has resulted in setting times shortening, workability and compressive strength reduction, sulfate expansion, and corrosion induction [13, 14]. Therefore, several studies have recommended that the replacement level of Portland cement by CKDW should not exceed 10 wt % [14]. The high alkali contents in CKDW (3-5 %) enhances the probability of its utilizing as an alternative activator in geopolymeric based materials [15-17]. Recently, 60 wt. % CKDW was successfully used as a good calcium source in the preparation of one-part geopolymer, in the presence of feldspar and sodium hydroxide, using vitrification process [6], and in another study, variety of CKDW contents from 33 - 50 wt. % were used in the production of sustainable pozzolanic materials with different whiteness and reactivity degrees [7]. Lead-bearing-sludge (LBS) from grinding and polishing of lead glass crystals, and sewage sludge ash (SSA) from the incineration of sewage sludge are categorized as silicate-rich-wastes [18]. It was estimated that each person annually generates 10e15 Kg of dry mass sewage sludge [19]. The hazardous impact of these wastes is mainly originated from the considerable heavy metals content within their chemical compositions [20-22].

These wastes can interact with alkalis to build alkali-activated binding materials [7, 23]. Though the fired clay-making bricks has a potential impact on the disposal of SSA and other industrial solid wastes [24-32], this industry requires high processing energy (900-1100 ˚C), having a negative impact on the environment.

Objectives of the study

The recycling of SSA in the cleaner production of building bricks with low processing energy requirements is the urgent need to mitigate the environmental pollution, and also to minimize the manufacturing cost of bricks. Therefore, this paper pays attention to the implementation of an eco-sustainable approach for the disposal of CKDW and SSA in the green production of low energy-bricks. The activation of SSA by the alkali-rich CKDW, often yields hardened materials at ambient temperature. The utilization of CKDW, instead of the high expensive chemical alkali-activators, strongly contributes to the minimization of both cost and the mitigation of CO_2 emission generated from the production of other chemical activators. Regardless the applied strategy which is directly reflected on the mitigation of deleterious impact of CKDW and SSA on the environment, it results in the conservation of naturally-occurring resources that are usually used in brick-making. The low specific gravity of these wastes could benefit in the production of lightweight bricks that could be utilized in many applications. The physical and mechanical properties of the prepared bricks were investigated noticing that the leaching of heavy metals from CKDW and SSA by their conducting to acetic acid leaching test to ensure the safe use of the fabricated bricks on the pilot scale or even high construction projects.

Experimental

Raw materials

Clay (CL), cement kiln dust waste (CKDW) and sewage sludge (SS) are the main raw materials used in the present work. The CL and CKDW samples were obtained from Tourah Cement Company, Giza, Egypt. The SS sample was provided from a local waste water Plant, Faysal, Giza, Egypt. The chemical analysis of the starting raw materials that was carried out by X-ray florescence (XRF) is shown in Table 1.

Table 1: Chemical analysis of the starting raw materials.

Materials oxides	Clay	CKDW	SS
SiO_2	51.47	10.84	44.48
Al_2O_3	28.78	2.26	16.50
Fe_2O_3	3.99	2.53	3.23
CaO	0.61	52.51	8.41
MgO	1.38	0.84	2.53
MnO	0.04	0.6	0.15
Na_2O	1.15	3.83	1.14
K_2O	1.19	1.65	0.67
SO_3	-----	4.43	3.46
TiO_2	1.14	-----	0.11
P_2O_5	0.53	-----	5.41
Cl^-	-----	-----	0.41
PbO	-----	0.03	0.12
ZnO	-----	0.05	0.11
LOI	9.72	24.51	4.79

Preparation of bricks

Firstly, SS sample was let for drying in the open air for seven days, and then for another seven days in a suitable dryer at 105 ˚C till the complete drying. The dried SS was then crushed and well ground. The constitution of the various prepared clay brick batches is shown in Table 2. One mixture was composed of 50 wt. % CL and 50 wt. % SS, which was considered as a blank (K0) to which all results were compared. The SKDW was then added to the blank mix at the expense of SS with different rations as 0, 4, 8, 12, 16, 20 and 24 having the symbols T0, T1, T2, T3, T4, T5 and T6, respectively noticing that the clay content was kept constant by the ratio 50 wt. %, while the two other ingredients were variable.

The dry mixing was conducted using ball mill for two hours to reach the complete homogeneity of all brick batches.

The water was then gradually added to the prepared powder brick batches inside a suitable blender and stirred well till obtaining a brick paste of high workability. Before casting, all molds were oiled with a thin film of a motor engine oil to facilitate the release of the samples from the molds during the de-molding process. Thereafter, the pastes of the brick composites were inserted into 2.5 x 2.5 x 2.5 cm^3 stainless steel lab. cube molds for physical properties [31, 33], or inserted into cylindrical molds of 3 cm height and 1 cm diameter for compressive or crushing strength [34, 35]. Also, five rod-shaped samples of 1x1x7 cm^3 dimensions were cast for flexural strength (FS), where it could be carried out using a simple beam with three points loading system (Figure 1). After molding, the molds were de-molded in the next day, and the released fresh bricks were let to dry first in the open air and direct sun light for three days to get rid of the free and evaporable water content [33]. After that, the dried bricks were conducted to firing process at 900, 950 and 1000 ˚C. The furnace was left to cool gradually overnight till room temperature, and in the following day the fired bricks were excluded from the furnace.

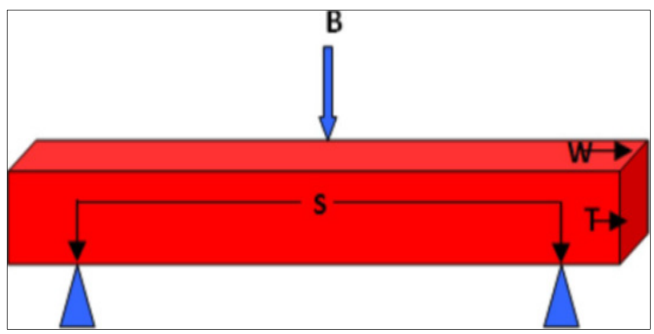

Fig 1: Schematic diagram of the flexural strength (B: beam or load, S: spam, T: thickness, W: width).

Table 2: Batch ratios of the prepared bricks, wt. %.

Materials mixes	Clay	SSA	CKDW
T0	50	50	-----
T1	50	46	4
T2	50	42	8
T3	50	38	12
T4	50	34	16
T5	50	30	20
T6	50	26	24
T7	50	22	28

Methods of investigation

The fired brick samples were immersed in boiling water for 5 hours [34]. Then, the physical properties [35, 36, 37] in terms of water absorption (WA, %), bulk density (g/cm^3) and apparent porosity (AP, %) can be determined from the following relations:-

$$W.A, \% = (W1 - W2)/(W3) \times 100 \quad (1)$$
$$B.D, g/cm^3 = (W3)/(W1 - W2) \quad (2)$$
$$A.P, \% = (W1 - W3)/(W1 - W2) \times 100 \quad (3)$$

Where, W1 is the saturated weight, W2 is the suspended or submerged weight and W3 is the dry weight, respectively.

The flexural or bending strength (FS) [34, 37] of the fired units could be calculated from the following equations:

$$FS = 2L\ (kg) \times S\ (cm) / 2W \times T\ (Kg/cm^2)/10.2\ (MPa) \quad (4)$$

Where, FS is the flexural strength (kg/cm^2), L is the load of rupture, kg, S is the Span (the distance between the two lower beams, 5 cm), W is the width of the sample, cm and T is the thickness of the sample, cm. The compressive or crushing strength was also measured on five fired samples from each brick batch, and the mean value was considered [37, 38] using the following relation:-

$$CS = (D)/(L) \times (w) = kg/cm\ (6)\ 2/10.2\ MPa \quad (5)$$

Where, CS is the compressive strength kg/cm^2, D is the load kg, L and W are the length and width of the samples, respectively.

The fourier transform infrared spectra (FT-IR) were performed by Pye-Unicum SP-1100 in the range of 4000-400 cm^{-1}. The X-ray diffraction analysis (XRD) was employed by a Philips X-Ray Diffractometer of Mod. P.W. 1390 with Ni-filtered Cu-Kα radiation. The particle size distribution (PSD) as well as X-ray fluorescence (XRF) and X-ray diffraction patterns (XRD) analyses were carried out in the Metals Institute, El-Tabbine, Cairo, Egypt. The FT-IR analysis was done in the National Research Centre, Dokki, Cairo, Egypt.

Results and Discussion

Characterization of raw materials

As it is clear from Table 1, the CaO, Na_2O and K_2O represent ~58 wt. % of the total oxides in CKDW. This proved that the CKDW having a high alkali content. The chemical analysis also proved that SSA is mainly composed of SiO_2 and Al_2O_3 with also CaO, SO_3, Fe_2O_3, and low ratios of heavy metals PbO, ZnO, and MnO. The clay sample was mainly composed of kaolinite ($Al_2O_3.2SiO_2.2H_2O$), alumina (Al_2O_3) and silica (SiO_2).

Fourier transform infrared (FT-IR)-spectra (Fig. 2) proved that the CKDW represents different transmittance bands related to stretching vibration of C-O at 1432 and 876 cm^{-1}, and S-O at 1116 cm^{-1} bonded within SO_4^{2-} phase, respectively. A sharp stretching vibration band of OH^- group within Ca $(OH)_2$ was detected at 3644-3640 cm^{-1}. Another band referred to Si-O vibration was identified at 987 cm^{-1}, suggesting the presence of silicate phase. Moreover, the disappearance of bands related to carbonyl and alkyl groups within organic matter at 1760-1710 and 2950-2850 cm^{-1} in case of SS is an evidence for the dissociation of the organic matter in the sewage sludge due to the heat treatment.

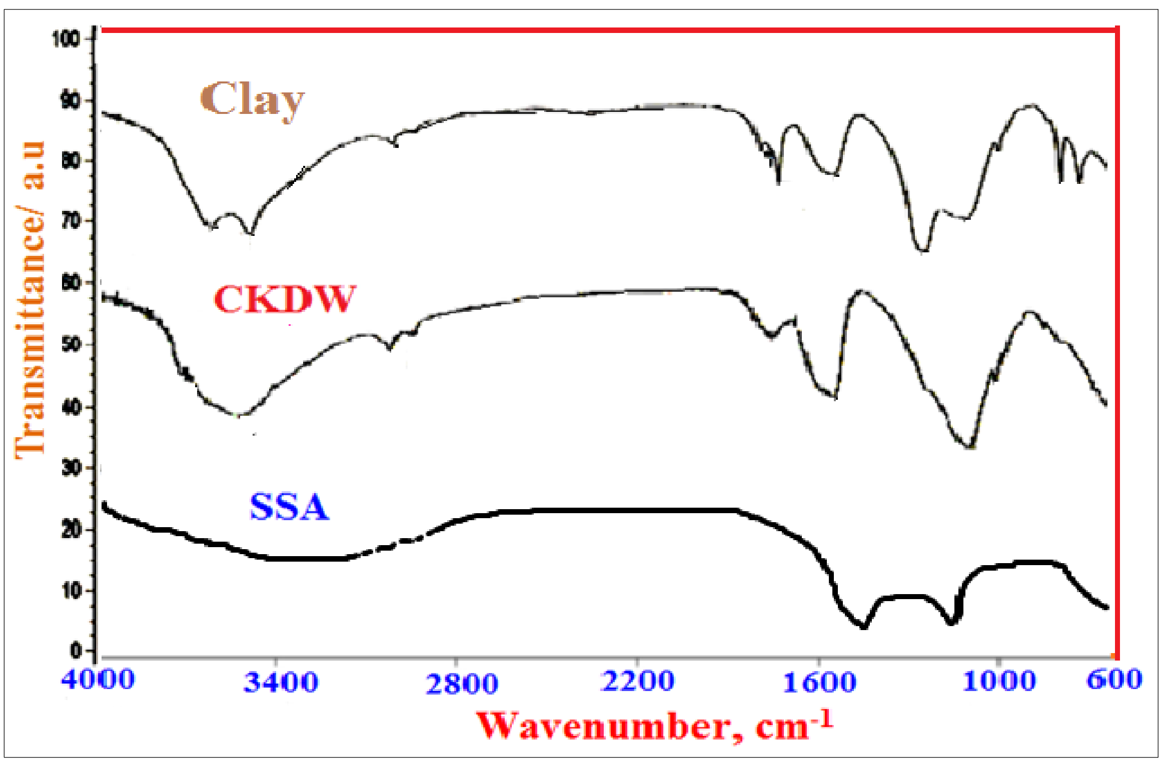

Fig 2: FT-IR spectra of the clay, cement kiln dust waste (CKDW) and sewage sludge (SS) samples.

The XRD patterns of the used raw materials (Figure 3) showed the major four crystalline phases in clay sample as kaolinite ($Al_2O_3.2SiO_2.2H_2O$), montmorillonite ($Al_2H_2O_{12}Si_4$), Quartz (SiO_2) and calcite (Ca CO_3), The lime (CaO), slica (SiO_2) and

Portlandite $Ca(OH)_2$ are the main constituents in CKDW. In case of SSA, new minerals as albite $NaAlSi_3O_8$ and hematite Fe_2O_3 were detected**.**

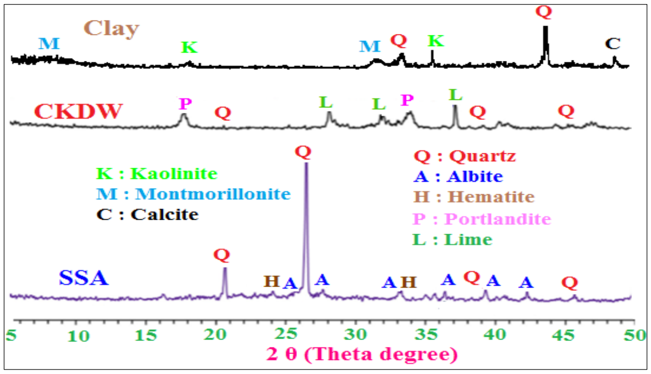

Fig 3: XRD patterns of the clay, cement kiln dust waste (CKDW) and sewage sludge (SS) samples.

Water absorption

The water absorption of the prepared fired brick samples composed of 50 wt. % Clay (CL) and 50 wt. % sewage sludge (SS) which was the control (T0) in which the SS content was substituted with different ratios of CKDW by 0, 4, 8, 12, 16 and 20 wt. % at the expense of SS fired at 900, 950 and 1000 ˚C, respectively is graphically represented in Figure 4. Generally, the water absorption of brick samples of the control (T0) decreased with the incorporation of CKDW only up to 12 wt. % (T3), but increased with further increase of CKDW (T4-T7). Moreover, the water absorption decreased more with firing temperature displaying the same trend. This means that. a positive response was took place with firing temperature. The decrease of water absorption is essentially attributed to the thermal reactions that happened between the constituents of clay and/or sludge with those of CKDW forming new phases closing up the pore structure of the fired bricks, in addition to the activation effect of the nanosilica of the CKDW [34, 37]. With any further increase of these waste ashes, the water absorption started to increase due to the spongy nature of SS which made the bricks to absorb more water due to the more open pore structure [39, 40]. In addition, the large content of nano-silica enhances the total porosity. As a result, the pore structure of the fired samples could be increased. With the increase of firing temperature, the water absorption further decreased.

This is mainly contributed to the increase of thermal reaction between the different ingredients [36, 41-43].

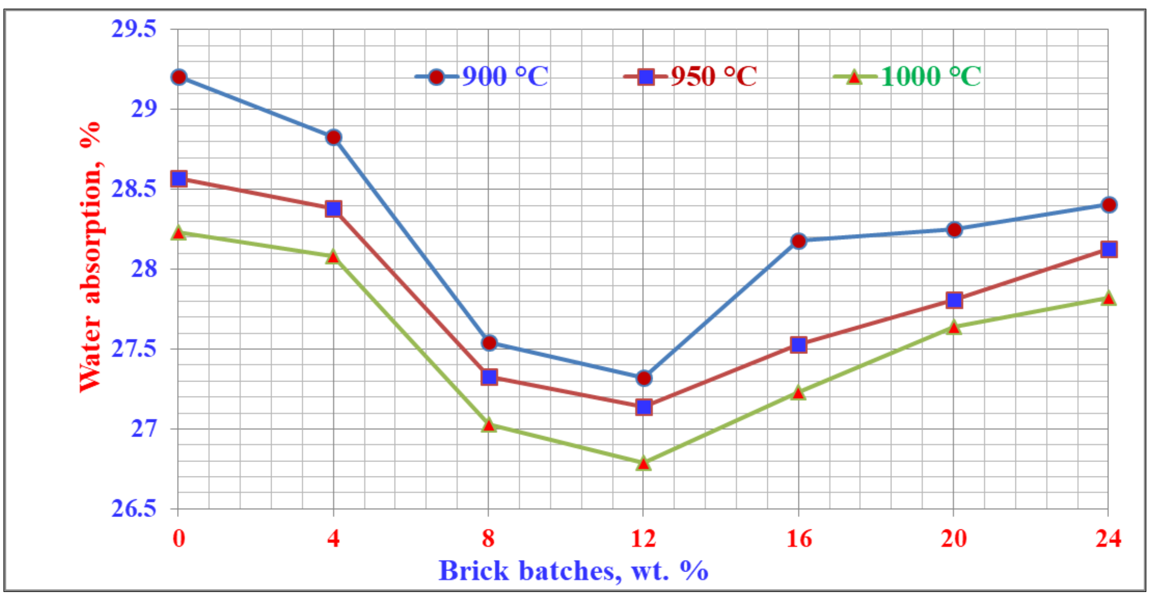

Fig 4: Water absorption of the various brick batches at different firing temperatures.

Apparent porosity

The apparent porosity of the prepared fired brick samples composed of 50 wt. % Clay (CL) and 50 wt. % sewage sludge (SS) which was the control (T0) in which the SS content was substituted with different ratios of CKDW by 0, 4, 8, 12, 16 and 20 wt. % at the expense of SS fired at 900, 950 and 1000 ˚C, respectively is graphically represented in Figure 5. The apparent porosity of the brick of the blank (T0) decreased slightly with the addition of CKDW at the expense of sewage sludge (SS) only up till 12 wt. %, and then enhanced gradually up to 20 wt. % (T6). The decrease of the apparent porosity may be attributed to the thermal reactions occurring inside furnace during firing among the constituents of the CL/SS and those of CKDW forming new phases that blocked the pore system of the fired bricks. With any further increase of these CKDW, the apparent porosity tended to increase. This could be led to produce porous bricks. This results are similar to those of previous researches [25, 28, 30, 44]. The resulting porous bricks are generally preferred owing to its insulating properties, and it could be used to resist the high heat of the atmosphere [27, 45-48]. Moreover, as the firing temperature was increased, the apparent porosity decreased more, i.e. the same trend was displayed by all brick batches but with lower values. The optimum brick batch is that containing 12 wt.% CKDW.

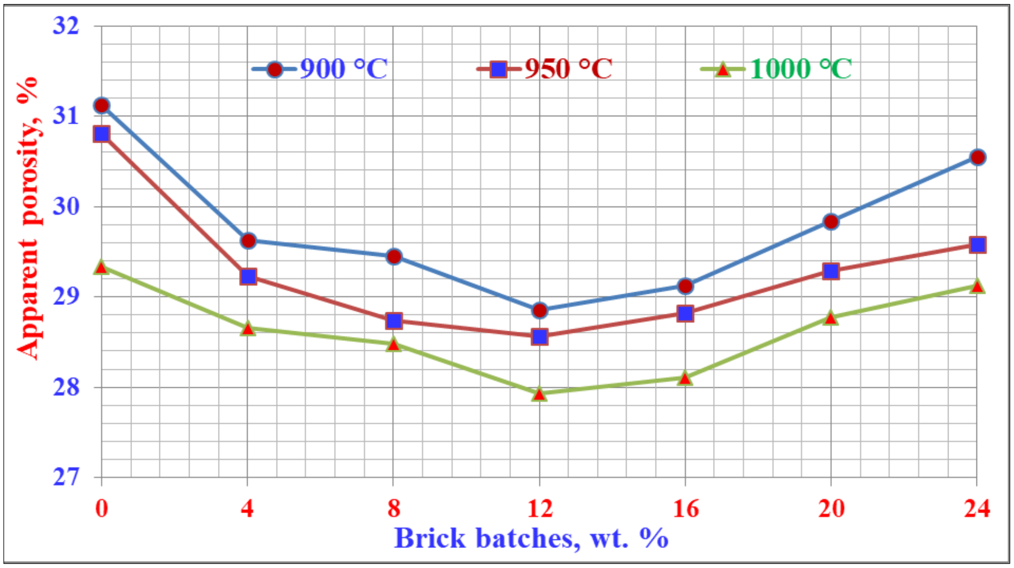

Fig 5: Apparent porosity of the various brick batches at different firing temperatures.

Bulk density

The bulk density of the prepared fired brick samples composed of 50 wt. % Clay (CL) and 50 wt. % sewage sludge (SS) which was the control (T0) in which the SS content was substituted with different ratios of CKDW by 0, 4, 8, 12, 16 and 20 wt. % at the expense of SS fired at 900, 950 and 1000 ˚C, respectively is graphically represented in Figure 6. The bulk density of the fired brick samples of the blank slightly improved and enhanced with the addition of CKDW only up to 12 wt. % (T3). This is essentially contributed to the activation factor by the high alkali content of CKDW [25, 41-44, 47]. Moreover, the bulk density improved and enhanced as the firing temperature increased. This is mainly due to the fact that the high firing temperature gives a big chance for the various ingredients to react with each other's [41, 47]. With any further increase of CKDW more than 12 wt. %, the bulk density started to decrease. This is mainly attributed to that the used CKDW are too light to decrease the bulk density compared with of sludge, in addition to that the increase of the alkali content reflected negatively on the bulk density, or generally on the physical and mechanical properties [27, 28, 43, 48]. Furthermore, the increment in the total porosity due to that replacement played a significant vital role in decreasing the weight of the brick samples on account of the lower specific gravity of CKDW compared with that of clay and/or sludge. Therefore, with the higher percentages of CKDW in the bricks, the weight of the brick will be lighter, i.e. as the contents of CKDW increased in the bricks, the bricks became much lighter. Accordingly, the higher amounts of the CKDW must be avoided. However, the lighter clay bricks would be desired in building construction due to its beneficial reduction in the weight of building, and also it acts as an isolating layer against heat [25, 45, 46, 49].

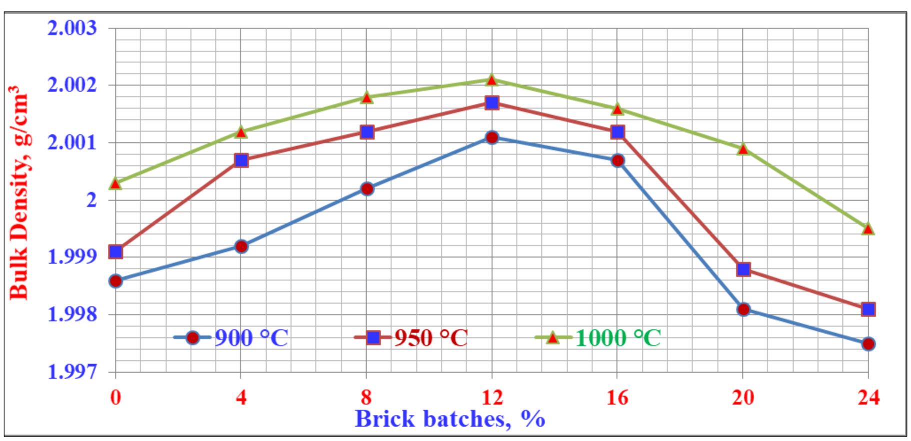

Fig 6: Bulk density of the various brick batches at different firing temperatures.

Flexural strength

The flexural strength of the prepared fired brick samples composed of 50 wt. % Clay (CL) and 50 wt. % sewage sludge (SS) which was the control (T0) in which the SS content was substituted with different ratios of CKDW by 0, 4, 8, 12, 16 and 20 wt. % at the expense of SS fired at 900, 950 and 1000 ˚C, respectively is graphically represented in Figure 7. As the CKDW content increased, the flexural strength of the fired bricks of the blank (T0) improved and slightly enhanced up to 12 wt. %, and then declined, i.e. The brick batch containing 12 wt. % CKDW recorded the higher values of flexural strength at all firing temperatures, while that containing 20 wt. % exhibited the lowest, noticing that the same trend was displayed by all brick batches at all firing temperatures. The increase of flexural strength is essentially contributed to the thermal reactions that could be taken place between the various particles of the CL, SS and the nano-silica of the CKDW [25, 27, 34, 36, 43]. The decrease of the flexural strength is principally due to that the larger quantities of CKDW (16-20 wt. %) increased the apparent porosity which in turn decreased the bulk density of the bricks. This was generally reflected negatively on the mechanical properties [31, 36, 46-49]. Furthermore, the flying of the volatile materials during firing, and the high quantity of silica could be led to the increase of the total porosity of the fired bricks, i.e. the larger quantity of silica is unwelcomed in brick-making [25, 31, 43, 46, 48]. Therefore, from an economic point of view, the production of bricks could be successfully achieved by using CKDW due to their contents of silica.

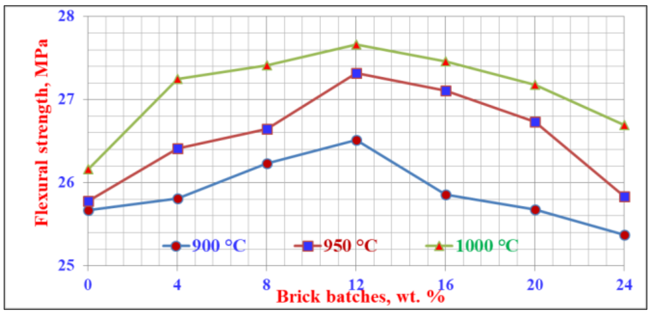

Fig 7: Flexural strength of the various brick batches at different firing temperatures.

Crushing strength

The crushing strength of the prepared fired brick samples composed of 50 wt. % Clay (CL) and 50 wt. % sewage sludge (SS) which was the control (T0) in which the SS content was substituted with different ratios of CKDW by 0, 4, 8, 12, 16 and 20 wt. % at the expense of SS fired at 900, 950 and 1000 ˚C, respectively is graphically represented in Figure 8. The crushing strength of the fired blank bricks increased with the incorporation of CKDW only up to 12 wt. %, and then decreased. The brick batch containing 12 wt. % CKDW achieved the highest values of compressive strength at all firing temperatures, while that containing 20 wt. % CKDW exhibited the lowest, noticing that the same trend was displayed by all brick batches at all firing temperatures [50, 51]. The increase of crushing strength is mainly due to the thermal reactions that happened between the different constituents of CL, SS and the nano-silica and other oxides of CKDW forming new phases corresponding to the strength improvements [25, 27, 34, 36, 43, 46]. The higher reactive aluminosilicates of the raw materials helped much for these thermal reactions [47]. The decrease of the crushing strength is essentially attributed to the fact that the larger amounts of CKDW decreased the bulk density of the fired bricks and decreased the total porosity. This in turn reflected negatively on the mechanical properties in general [31, 36, 44-46]. Furthermore, the flying of volatile materials during firing, and the high quantity of silica could be led to the increase of the porosity, i.e. the larger quantity of silica is unwanted in brick-making [31, 43, 45, 46]. Therefore, from an economic point of view, the production of bricks could be successfully achieved by using CKDW due to its activation response. As a result, the optimum brick batch was that containing not more than 12 wt. % CKDW (T3), and the larger quantities must be eliminated.

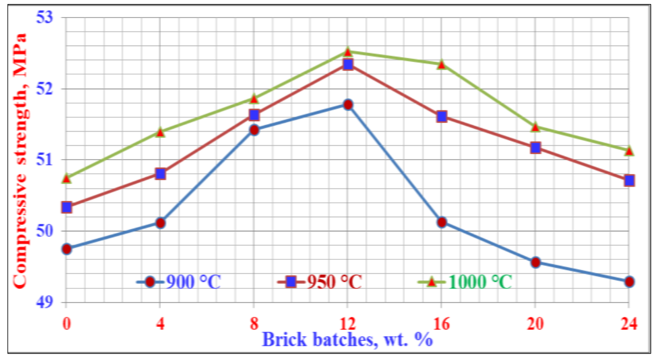

Fig 8: Crushing strength of the various brick batches at different firing temperatures.

General discussion

To throw light on the behavior of samples during firing, the firing cycle for the green samples started with the evaporation of any moisture or combined water content left in the samples after drying and also any hygroscopic moisture that picked up from the atmosphere were also driven off at 300 °C. At the temperature range 500–600 ˚C, the kaolinite ($Al_2O_3{\cdot}2SiO_2.H_2O$) was converted to metakaolin ($Al_2O_3{\cdot}2SiO_2$) as shown in Equation 6. At 800 ˚C, the organic matter existed in the raw materials were burned off. At 980 ˚C, the formed metakaolin was converted to mullite phase ($3Al_2O_3{\cdot}2SiO_2$) as shown in Equation 7.

$$Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O \rightarrow Al_2O_3{\cdot}2SiO_2 \quad (6)$$

$$Al_2O_3{\cdot}2SiO_2 \rightarrow 3Al_2O_3{\cdot}2SiO_2 \quad (7)$$

In presence of mullite, the thermal reactions could be enhanced and some calcium rich phases were formed [24, 37, 43, 46, 50, 51]. The thermal reactions enhanced in presence of CaO, SiO_2, Al_2O_3 besides the alkali oxides (Na_2O andK_2O) that were available in the CKDW. Mullite could be reacted with the available CaO and MgO to form cordierite ($2MgO{\cdot}2Al_2O_3{\cdot}5SiO_2$) as shown in Equation 8.

$$3Al_2O_3{\cdot}2SiO_2 + 2MgO \rightarrow 2MgO{\cdot}2Al_2O_3{\cdot}5SiO_2 \quad (8)$$

The formation of these new phases could be combined to those already existing in the fired samples, is an advantage for sintering of the fired clay bricks. Since, this could be reflected positively on the mechanical strength. Moreover, the collapse or the partial decomposition of other crystalline phases, would favor the abundant viscous flow phase formation, which fill the pore volume, involving a decrease in the apparent porosity and water absorption [25, 27, 36, 43, 45]. So, the bulk density, flexural and crushing strengths were improved. The excess of the CKDW increased the silica content in the brick body, which in turn reflected negatively on both physical and mechanical properties of the fired bricks. Therefore, the large replacement of the CKDW is undesirable [27, 47-51]. Therefore, the optimum brick batch is that incorporating 12 wt. % CKDW (T3) at all firing temperatures.

It is good mention that the higher firing temperature 1000 ˚C seemed to achieve the highest and best results.

Conclusions

An innovative eco-sustainable approach was performed to valorize cement kiln dust and sewage sludge wastes in the production of eco-friendly lightweight bricks. The conclusions from the obtained results can be represented in the following points:-

- The fresh cement kiln dust acts as alkali-bearing waste with high efficacy in the interaction with amorphous aluminosilicate within sludge, yielding hardened materials.
- The high organic content of the dry- sludge is the main reason that caused the reduction of the physical and mechanical properties. So, the firing removed at most 95 % of its organic matter.
- The water absorption and apparent porosity were improved and then decreased with the incorporation of CKDW only up to 12 wt. %, but then affected adversely with any further increase of CKDW content.
- The bulk density, flexural and crushing strengths of the fired brick samples were also improved and enhanced with the increase of CKDW content only till reach to 12 wt. % (T3), and then adversely affect with any further content.
- The higher firing temperature served too much to increase the rate of thermal reactions between the different nanoparticles.
- The optimum brick batch was that containing 12 wt. % CKDW (T3) at any firing temperature. However, the higher firing temperature is preferred due to its highest results.

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Compliance with ethical standards

The author declared that there is no any conflict of interest anywhere.

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