Future of Clay-Based Construction Materials- A review

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Abstract

Sustainability in the manufacture of different construction materials raises many important issues. Nowadays, there is increasing demand for such materials to be produced using environmentally friendly, low energy consuming production methods. This paper presents a review of the current research relating to the use of various production techniques for clay-based construction materials. The techniques which will be reviewed are: blending and stabilising, alkali activation (geopolymerisation) and the use of microwave heating as an innovative sintering, curing and drying method. The advantages and disadvantages of each technique will be discussed. Additionally, a comparison between the environmental and economic aspects of the studied production techniques along with some suggestions to improve the sustainability of different production techniques will be discussed.

Keywords: Alkali activation; blending and stabilising; clay-based construction materials; compressive strength; environmental impact; Geopolymerisation; microwave heating.

1. Introduction

For many thousands of years, clay has been widely used as an integral part of construction materials and products. Examples of the main structural clay products are bricks, blocks and roof tiles. Floor and wall tiles are examples of non-structural products made from clay. Buildings made from clay materials date back to the earliest periods of civilized development [1, 2].

The desirable properties of clay-based products such as the durability, strength, heat and sound insulation along with fire-resistance mean that there is still considerable demand for them in a variety of sectors, despite the availability of modern alternative materials such as concrete, glass-fibre/resin composites, steel and plastics [3].

Sun-baked clay bricks are thought to have been first used circa 8000 B.C while fired clay bricks where used circa 4500 B.C [4, 5]. In Europe, the Romans introduced clay-based brick during the 9th and 10th centuries and thousands of churches and cathedrals were built in masonry during the middle Ages [4]. The oldest skyscraper buildings in the world are located in the city of Shibam in Yemen [6]. These 500 huddled buildings, ranging from 5 to 11 stories high, reaching about 30m, were built with clay blocks [6, 7].

In 2013, the annual production of bricks was about 1391 billion units worldwide [5]. This number is expected to increase through the rapid development of the construction industry globally, together with an expected increase in the world population [8]. The conventional process of converting clay into brick involves firing the brick at temperatures ranging between 900 and 1150°C, depending on the type of clay [9, 10]. During this process, clay minerals break down and sinter forming a glassy bond with other minerals and materials in the brick. The main purpose of the firing process is to transform the porous and weak dried clay into strong, dense bricks with low porosity [3, 11]. This process requires high levels of energy consumption and a resulting release of greenhouse gases into the atmosphere. The production of one brick requires some 2.0 kWh of energy and the release of approximately 0.4 kg of CO_2 [9]. These undesirable features of the manufacturing process are the main driving force behind research into more sustainable alternatives [12].

New methods have been developed to produce alternative clay-based construction products with better performance and properties than those created in the firing process. One of the oldest techniques is the blending and stabilisation of clay with other cementing materials such as cement, lime and/or other waste materials [9, 13, 14]. Blending and stabilising clays with other waste or by-product materials has many benefits such as reducing land-fill, solving the issues of waste management, protecting the environment and saving energy, which in turn, reduces the cost of the final product [9].

In addition to the use of blended and stabilised clay-based construction products, researchers have investigated the use of alkali activation techniques (geopolymerisation). The concept of developing clay-based geopolymer construction products is an attractive one, as they can provide structural strength in a very short time, they are sufficiently durable and CO_2 emissions are reduced [15, 16]. Generally, geopolymer is formed by mixing an alumina-silicate precursor with an alkali solution [17-21]. This technique relies on the chemical reaction between the alumina-silicate precursor and a high alkaline solution to produce amorphous to semi-crystalline geopolymer [17, 21-23].

Heat is essential for the curing, sintering and drying of clay-based construction products in order to gain an adequate strength for civil engineering applications [24-26]. However, the use of conventional heating methods is relatively slow due to the low thermal conductivity of clay-based construction materials and the slow rate of heat transfer from their surface to their core [26, 27]. In addition, researchers have identified the disadvantages associated with conventional heating technologies such as high-energy consumption, long processing times, high processing temperatures and the associated negative environmental impacts [24, 26, 28, 29].

In the search for alternatives, innovative research has been carried out employing microwave technology as a sintering, curing and drying technique in the production of clay-based construction products [24-27]. The utilisation of microwaves has many advantages over conventional heating methods. Microwave treatment provides efficient internal heating, as energy is supplied directly and penetrates the material through molecular interaction with the electromagnetic field therein minimising substantial temperature gradients between the interior and the surface [24, 30-34]. Microwave treatment reduces energy consumption via rapid heating rates and processing times are significantly reduced leading to fewer negative environmental effects. Physical and mechanical properties are also improved through resulting higher density materials with better grain distribution [24, 30-33].

This paper presents a review of the research on the various techniques for the manufacture of clay-based construction products. The studied techniques including blending and stabilising, alkali activation (geopolymerisation) along with the use of microwave heating are presented as an innovative sintering, curing and drying technique in the production of clay-based construction products. Additionally, this paper also provide a comprehensive comparisons regarding the environmental and financial aspects associated with different production techniques along with some suggestions for future trend to improve the sustainability of the studied production techniques.

2. Review of Research

In this study, the production of different clay-based construction materials are divided into three groups: blending and stabilising, alkali activation and microwave sintering, curing and drying.

2.1 Characterization of the used clays

It is well understood that the chemical compositions of clay as raw material have significant influence upon the properties of the clay-based construction materials [9]. Therefore, the chemical composition of different types of clay should be tested to elucidate the performance of these materials when they are combined with stabilisers or being activated chemically by different activators. The chemical composition of different types of clay as collected from the Energy Dispersive X-ray Florescence Spectrometer (EDXRF) test for all the reviewed papers that providing such information are presented in Fig. 1. Fig. 1 displaying the ranges and frequencies of the most common chemical compounds (SiO_2, CaO and Al_2O_3) of the clay powder materials used for the preparation of different clay-based construction materials.

It can be seen from Fig.1A that about 75% of the clays used in the production of different clay-based construction materials have SiO_2 content in the range between 40% to 60%. Additionally, 12.5% of the clays have showed SiO_2 content in the range of 70-80 % and the other 12.5% have SiO2 content in the range of 20-30%. The second chemical compound that can be found in abundant a quantity in different types of clay is the Al_2O_3. Fig.1B shows that the data of the Al_2O_3 content collected from different types of clay ranges from 0% to 45% and the majority of the observations lies between 15% and 30%. Another important compound is the CaO content. Fig.1C indicated that 67% of the clays have relatively small CaO content (below 5%), while 25% of the clays have a CaO content in the range of 5-10% and 25-30% (12.5% for each range).

As observed from Fig. 1 that most of the clays utilised in the production of different clay-based construction materials displayed similar ranges of SiO_2, CaO and Al_2O_3 although they are came from different origins and places around the world.

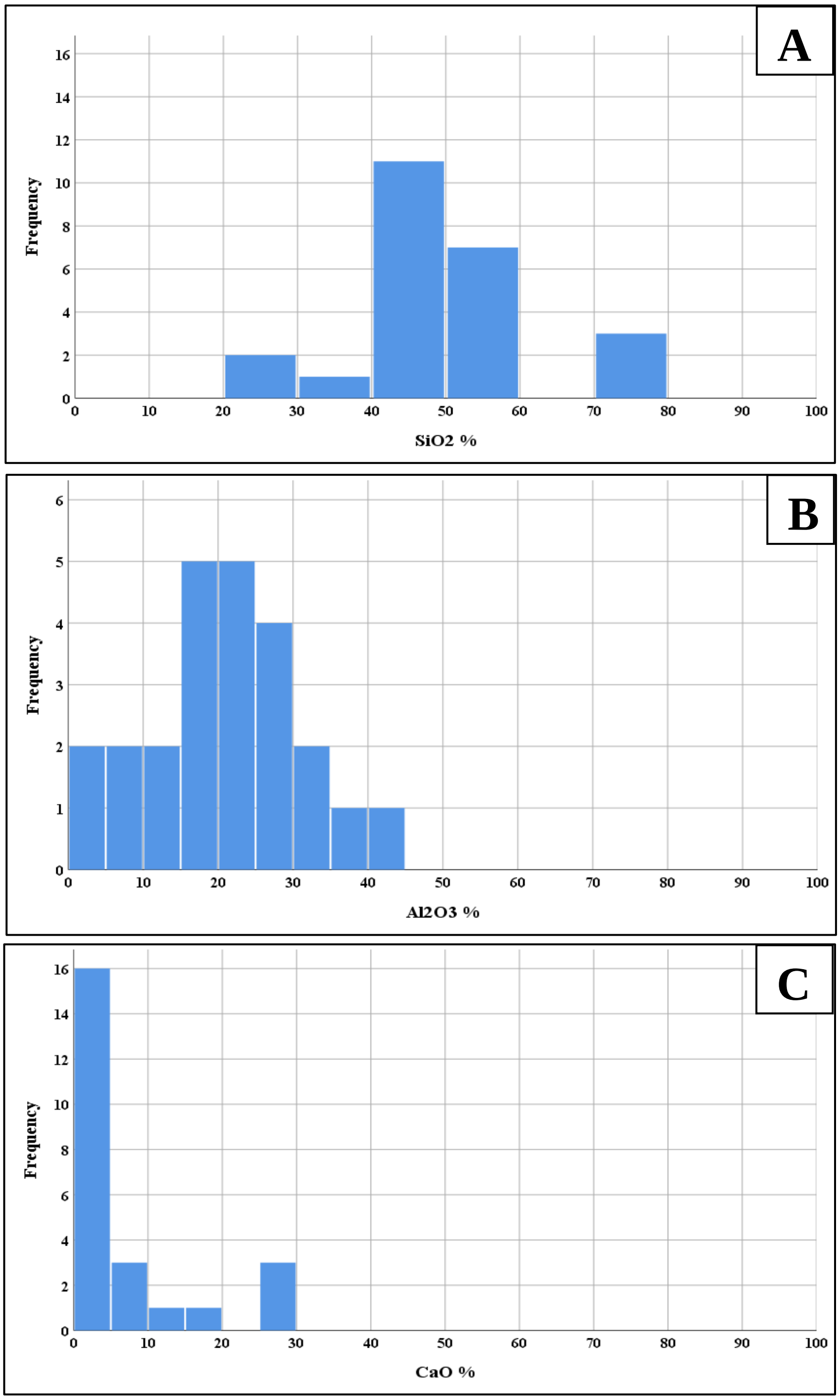

Fig. 1. Chemical composition of used clays

2.2 Production of clay-based construction materials through blending and stabilizing

Stabilization is a process of mixing the clay with different types of binders with the aim of enhancing its strength, durability and volume stability [35]. The performance of different stabilised clay-based construction materials is depend upon the characteristics of soil, binder and the mix design. This technique relies mainly on the formation of hydration products such as C–S–H gel and C–A–S–H gel produced from the chemical reaction between the silica sources (mainly the clay) and the CaO from the stabilisers.

In most of the reviewed papers, the clays have high percentages of SiO_2 and Al_2O_3, while having only small CaO content. Therefore, cement, lime and other binders with high CaO content are added in small dosages to form C–S–H gel and C–A–S–H gel that enhancing the mechanical and durability performance of the final product. The development of unfired clay-based construction products with comparable or better performance than fired products significantly reduces CO_2 emissions, reduces consumption of energy that in turn leads to cheaper products with reduced environmental impact. A brief summary of key experimental research work on this clay processing technique can be found in Table 1.

El-Mahllawy et al. [36] investigated the effectiveness of combining Kafr Homied clay (KHC), Marble Cutting Waste (MCW), hydrated lime (HL) and Portland cement (PC) in the production of sustainable unfired clay brick. The results indicated that the water absorption decreased while the bulk density and compressive strength increased with extended curing time and increase of the MCW content in the presence of HL. This was mainly due to the pozzolanic reaction between KHC, HL and MCW that leads to the formation of cement phases that reduced the numbers of pores, decreased the water absorption and evidenced the densification of the mixtures. The X-ray powder diffraction (XRD) results indicated a reduction in the peaks of clay minerals and quartz intensity with increasing MCW content and curing time. This was attributed to the progress of the pozzolanic reaction due to both the high alkalinity environment and the reaction between silica from the clay and lime from both HL and MCW that led to the formation of C-S-H gel.

Sekhar and Nayak. [37] studied the influence of using Ground Granulated Blast Furnace Slag (GGBS) and cement in the production of compressed stabilized earth blocks (CSEB) made from lithomargic clay. Compressive strength and water absorption of CSEB were evaluated after 28 days. The results indicated a reduction in the water absorption and an increase in the compressive strength with increase in the cement dosage and the air cured CSEB provided higher strength relative to water cured CSEB. The improvement in strength and reduction in water absorption with increase in the cement content was attributed to the formation of additional hydration products that created strong bonds that filled the pores of the soil matrix and connected the soil particles in an enhanced structure.

Sitton et al., [38] studied the effect of stabiliser (cement) content and soil to sand ratio (SSR) on the mechanical performance of compressed earth blocks (CSBs) made from silty-clayey soil. Flexural and compressive strength tests after 7 and 28 days of curing either in water or in air were employed to evaluate the performance of the CSBs. The results indicated that strength of the CEBs increased with increasing the cement content because the cement has better binding properties than the clay on its own. Additionally, the CSBs under water curing exhibited higher strength than that under air curing. This was attributed to the fact that more hydration products from the reaction between the cement and soil could be formed in the presence of water over extended periods. The highest compressive and flexural strengths of 15.15 MPa and 1.84 MPa were achieved at cement content of 10.91%, SSR of 3.36 and water content of 11.4% after 28 days under water curing, respectively.

Saidi et al. [39] evaluated the effect of cement and lime content on the thermal conductivity of stabilised earth blocks (SEB). The results indicated that with increased stabiliser content, the thermal conductivity increased, which in turn resulted in decreasing the thermal insulation. The results also indicated that lime SEB exhibited lower thermal conductivity relative to cement SEB at the same levels of stabilisation. The increase in cement and lime content in SEB resulted in an increase in the thermal conductivity in comparison with un-stabilised blocks. The increase in thermal conductivity of SEB with increasing stabiliser content was attributed to the formation of additional hydration products that filled spaces between the soil particles and produced a denser structure.

Nshimiyimana et al. [40] carried out experimental work to investigated the effect of using Calcium Carbide Residue (CCR) and Rice Husk Ash (RHA) in the manufacturing of compressed earth blocks (CEBs) made from reddish clayey soil. Compressive strength test after 45 days was employed to evaluate the performance of the CEBs. The results indicated that the highest compressive strength of 3.4 MPa was achieved with CCR content of 8% that was about 180% the compressive strength of the control CEBs (100% reddish clayey soil). Additionally, the compressive strengths were significantly improved by the addition of RHA along with the CCR. The highest compressive strength of 6.6 MPa was achieved at replacement level of 15% (10.5% CCR and 4.5% RHA) that was almost 3.5 times the compressive strength of the control CEBs. The improvement in the compressive strength in the presence of CCR and RHA is believed to be due to the increased hydration products formed from the reaction of calcium from the CCR and the silica from the RHA.

Espuelas et al. [41] investigated the use of magnesium oxide (MgO) rich kiln dust (PC-8) as a binder for the production of unfired clay bricks made from Spanish clay soil. The performance of specimens was assessed by measuring the unconfined compressive strength at 1, 7, 28, 56 and 90 days of curing and water absorption after immersion in water for 24h. The results indicated that the compressive strength increased and water absorption decreased with both (i) the curing time and (ii) increased PC-8 dosage. The results indicated that the optimum dosage of PC-8 was 15% that provided a compressive strength of 9.9MPa and a water absorption value of about 5% after 90 days of curing. The development of strength and durability aspects of the developed unfired bricks was attributed to the ability of MgO rich kiln dust binder to form cementitious gels that bind clay soils. Therefore, the results obtained confirmed the suitability of MgO based binders as alternative binders to cement or lime in the production of unfired bricks.

Abdullah et al. [42] examined the influence of different compactions (14MPa, 21MPa and 28MPa) on the performance of Compressed Stabilised Earth Bricks (CSEBs) made from either Laterite Soil, sand and cement or clay, sand and cement. For the evaluation of the performance of the compacted brick, compressive strength testing was performed after 7 and 28 days along with water absorption tests. The effect of compaction on compressive strength for clay and laterite soil was contradictory as the optimum strength was achieved by the samples subjected to compaction of 14MPa and 28MPa for laterite soil and clay, respectively. Water absorption testing found that water absorption was improved through increased compaction resulting in denser samples with less voids.

Zhang et al. [43] studied the effect of cement content and bulk density on the thermal conductivity and compressive strength of cement stabilised earth blocks (CSEB). The results indicated that the cement content caused only small variations in the thermal conductivity of the CSEB. This was mainly due to the small dosage of cement that had been added to the CSEB, so that it was not sufficient to cause a considerable effect on the thermal conductivity. However, the results of the compressive strength testing indicated a significant improvement in the strength of CSEB by increasing the cement dosage. The results also indicated that by increasing the bulk density, the thermal conductivity and compressive strength of the CSEB increased. This is because increasing the bulk density caused a reduction in the number of pores and decreased the pore diameters in the CSEB significantly.

Taallah and Guettala, 2016 [44] investigated the production of compressed stabilised earth blocks (CSBs) made from Biskra soil and three different percentages of quicklime. Compressive strength and tensile strength were used to evaluate the performance of the CSBs after 28 days of either water or air curing. The results indicated higher compressive and tensile strengths of the CSBs under air curing relative to water curing. The results also showed an increased strength with increasing the quicklime content until the optimum dosage of 10%, however, behind this level the strength tend to decrease. The improvement in the strength with increasing the quicklime content was attributed to the formation of additional C-S-H gel. On the other hand, the reduction in the strength of CSBs made with more than 10% quicklime content was attributed to the excessive contents of calcite and portlandite ($Ca(OH)_2$) with increasing quicklime content that resulted in reduced strength.

Rahmat et al. [45] investigated the development of unfired brick made with Lower Oxford Clay (LOC) and pulverised fuel ash (PFA). In this study, four stabilisers were used: Lime (L), Portland Cement (PC), lime-GGBS (30:70) and PC-GGBS (40:60). The investigation included unconfined compressive strength, water absorption, thermal conductivity and freeze and thaw tests alongside an evaluation of the environmental performance. The results of compressive strength and water absorption tests indicated that blending GGBS with lime or PC provided better performance than using only PC or Lime. This was mainly due to the combined pozzolanic reaction that leads to the formation of additional C-A-S-H gel that fills the voids, thus enhancing the strength and reducing the porosity of the brick to a minimum. In addition, the results of thermal conductivity testing indicated that bricks stabilised with PC-GGBS provided the lowest thermal conductivity value. Moreover, the results of the freezing and thawing at the end of the 30th cycle indicated that the weight loss of the bricks increased with increasing the freezing and thawing cycles and the bricks stabilised with PC-GGBS achieved the lowest percentage of weight loss. Finally, the results of the environmental performance review suggested that the developed brick can be considered to be green brick with low energy usage and CO2 emissions and is suitable for the construction of internal walls.

Oti et al. [46] studied the possibility of combining Brick Dust Waste (BDW) from the cutting of fired clay bricks with Mercia Mudstone Clay (MMC) in the development of unfired clay (mortar, block and brick). The results indicated an increase in compressive strength with increased percentages of BDW in the mixtures. This was mainly due to the pozzolanic reaction of GGBS and lime that led to the formation of additional C–S–H gel within the pore structure. The results also showed that the water absorption rate for all the mixtures was extremely low. Additionally, the results of the weight loss of samples after 7, 28, 56 and 100 cycles of freezing and thawing indicated an increase in the weight loss with increasing BDW content. Overall, the results indicated the potential production of unfired clay products using up to 20% BDW as replacement to MMC with acceptable performance of stabilised clay masonry units.

Nagaraj et al. [35] studied the effect of combining cement and lime on the long-term properties of compressed stabilised earth blocks (CSEBs) prepared from red earth. For evaluating the engendering properties of CSEBs, compressive strength and water absorption tests were conducted after 7, 15, 30, 60, 120, 180 days; 1, 2 and 5 years. The results indicated that the compressive strength increased and water absorption decreased with increasing the age of curing for all the mixtures. The results also showed that up to the age of 120 days, the strength of the CSEBs stabilised with cement alone was higher than that stabilised with cement and lime. This was attributed to the quick hydration of cement relative to lime that helps the formation of hydration product within the CSEBs. At the age of 180 days onward, the CSEBs stabilised with 4% cement and 4% lime provided better strength than that stabilised with 8% cement. After 5 years of curing, the CSEBs with 4% cement and 4% lime have showed a compressive strength of 7.2 MPa that was about 167% the strength of CSEBs stabilised with cement alone (4.3 MPa). This behaviour was attributed to the availability of adequate quantity of lime that possibly resulted in increasing the pH of the system and allow the alumina and silica in the clay to be dissolved and to combine with Ca^{++} to form calcium-alumino silicates (C-A-S) and thereby binds the particles of clay existing in the matrix.

Miqueleiz et al. [47] evaluated the development of unfired clay brick by blending marl clay soil and alumina filler (AF) waste. The stabilizers used in this investigation were a combination of Pulverised fuel ash (PFA) and lime (L) (70% PFA: 30% L). All mixtures were tested for compressive strength, water absorption and underwent 45 freeze/thaw cycles. The results of the compressive strength testing indicated that increasing the level of AF caused a significant reduction in the compressive strength relative to mixtures made with marl clay soil only at all curing ages. The results of water absorption tests showed that the presence of up to 40% AF have a water absorption rate of less than 20%, however the bricks with 60% AF collapsed upon immersion in water at all curing ages. This was attributed to the lower percentages of silica provided by marl clay that combined with calcium from the lime and results in the formation of less hydration products. The results of durability tests indicated that all mixtures were able to withstand the repeated 48-hour freezing/thawing cycles without any surface cracks.

Table 1. Studies on production of clay-based construction and building materials through blending and/or stabilising

Reference	Clay type	Blended materials		Clay-based product	Curing condition	Tests conducted
		Replacement material	**Stabilising material**			
[36]	Kafr Homied clay	Marble Cutting Waste (0%, 10%, 15% and 20%)	Hydrated lime (0%, 10%, 15% and 20%) and 5% Portland cement	Brick	Cured in a humidity chamber at 40ºC±2 for 14 and 28 days	Compressive strength, water absorption, bulk density, and XRD
[37]	Lithomargic clay	GGBS 25%	Cement (0, 6, 8, 10 and 12 %)	Compressed stabilised earth blocks	Cured in water and air for 28 days	Compressive strength and water absorption
[38]	Silty-clayey soil	-	Cement (3.6, 5.5, 9.1 and 10.9 %)	Compressed stabilised earth blocks	Cured in water and air for 7 and 28 days	Compressive strength and flexural strength
[39]	Sidi Amor soil	-	Cement (0, 5, 8, 10 and 12%) or lime (0, 5, 8, 10 and 12%)	Stabilised earth blocks	Cured in a humid atmosphere for 28 days at temperature of 20±2ºC	Thermal conductivity
[40]	Reddish clayey soil	-	Calcium carbide residue (0, 5, 8, 10 and 15 %) or calcium carbide residue and rice husk ash (0, 5, 8, 10 and 15 %)	Compressed stabilised earth blocks	Cured in ambient condition (30 ± 5°C) for 45 days.	Compressive strength and SEM

[41]	Spanish clay soil	-	Magnesium oxide rich kiln dust (0, 3, 6, 9, 12, 15 and 18%)	Brick	Cured in wet chamber	Compressive strength and water absorption
[42]	Laterite Soil or clay	Building sand (20%) or (50%)	Cement (10%) or (20%)	Compressed Stabilised earth brick	Spraying the samples with water every day up to 7 or 28 days.	Compressive strength and water absorption
[43]	Local soil in Xinjiang	-	Cement (3, 5, 7 and 9 %)	Stabilized earth blocks	Samples wrapped with plastic foils and placed in the laboratory for 28 days at temperature of 20 ± 1^{o}C	Compressive strength and thermal conductivity
[44]	Biskra soil	-	Quicklime (8, 10 and 12%)	Compressed stabilised earth blocks	Cured in water and air for 28 days	Compressive strength and tensile strengths.
[45]	Lower Oxford Clay	PFA (50%)	Lime-GGBS (30:70) and cement-GGBS (40:60) (10%)	Brick	Curing in humidity chamber at 20^{o}C for 7 and 28 days	Compressive Strength, Water Absorption, thermal conductivity freeze and thaw, and environmental performance.

[46]	Mercia mudstone clay	Brick dust waste (5%, 10%, 15% and 20%)	GGBS and lime (22%)	Mortar, block and brick	The samples were moist-cured for 3, 7, 14, 28 and 56 days at room temperature of about 20°C.	Compressive Strength, water absorption and freeze and thaw
[35]	Red soil	-	Cement (4, 6 and 8%) and lime (0%, 2% and 4%)	Compressed stabilised earth blocks	Cured in water for 7, 15, 30, 60, 120, 180 days; 1, 2 and 5 years	Compressive strength and water absorption
[47]	Marl clay soil	Alumina filler (0, 20, 40 and 60 %)	PFA-Lime (70: 30) (12%)	Brick	Cured in a moisture chamber for 1, 7, 28, 56 and 90 days	Compressive Strength, water absorption and freeze and thaw

2.2.1 Critical evaluation

The technique of producing clay-based building materials by blending and stabilising clay is considered an important step in the fabrication of different clay-based construction materials. The main aim of this technique (that depends mainly on the production of hydration products such as C–S–H and C–A–S–H phases) is enhancing the mechanical and durability performance of the produced product.

According to the reviewed studies and amongst the variety of stabilizers utilised, cement and lime have been the most popular stabilizers in the production of stabilised clay-based construction materials. Cement and/or lime were used either alone [37-39, 42-44], in combination with each other [35, 36] or in combination with other stabilisers such as GGBS or PFA [45-47]. However, two of the reviewed studies were used different stabilisers such as calcium carbide residue with rice husk ash [40] and magnesium oxide rich kiln dust [41].

The dosage of the stabilisers in the reviewed studies varied depending on the type of stabiliser. For example, the cement dosage was ranging between 3% and 12% [37-39, 43] and only one paper [42] have showed the usage of 20% cement as stabiliser. The dosage of lime as stabiliser was similar to that of the cement (ranging between 2% and 12%). Additionally, the lime and cement were blended with GGBS or PFA to boost the hydration process of these materials by the highly alkaline environment ($pH > 12$) and accelerate the production of cementitious compound that binds the soil together [45, 46]. In some cases, the stabiliser dosage were relatively high with 22% for [46] and 25% for [36]. Regarding the dosage of stabiliser for the paper with calcium carbide residue and rice husk ash [40] were in the range of 5-12% while the magnesium oxide rich kiln dust [41] was in the range of 3-18%.

The reviewed studies indicated that the production of C–S–H and C–A–S–H gel phases increased with increasing the amounts of stabiliser in the mixture [36, 37, 39, 40, 45]. This was due to the chemical reaction occurring between the CaO from the cement, lime and other stabilisers and amorphous silica provided by clay together with the high alkalinity environment of cement or lime [37, 39, 45, 46]. These gels tend to fill pores and grow into capillary spaces, resulting in a more impermeable, dense and higher-strength structure [48, 49]. However, high dosage of stabiliser with high CaO content might negatively affect the performance of the product because this might resulted in free CaO that could lead to expansion and cracks in the final product [9].

2.3 Production of geopolymer clay-based construction materials through alkali activation (Geopolymerisation)

During the development of construction materials using the technique of geopolymerisation, the most important chemical compounds that should be available in high a quantity are the SiO_2 and Al_2O_3 because they react with a high alkaline solution to produce amorphous to semi-crystalline geopolymer material [5, 17]. Preferably, the total composition of the SiO_2 and Al_2O_3 compounds should be more than 70% [17]. Yun-Ming et al. [17] stated that the raw materials with abundantly amount of SiO_2 and Al_2O_3 that is suitable for the production of geopolymer materials can be found in different types of clay. These observations are in consistent with the results obtained from Fig.1 for different types of clay that were used in the production of geopoylmer clay-based construction materials.

This technique is of great research interest in the field of sustainable construction materials due to its characteristics such as developing high mechanical strength within a very short time, enhanced durability, high fire resistance and considerably decreased greenhouse gas emissions and energy consumption [23, 50, 51]. Many researchers have investigated the production of clay-based construction materials using the technique of alkali activation (geopolymerisation) (see Table 2).

Faqir et al. [52] conducted experimental work to investigate the utilisation of kaolin clay activated with NaOH in different concentrations in the fabrication of geopolymer mortar. In this study, the effect of sand to kaolin clay ratio and NaOH with different concentrations to kaolin clay ratio were evaluated by determine the compressive strength of geopoymer samples after 7 days of water and air curing. The results indicated that with decreasing the sand to kaolin clay ratio and increasing both the concentration and the amount of the NaOH, the compressive strength increased for both curing methods. The highest compressive strength were 27.1 MPa and 18.1 MPa achieved at sand to kaolin clay ratio of 1.5 and NaOH (with concentration of 17 M) to kaolin clay ratio of 0.17 under air curing and water curing, respectively. Additionally, the results of the water absorption test indicated that the geopolymer mortar exhibits lower water absorption rate with increasing the concentration of the NaOH and the lowest water absorption was about 3.7 % achieved for the geopolymer mortar that showed the highest compressive strength. The improvement in the strength and durability of the geopolymer mortar with increasing the NaOH concentration is believed to be due to the formation of denser microstructure that bonded the kaolin clay and the sand with less numbers of pores.

Dassekpo et al. [53] evaluated the use of clay waste (CW) from construction sites, class F fly ash (FA), sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) in the production of geopolymer paste. The experimental programme included evaluation compressive strength, Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Spectroscopy (EDX) and the leaching behaviour of the geopolymer paste. The results indicated an increase in the compressive strength with increases in the curing period and the FA content. This was due to the enhanced polymerisation process with longer curing periods and the increased Si/Al ratio with increased content of FA, which in turn resulted in increasing the amount of Si-O-Si bonds that formed during the geopolymerisation process, as evidenced by the EDX test. The SEM images showed an increase in the degree of compaction and formation of a denser microstructure as the amount of FA in the pastes increased. The leaching test was conducted for samples soaked in deionized water for 4, 8, 12, 24, 72 and 336 hours to measure the concentration of Aluminium (Al) and Arsenic (As). The results indicated that with increasing the FA content, the Al concentration decreased and As concentration increased.

Sore et al. [51] investigated the development of geopolymer compressed earth blocks (CEB) using laterite clay, metakaolin (MK) and sodium hydroxide. The experimental programme included weight loss after curing, porosity, apparent density, compressive strength, flexural strength, thermal diffusivity and thermal conductivity. The results indicated that with increasing MK content, the weight loss and porosity increased, while the apparent density decreased. In addition, the results of compressive and flexural strength tests revealed that with increased MK content, the strength of geopolymer CEB improved. This improvement in the mechanical strength was attributed to the formation of higher levels of geopolymer gels after a polymerisation reaction between the NaOH and the MK that resulted in increasing the bond of particles, resulting in a more resistant and more compact structure. Furthermore, the results also indicated low thermal diffusivity and thermal conductivity with all MK percentages.

Phummiphan et al. [22] studied the development of low carbon pavement base material produced from lateritic soil (LS), class C FA, Granulated Blast Furnace Slag (GBFS), sodium hydroxide and sodium silicate. The performance of the low carbon pavement base material was evaluated in terms of unconfined compressive strength, SEM and XRD tests after 7, 28 and 60 days. The results indicated that the highest compressive strength values after 28 and 60 days were found at LS: FA: GBFS = 60:30:10 and Na2SiO3: NaOH of 90:10. This mixture was considered to be the recommended optimum ratio in practice and was further investigated for SEM and XRD tests. The results of SEM and XRD tests indicated that the geopolymerisation products increased in volume as the curing time increased.

Miranda et al. [54] investigated the development of low carbon alkali activated mortar (AAM) produced from granitic residual soil (GRS), FA, sodium silicate and sodium hydroxide. The mechanical performance of the AAM were evaluated by means of compressive strength and flexural strength after 30, 60 and 90 days of curing. The results indicated an improvement in the compressive and flexural strengths with increasing the curing time and FA content. In addition, the performance of the developed mortars was also assessed by building masonry walls using compressed earth blocks utilising the AAM. The results showed that walls incorporating AAM with 15% FA had better performance than walls incorporating AAM with 5% FA, but the increment was minimal.

Leitão et al. [55] evaluated the mechanical and thermal performances of Alkali Activated Interlocking Compressed Earth Blocks (AAICEBs) made from 85% granitic residual soil, 15% FA, sodium hydroxide and sodium silicate. For assessing the mechanical performance of AAICEBs, the compressive strength test was conducted on the AAICEBs after 28 days. Additionally, the developed AAICEBs were used after 28 days in the building of a masonry wall and then the thermal conductivity of that wall was evaluated. The results indicated a compressive strength of 3MPa after 28 days of curing. The results of the thermal conductivity of the masonry wall suggested that the use of alkaline activators in the presence of 15% FA improved the thermal properties of the wall with respect to heat transference.

Messina et al. [56] investigated the utilisation of calcined clay sediments (CCS) and calcined water potabilization sludge (CWPS) in the production of precast geopolymer paving elements. The raw materials were calcined at 750^{o}C for two hours, and then different proportions of the calcined raw materials were blended with Na_2SiO_3 and NaOH to produce geopolymer paste. The developed paste was then mixed with building sand to produce geopolymer mortar. Compressive strength test was used to evaluate the performance of the geopolymer paste and mortar after 7 days of curing. The results indicated that the compressive strength of the developed pastes and mortars were very similar and were in the range between 17-23 MPa. The developed mortar with CCS/WPS ratio of 50/50 was then mixed with natural aggregate to produce paving bricks that have been evaluated by measuring the splitting tensile strength after 7 days of curing. The developed paving bricks have showed splitting tensile strength between 0.82-2.01 MPa. The durability assessment of the developed bricks after 180 days of exposure to room conditions showed that there was no cracking and no efflorescence was formed on the surface of the developed paving brick.

Slaty et al. [23] studied the durability performance of geopolymer mortar and paste made from Jordanian Hiswa kaolinite (JHK) clay and sodium hydroxide. The experimental programme included drying shrinkage, wetting and drying conditions, sea water attack and alkali-silica reaction. The results indicated a very low drying shrinkage for all samples and the presence of sand in mortar significantly reduced the shrinkage relative to geopolymer paste. The results also showed that there was a 50% reduction in the compressive strength of specimens subjected to 100 cycles of wetting and drying conditions relative to geopolymer specimens cured under dry conditions. This was attributed to effect of water in weakening the bond strength of Si-O-Si in the alumina-silicates resource and because clay minerals have a high tendency to absorb water and become plastic rather than stiff. In addition, the results indicated a very good mechanical performance for geopolymer mortar and paste immersed in sea water with a small formation of efflorescent material on the external surface of the samples. Furthermore, the alkali–silica reaction seriously affected the geopolymer specimens and produced expansion, cracking, and loss of the mechanical strength as a function of time.

Poowancum and Horpibulsuk [57] investigated the use of Dan Kwian sedimentary clay (DKSC) in the development of geopolymer binder. During this investigation, the DKSC was calcined at 600°C for 1, 2 and 5 h and mixed with Na_2SiO_3 solution and NaOH solution in three different Na_2SiO_3/NaOH ratios (0.5, 1 and 1.5). Setting time, compressive strength and porosity were used to evaluate the effect of different calcination temperatures and Na_2SiO_3/NaOH ratios on the properties of the geopolymer paste. The results indicated that for a fixed Na_2SiO_3/NaOH ratio, the setting time of the paste calcined for 1 and 2 h was about 55 min and was about 60 min for the paste calcined for 5 h. The increase in the setting time with increasing the calcination time was associated with a reduction in the compressive strength and higher porosity of the geopolymer paste. The results also showed that the compressive strength of the geopolymer paste decreased with increasing the Na_2SiO_3/NaOH ratio and the lowest compressive strength was recorded for Na_2SiO_3/NaOH ratio of 1. Beyond this ratio, the compressive strength improved with increasing Na_2SiO_3/NaOH ratio. The highest compressive strength of 27 MPa and lowest porosity of 35% was achieved with calcination of the DKSC for 2 h and Na_2SiO_3/NaOH ratio of 0.5.

Silva et al. [58] investigated the production of compressed earth blocks (CEBs) from granitic residual soil, FA, sodium hydroxide and sodium silicate. Compressive strength and flexural strength after 180 days of curing were used for assessing the performance of the CEBs. The results showed superior compressive and flexural strengths of CEBs incorporating 15% FA relative to the CEBs with 10% FA. This was attributed to the formation of more geopolymer products along with the enhanced structure due to higher density. The performance of the CEBs in saturated conditions was also evaluated by submerging CEBs in water for 24 hours prior to the test. The results indicated a maximum reduction in the compressive and flexural strengths of 36% and 61%, respectively for the mixture with 10% FA in comparison to CEBs samples cured in dry conditions.

Ferone et al. [59] carried out experimental works to investigate the possibility of employing Sabetta clay sediments (SCS) in the production of geopolymer binder. During this investigation, the SCS was calcined at two different temperatures (400^{o}C or 750^{o}C) for 120 minutes and activated by NaOH alone or a mixture of NaOH and Na_2SiO_3. Compressive strength test was conducted after 28 days to assess the behaviour of the binder under different conditions of calcination and activation. The results indicated that compressive strength of the geopolymer binder was significantly enhanced with increasing the calcination temperature from 400^{o}C to 750^{o}C. Additionally, the results showed that the compressive strength was improved with increasing the concentration of the NaOH and when the SCS was activated by a mixture of NaOH and Na_2SiO_3. The compressive strength was further enhanced by the addition of 17 % GGBS. The highest compressive strength value of the geopolymer binder was

38.9 MPa achieved with SCS treated at 750 °C mixed with 17 % GGBS and activated by a mixture of NaOH and Na_2SiO_3. The SEM images showed that the addition of GGBS to the geopolymer binder in the presence of NaOH and Na_2SiO_3 leads to the formation of a very dense and homogenous microstructure due to the simultaneous formation of N-A-S-H and C-A-S-H gels as evidenced by the EDX test.

Phetchuay et al. [60] evaluated the development of pavement subgrade material from silty clay soil, FA, Calcium Carbide Residue (CCR) and sodium silicate. In this investigation, the influential factors were FA replacement level, Na2SiO3/water ratio, curing temperature and curing time for a fixed CCR content of 7%. Compressive strength and SEM tests were used for evaluating the effect of different factors on the strength and microstructure of the pavement subgrade material. The results indicated that the optimum FA replacement level was 15%. Regarding the effect of Na2SiO3/water ratio, the results showed that it was 0.6 for samples under water curing and 1.4 for samples under air curing. Additionally, the results also indicated an increase in the compressive strength with the increase in curing period and curing temperature. The SEM images confirmed the results of compressive strength test that at optimum conditions, a denser microstructure was formed.

Molino et al. [61] studied the effect of different calcination temperatures and alkaline activators on the performance of geopolymer binder produced from Occhito clay sediments. During this research, the raw materials were calcined at either 650^{o}C or 750^{o}C for 60 minutes and activated by three alkaline activators, namely NaOH solution, sodium aluminate solution and potassium aluminate solution. Compressive strength test after 3 and 14 days of curing was employed to evaluate the performance of the binder under different conditions of calcination and activation. At the age of 3 days, the results indicated an improvement in the compressive strength of the binder with increasing the temperature of calcination from 650^{o}C to 750^{o}C for the samples activated with either NaOH solution or sodium aluminate solution, while decreased for samples activated with potassium aluminate solution. After 14 days of curing, the results indicated higher compressive strength with increasing the temperature of calcination for all the used activators. The SEM images of the samples made with sodium aluminate solution showed a compacted microstructure with no significant changes with increasing the age of curing or the temperature of calcination. In summary, the utilisation of sodium aluminate activator at calcination temperature of 650^{o}C provided higher compressive strength than other tested activators with calcination temperature of 750^{o}C, thus the use of this activator could significantly reduce the energy usage and improve the sustainability of the final product.

Slaty et al. [62] investigated the development of alkali-activated mortar using kaolinitic clay, silica sand and sodium hydroxide. The experimental programme included optimising the sand to binder ratio, curing temperature, and curing period. The results showed that by increasing the sand content, the workability of mortar improved and the highest compressive strength value was achieved when the sand to clay ratio was 1. The results also indicated that with increasing the curing temperature from 50oC to 80oC, the compressive strength increased from 14MPa to 32MPa after 24h of curing. Additionally, the results indicated an increase in compressive strength with increased curing time. This study concluded that the optimum conditions for producing kaolinitic clay-based mortar were; sand to kaolinitic clay ratio of 1, a curing temperature of 80oC and curing time of 24h. Furthermore, the optimised samples were tested under wet and dry conditions. The results showed a reduction in compressive strength by half for samples under wet conditions relative to dry conditions. This was attributed to the hydrolysis of the Si-O-Si bonds upon immersion in water. The results of the SEM and XRD tests evidenced the formation of crystalline reaction products that filled the pore spaces and helped bind the matrix.

Sukmak et al. [63] examined the development of geopolymer brick using silty clay soil, FA, sodium hydroxide and sodium silicate. The Na2SiO3 / NaOH ratios studied were 0.4, 0.7, 1.0

and 1.5. Additionally, different Liquid (L)/FA ratios (0.4, 0.5, 0.6 and 0.7) and FA/clay ratios (0.3, 0.5 and 0.7) were investigated. The experimental programme included measuring the compressive strength of brick after 7, 14, 28, 60, and 90 days of curing at ambient temperature. The results indicated that for different L/FA and FA/clay ratios, the optimum compressive strength was for the mixtures with Na2SiO3/NaOH ratio of 0.7. For a given Na2SiO3/NaOH ratio, the strength increased with increasing L/FA ratio until its optimum value was reached, it then tended to decrease. The results also indicated that the compressive strength increased with increases in the FA content. This was due the increased geopolymerisation products produced because of the high alumina-silicate of FA. The overall results indicated that the optimum L/FA ratio was dependent upon only the FA/clay ratio. As the clay content decreases, the L required for the reaction decreases.

Mohsen and Mostafa [64] studied the use of calcined white clay (CWC) in the development of geopolymer bricks. The clay was calcined at 700^{o}C for two hours and then mixed with either NaOH alone or with a mixture of Na_2SiO_3 and NaOH to produce geopolymer bricks. For evaluating the performance of the geoploymer bricks, compressive strength test was conducted at (i) room temperature for 3 days, (ii) 75°C for 24 h and (iii) 150°C for 24 h. The results indicated that the compressive strength of the developed bricks with NaOH was improved from 19.8 MPa to about 22 MPa with increasing the curing temperature from room temperature to 75°C. However, increasing the curing temperature to 150°C resulted in a slight reduction in the compressive strength (18 MPa). Additionally, the compressive strength results of the geopolymer bricks activated with Na_2SiO_3 and NaOH improved from 44 MPa to about 79 MPa with increasing the curing temperature. The results of water absorption test indicated that increasing the curing temperature reduced the water absorption of the produced bricks for both activators. In summary, geopolymer bricks activated with Na_2SiO_3 and NaOH have showed higher compressive strength and much lower water absorption values than those activated with

NaOH solution only. This was attributed to the formation of denser geopolymer gel for bricks activated with Na_2SiO_3 and NaOH relative to those activated with NaOH solution only as observed by the SEM testing.

Table 2. Studies on production of clay-based construction and building materials through alkali activation (geopolymerisation)

Reference	Clay type	Blended material	Alkali activator	Clay-based product	Curing condition	Tests conducted
[52]	Kaolin clay	-	NaOH (13, 16.3, 17, 17.8 and 19.7 M)	Mortar	Cured in oven at $80^{o}C$ for 24 hours then at air or in water for 7 days	Compressive strength and water absorption
[53]	Clay waste from construction site	Class F fly ash (0, 10, 20 and 30%)	Na_2SiO_3 and NaOH (14M)	Paste	Cured in a humidity chamber at $75^{o}C\pm2$ for 24 hours then at ambient temperature for 7, 14 and 28 days	Compressive strength, SEM/EDX and leaching behaviour
[51]	Laterite clay	Metakaolin (0, 5, 10, 15 and 20%)	NaOH (12M)	Compressed earth blocks	Cured at ambient temperature of ($30^{o}C \pm 5^{o}C$) for 7 days and then placed in oven for another 7 days at $60^{o}C \pm 2^{o}C$	Weight loss after curing, porosity, apparent density, compressive strength, flexural strength, thermal diffusivity and thermal conductivity.
[22]	Lateritic soil	Class C fly ash (30%) and Granulated Blast Furnace Slag (10, 20 and 30%)	Na_2SiO_3 and NaOH (5M)	Pavement base material	Wrapped with plastic sheets and cured at room temperature between (27–30)$^{\circ}$C for 7, 28 and 60 days	Compressive Strength, SEM and XRD

[54]	Granitic residual soil	Fly ash (5% and 15%)	Na_2SiO_3 and NaOH (5M and 12.5M)	Mortar	Cured at ambient temperature for 30, 60 and 90 days	Compressive strength and flexural strength
[55]	Granitic residual soil	Fly ash (15%)	Na_2SiO_3 and NaOH (12.5M)	Compressed earth block	Cured at ambient temperature for 28 days	Compressive strength and thermal conductivity
[56]	Calcined clay sediments	Calcined water potabilization sludge (30, 50 and 70 %)	Na_2SiO_3 and NaOH (14 M)	Paste, mortar and paving brick	Cured for 24h or either at 20°C or 60°C and then at climatic chamber operating at 20°C until the age of 7 days.	Compressive strength, splitting tensile strength, SEM, XRD and visual assessment.
[23]	Jordanian Hiswa kaolinite clay	-	NaOH	Mortar and paste	Cured for 24h or 48h at 80 °C and then for 7, 30, 60, 90 and 180 days at ambient temperature.	Compressive strength, drying shrinkage, wetting and drying conditions, sea water attack and alkali-silica reaction
[57]	Dan Kwian sedimentary clay	-	Na_2SiO_3 and NaOH (8 M)	Paste	Cured at 60°C for 7 days	Setting time, compressive strength and Porosity.
[58]	Granitic residual soil	Fly ash (10% and 15%)	Na_2SiO_3 and NaOH (12.5M)	Compressed earth block	Cured at ambient temperature for 180 days	Compressive strength and flexural strength

[59]	Sabetta clay sediments	GGBS (0 and 17 %)	Na_2SiO_3 and NaOH (5, 7 and 10 M)	Paste	Cured for 3 days at 60°C in an oven, then at room temperature until the age of 28 days.	Compressive strength, SEM, EDX and XRD.
[60]	Silty clay soil	Fly ash (0, 5, 10, 15, and 20 %) and 7% Calcium Carbide Residue	Na_2SiO_3	Pavement subgrade material	Cured either at ambient temperature (27–30)°C or at 40°C for 7, 14, 28 and 60 days	Unconfined Compressive Strength and SEM
[61]	Occhito clay sediments	-	NaOH (5 M), sodium aluminate (8.5, 11, 13 and 17 M) and potassium aluminate (8.5, 11, 13 and 17 M)	Paste	Cured for 3 days at 60°C in an oven, then kept in air for 11 days	Unconfined Compressive Strength and SEM
[62]	Kaolinitic clay	Silica sand (25, 50, 100 and 150%)	NaOH	Mortar	Cured at temperature (50, 60, 70 and 80°C) for curing period (6, 12, 18, 24, 48 and 72h)	Workability, compressive strength, wetting and drying, SEM and XRD
[63]	Silty clay soil	Fly ash (30, 50 and 70%)	Na_2SiO_3 and NaOH (10M)	Brick	Cured at ambient temperature for 7, 14, 28, 60, and 90 days	Compressive strength

[64]	White clay	-	NaOH alone or Na2SiO3 and NaOH	Brick	Curried at (i) room temperature for 3 days, (ii) 75°C for 24 h and (iii) 150°C for 24 h	Compressive strength, Water absorption, SEM and XRD.

2.3.1 Critical evaluation

In some of the reviewed papers, the clay materials were blended with different materials such as FA [53-55, 58, 60, 63], GGBS [59], metakaolin [51] and calcined water potabilization sludge [56]. The main reason behind blending the clay with the aforementioned materials is to increase the geopolymerisation products that in turns resulted in better mechanical and durability performance [17].

In the reviewed studies, both class C and Class F fly ash types were used. The reaction between alkaline activator and class C fly ash forms in addition to the geopolymerisation products that normally formed during the activation of class F fly ash, Calcium Silicate Hydrate (C-S-H) gel and Calcium Alumino Hydrate (C-A-H) gel [22]. This behaviour is similar to the alkali activation of GGBS and is attributed to the adequate calcium content in class C fly ash and GGBS [21, 65]. The amount of fly ash blended with different types of clay that has high SiO_2 and Al_2O_3 content was in the range of 5-30% [22, 53-55, 58, 60]. However, the amount of blended fly ash reached about 70% in the case of clay with total SiO_2 and Al_2O_3 content of about 28% [63].

According to the reviewed studies, the most commonly used alkaline activator solutions were sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Sodium hydroxide was used alone as an activator [23, 51, 52, 62] or in combination with sodium silicate [22, 53-59, 63, 64]. The utilisation of both activators together in the production of clay-based geopolymer products was vital because NaOH is required for the dissolution of alumina-silicate precursor, while Na_2SiO_3 acts as binder or alkali reactant [17, 66-68]. Therefore, the final product will have better mechanical and durability performance [59, 64]. Additionally, the use of a combination of NaOH and Na_2SiO_3 is cost effective to produce clay-based geopolymer materials with good compressive strength and durability performance because NaOH is cheaper than Na_2SiO_3 [17, 57].

In many of the reviewed papers that utilised NaOH with different concentration (in the range of 5-19.7 M) [52, 59], the results indicated an improvement in the strength and reduction in the water absorption with increasing the NaOH concentration. This enhancement in the strength and durability perfomace of the geopolymer materials is believed to be due to the formation of denser microstructure that bonded the particles of the raw materials, thus resulted in less numbers of pores [17, 52].

Generally, the Na_2SiO_3/NaOH ratio in the preparation of clay-based geopolymer products is important [17, 68]. Based on the reviewed studies the Na_2SiO_3/NaOH ratios were in the range of 0.25 to 9. The optimum Na_2SiO_3/NaOH ratio in the reviewed studies varied significantly according to the type of clay, blended materials, methods of curing, etc. In general, increasing the Na_2SiO_3/NaOH ratio resulted in improved strength and durability of the final product. This could be attributed to the increased (Si) content that aids in the production of more of Si-O-Si bonds, and significantly enhanced the compressive strength of the clay-based geopolymer materials [63, 69, 70]. However, the strength started to decrease behind the optimum Na_2SiO_3/NaOH ratio. This could be due to the excessed Si content that hinders water evaporation and structure formation and negatively affect the geopolymerisation rate [63, 69, 70].

In addition to the aforementioned alkaline activators, sodium aluminate and potassium aluminate activators were used by Molino et al. [61] with the aim of improving the performance of the raw materials with low Al_2O_3 content (16.33%). The results indicated an improvement in the performance of geopolymer binder with the use of alkaline aluminate solutions relative to NaOH solution.

In some of the reviewed geopolymer-related studies, the raw materials (clays) were calcined at different temperatures and times [56, 57, 59, 61, 64], while the other studies used non-calcined clays. Ferone et al., 2015 [59] stated that calcined clay could provide better performance than non-calcined clay. This is because heat treatment helps to transform the crystalline phases into reactive amorphous of raw materials that leads to enhance the strength of geopolymers [17, 59, 71]. Additionally, the reviewed studies showed that the temperature at which the clays were calcined were in the range of 400^{o}C to 750^{o}C while the calcination time was between 1-5 hours. Generally, the strength of different calcined clay-based construction materials has improved with increasing the temperatures of calcination [59, 64] and the optimum calcination time was 2 hours [56, 57, 59, 64]. The improvement in the strength with increasing the calcination temperature is believed to be due to the increased surface area of raw materials that dissolves quicker in the alkaline solution and consequent improve the geopolymerisation reaction [17]. On the other hand, the reduction in strength with increasing the time of calcination for more than two hours is attributed to the over calcination that leads in the transformation of reactive amorphous phase into mullite crystalline phases that are dead burnt and not reactive [17].

2.4 Microwave sintering, curing and drying of clay-based construction materials.

Microwaves are electromagnetic radiation with frequencies in the range of 300GHz -- 300MHz and wavelengths between 1mm and 1m in free space [31, 72]. Standard microwave for scientific or industrial processing operates at a frequency of 2.45GHz [29, 31, 72, 73]. Sintering, curing and drying of clay-based building materials via microwave technique depends mainly on the deep penetration with uniform volumetric heating that significantly reduces processing times due to the rapid heating rate [74-76]. Although many studies have been carried out on the use of microwave techniques in the processing of construction materials [30, 34, 74-82], only limited research has been conducted on clay-based construction materials as shown in Table 3.

Hájková [83] investigated the utilisation of microwave technique to accelerate the curing of geopolymer mortar based on calcined kaolinite claystone (CKC). The geopolymer mortar was manufactured my mixing CKC (calcined at temperature of 750^{o}C), sand and potassium water glass. The variables investigated during this study were the density of the potassium water glass (1.2, 1.3, 1.4, 1.5 and 1.6 g/cm^3) used in the preparation of the geopolymer mortar and the method of microwave curing. The microwave curing methods employed were (1) the application of microwave for 26 min immediately after casting the geopolemer mortar (MW) and (2) the application of microwave for 26 min after 24 hours of casting the samples and solidification at room temperature (MW/2). Compressive strength test after 7 and 28 days, leaching test of the Si, Al, K and Na elements after 28 days and porosity test were used to evaluate the performance of the geopolymer mortar. The results indicated that the compressive strength was increased with increasing the potassium water glass densities for both curing methods. Additionally, the compressive strengths for all the tested densities and for both curing methods were almost the same at the age of 7 and 28 days. This could be attributed to the fast solidification of the geopolymer mortars under microwave curing that force the polymerization process to stop quickly that resulted in similar strengths. The leaching test results indicated an increasing in the leaching of Si, K and Na and reduction in the leaching of Al with increasing the potassium water glass densities. Moreover, the porosity test result indicated that the porosity decreased with increasing the potassium water glass densities and the samples with MW curing have higher pore volumes and pore diameters relative to that with MW/2 curing. In summary, the results showed the probable production of geopolymer mortar with compressive strength of more than 60 MPa from CKC at the optimum microwave curing conditions detailed in Table 3.

Taurino et al. [24] investigated the feasibility of using microwave sintering in the production of brick from kaolin clay and municipal solid waste incineration bottom ash (BA). Sintering experiments were carried out at a power rating of 950W for 5 minutes holding at three different temperatures (800, 900 and 1000ºC). Compressive strength, linear shrinkage and water absorption tests were used to evaluate the performance of the newly developed brick. The results indicated that by increasing the temperature, the liner shrinkage and water absorption reduced, while the compressive strength improved. This study concluded that the microwave sintering at optimum microwave conditions detailed in Table 3 for the mix with 55% BA with 45% kaolin clay was sufficient to produce brick with 65MPa strength after 28 days of curing,

Bagaber and Sudin, [25] examined the effectiveness of the microwave technique in drying of clay bricks as an alternative method to oven drying. In this study, the brick was made from 97% red clay and 3% charcoal. The main reason for adding a small percentage of charcoal was to enhance microwave absorption. The performance of dried brick using the microwave technique was evaluated by measuring density, cracks and water absorption with comparisons made with those dried in a conventional electrical oven. Dried clay bricks using the microwave technique showed improved density, less water absorption and were free from cracks as compared with drying in a conventional electrical oven. In addition, using the microwave technique at optimum conditions, as identified in Table 3, significantly reduced the temperature and time of drying compared to conventional electrical oven treatment.

Kim et al. [26] evaluated the employment of the microwave technique to accelerate the curing of alkali activated Hwangtoh clay (AAHC) Paste. In this investigation, the alkali activator was a combination of Na_2SiO_3 and NaOH. Internal temperature distribution, porosity and compressive strength tests were used for evaluating the performance of the AAHC paste. For comparison purposes, there were some samples cured using heat curing at 60oC.The results of the internal temperature distribution indicated that the core temperature was generally higher than the surface temperature. However, the maximum difference between core and surface was less than 10oC, this evidenced the uniform heating of the microwave technique. The results also showed a reduction in the cumulative pore volume and improvement in the compressive strength of AAHC paste with increased microwave curing time. This was due to the gradual filling of larger pores with the reaction products of alkali activation. Additionally, the results revealed the possible production of paste with compressive strength of about 21MPa at the optimum microwave curing conditions detailed in Table 3. These results were higher than those achieved with conventional heat curing at 60oC for 72 hours.

Itaya et al. [27] studied the possibility of using microwave techniques in the drying of kaolin clay bricks as an alternative to conventional oven drying. Deformation and formation of cracks within the brick were used to assess the effectiveness of the microwave drying technique. The results indicated that microwave drying of bricks with constant power resulted in large cracks and breaking of samples when the internal temperature reached about 100oC. However, the results showed successful drying without any deformation or crack formation when the drying process was conducted at optimum drying conditions stated in Table 3. In addition, the use of optimum drying conditions significantly reduced the drying time of kaolin clay brick relative to conventional oven drying

Table 3. Studies on the use of microwave as sintering, curing and drying technique of clay-based construction materials.

Reference	Clay type	Microwave Process	Microwave Power (W)	Microwave Time (minutes)	Clay-based product	Tests conducted	Optimum Microwave Conditions
[83]	Kaolinite claystone	Curing	3000	26	Mortar	Compressive strength, leaching and porosity	The application of microwave for 26 min with power of 3000 W after 24 hours of casting the samples
[24]	Kaolin clay	Sintering	950	5	Brick	Compressive strength linear shrinkage and water absorption	5 minutes of microwave sintering with a power of 950 W at temperature of $900^{o}C$
[25]	Red clay	Drying	700	6, 8 and 10	Brick	Density, cracks generation and water absorption	8 minutes of microwave drying with a power of 700 W at temperature of $70^{o}C$
[26]	Hwangtoh clay	Curing	40, 60 and 80	30, 60, 90, 120,150, 180, 210 and 240	Paste	Internal temperature distribution, porosity and compressive strength	240 minutes of microwave curing with a power of 60 W
[27]	Kaolin clay	Drying	100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000	-	Brick	Deformation and generation of cracks	21 minutes of microwave drying with a power of 600 W for 3.5m, 200W

							for the next 6.5 m and 100 W until the drying completion

2.4.1 Critical evaluation

The use of microwave heating for sintering, curing and drying of clay-based construction materials relies upon the uniform volumetric heating that directly penetrates the material leading to enhanced consolidation efficiency and accelerates densification, enhancing mechanical and durability performance [74-76]. This deep penetration combined with the uniform, volumetric heating can significantly reduce energy usage due to the short processing times and rapid heating rate [74-76].

The absorption of microwave energy depends to a large extent upon the chemical composition of raw materials [26, 84]. It has been reported by Kim et al. [26] that the existence of high content of SiO_2 and Al_2O_3 in raw materials will allow them to absorb microwave energy very well and enhance curing of clay-based construction materials. Therefore, the total amount of SiO_2 and Al_2O_3 in the clay materials that have been cured or sintered with microwave were more than 80% [24, 26, 83]. According to the reviewed studies, the chemical composition of raw materials were not been reported for the studies that used microwave for drying of clay materials.

The reviewed studies in Table 3 show that the microwave processing time is reduced with increases in microwave power. Additionally, all the reviewed studies indicate a considerable reduction in processing time by using microwave heating compared to a conventional electrical oven. This is because the volumetric heating process is significantly more efficient in comparison with resistance heating [72, 85].

As heat is favourable for improving the performance of geopolymer materials, however, the use of conventional ovens is not an energy efficient technique as it takes a long time and consumes energy along with the negative environmental impact associated with it. Therefore, the produced geopolymer materials have used the microwave as an environmentally friendly source of heating. In the reviewed studies that employed the microwave as a curing technique, the microwave powers varied significantly with 40, 60 and 80 W for [26] and 3000 W for [83]. These variations in the power explain why the required processing time in [26] was 4 times the time required in [83].

Regarding the utilisation of microwave as drying technique of brick, the reviewed studies have also showed a range of microwave powers that have been employed between 100-1000 W. Additionally and similar to the use of microwave as curing technique, the utilisation of higher power resulted in reducing the processing time as the temperature inside the microwave is directly related with the microwave power.

For the use of microwave as sintering technique, Taurino et al. [24] indicated that the utilisation of microwave with a power of 950 W for 5 minutes was sufficient to produce brick with a compressive strength of 65 MPa.

3. Discussion

3.1 Characterisation of clay-based construction materials

Tables 1-3 exhibit the wide range of clay-based materials and methodologies that have been developed and subjected to various research investigations.

A range of tests were carried out on the resulting products to evaluate their performance following different standards. Compressive strength was the common test considered by most of the reviewed studies as the compressive strength is considered a basic and universally acceptable unit of measurement to specify the quality of clay-based construction materials as stated by common standards [35].

Other tests were also used in assessing the performance of the products. For example, the water absorption test was conducted for most of the resulting bricks, blocks, stabilized earth blocks and compressed stabilized earth blocks as a durability measurement [24, 25, 35-37, 41, 42, 45-47, 64].

Since clay-based brick and blocks are recognised as materials which contribute towards the thermal insulation of buildings and consequently increase indoor comfort, some of the research projects [39, 43, 45, 51, 55] investigated this property. The results indicated that the thermal isolation of the clay-based unities have been reduced slightly with increasing the stabiliser content [39, 43, 45], however, the use of alkaline activators and especially in the presence of FA improved the thermal isolation of the clay-based unites [51, 55].

Freezing/thawing and wetting/drying tests were evaluated for different clay-based materials produced in countries that experienced these conditions such as the United Kingdom, Spain and Belgium. [23, 45-47, 62].

In order to identify potential toxic agents within the produced materials, some researchers conducted leaching test [53, 83]. Dassekpo et al. [53] have conducted leaching test to identify the Arsenic content as a toxic material because the raw materials were clay waste from construction sites. Additionally, Hájková [83] conducted the leaching for the alkali (K and Na) elements to decrease efflorescence of the mortar due to the alkali effect.

Different tests were conducted for evaluating the performance of the clay-based construction products for different application of microwaves. Porosity test was conducted when the microwave was used as a curing technique because reducing the curing time by increasing the temperature of curing can significantly produce larger pores with larger diameters and consequently reduce the compressive strength at later ages [69, 83]. However, generation of cracks were investigated when the microwave was used as drying technique due to the high temperature of the core of the clay-based produces [25, 27]. Other tests such as linear shrinkage and internal temperature distribution were conducted when the microwave was used as sintering and curing technique, respectively.

Although most of the reviewed studies aimed to reduce the negative environmental impact of the clay-based construction materials, only one research project actually investigated the environmental performance of the final product [45]. As such, more detailed environmental impact assessments of the other techniques will be required before they can be compared with conventional production methods.

3.2 Curing of clay-based construction materials

The term curing is a process that normally associated with the production of different construction materials such as concrete, mortar, stabilised earth blocks, etc. The curing process can significantly affect the performance of the construction materials and it usually aims at acquisition the full strength of developed product [86]. As the method of curing can be varied according to the process of production, therefore, this section will be divided into two sections: curing of blended and stabilized clay-based construction materials and curing of geopolymer clay-based construction materials.

3.2.1 Curing of blended and stabilized clay-based construction materials

Curing is very important process for stabilized clay-based construction materials, especially when cement or lime is used in preparation of these products as a stabilizing agent. Water curing would aid in enhancing the hydration process of the cement/lime as this process can take place more efficiently in the presence of water that results in hardening the materials treated with cement/lime. Table 1 shows the methods of curing that was used for each of the stabilized clay-based construction materials

According to the reviewed studies [36-39, 42, 44, 45], the produced clay-based construction materials that incorporated cement and/or lime were kept moist for 28 days by immersing in water, spraying with water or placed in humidity chamber at ambient temperature that ranged between 20-40^{o}C according to the weather conditions in the country where the experiments were conducted. This is because the presence of moisture will allow unreacted cement or/and lime particles to hydrate further, producing additional cementing gel as reported by Joel and Edeh [86]. Additionally, increasing the age of cuing to 28 days or even longer [35, 46, 47] in the presence of moisture will aid the formation of secondary cementing gel that is formed due to the chemical reaction between calcium from portlandite phase (CH) and silicates from the clays [2].

3.2.2 Curing of geopolymer clay-based construction materials.

The method and period of curing can significantly affect the properties of the geopolymer clay-based construction materials [17, 69]. Geopolymer clay-based construction materials are usually cured at ambient or slightly higher temperature after mixing. Normally, the curing temperature is preferable to be less than 100^{o}C [17].Based on the reviewed studies [22, 23, 51-64], different curing temperatures with various periods of times were employed in the production of different geopolymer clay-based construction materials.

According to the reviewed studies, air curing was considered by many of the researchers under ambient temperatures that ranged between 20-35^{o}C. For the geopolymer clay-based construction materials under air curing, the periods of curing was a minimum of 7 days and some of the studies extended the time to 28 days [55], 60 days [22, 60], 90 days [54, 63] and even 180 days [58]. This is because the geopolymerisation reaction is very slow at ambient temperature and extending the period of curing is essential to produce materials with enhanced strength and reduced water absorption due to the formation of additional geopolymerisation products [17, 22, 54, 58, 87].

In addition, oven curing was one of the techniques used in the curing of geopolymer clay-based construction materials due to that fact that heat is essential to improve the reaction by accelerating the dissolution of silica and alumina species from the raw materials [88-90]. According to the reviewed studies, the curing temperatures were reported in the range between 40^{o}C and 150^{o}C and the period under oven curing ranged between 6 hours to 7 days. Slaty et al. [62] reported that increasing the temperature (50^{o}C, 60^{o}C, 70^{o}C and 80^{o}C) improved the strength gain after 6-72 hours. However, high curing temperature (150^{o}C) resulted in reduced compressive strength due to the formation of large pores [64].

In general, adequate curing for clay-based construction materials is required to produce materials with good mechanical and durability performance to maintain their structural integrity.

3.3 Comparative assessment of the techniques used in the production of clay-based construction materials:

The sustainable development in the construction industry required evaluating different parameters of the production techniques. The criteria considered in this study for the assessment are environmental and economic aspects for the production of different clay-based construction materials. The study presents comprehensive evaluation of environmental impacts associated with different techniques to produce clay-based construction materials. Additionally, the study provide some facts about the economic feasibility of different production techniques.

3.3.1 Environmental assessment

From an environmental point of view, the construction industry is responsible for about 40% of the energy consumption worldwide, nearly 30% of the global greenhouse gas emissions, generation of solid waste, depletion of natural resources and environmental damage [91]. Therefore, the construction industry is looking for alternative techniques and materials with the aim of moving towards sustainable development. The main advantages of using sustainable techniques and materials are to protect the environment and ecology, reduce the depletion of natural resources, energy efficiency and healthy outdoor and indoor environment [91, 92].

The main goal of this study is to assess the environmental impact of different unfired clay-based construction materials, and to compare them with traditional fired clay-based construction materials. The assessment criteria including quantifying the consumption of energy, consumption of natural resources, consumption of fossil fuel and production of greenhouse gases.

The production of clay-based construction materials through firing is considered the most significant impact on the environment. This is because of the high temperature kiln firing needed that consumes significant amount of energy along with releasing large quantities of greenhouse gases including CO_2 (attributed to the utilisation of coal for the firing process)[5, 91]. Additionally, in some cases where the coal used for firing is of low quality, this could significantly contributes to the acidification due to the release of SO_2 emissions and the formation of NOx [91, 93]. Furthermore, the production of fired clay-based construction materials contribute considerably to the depletion of fossil fuels as firing obtained mainly from coal [91].

On the other hand, the production of unfired clay-based construction materials through stabilisation seem to be the trend to follow to achieve sustainable development in the construction industry in terms of environmental concerns. However, the stabilisation technique involves the addition of cementing material(s) such as lime or/and cement, whose manufacture required intensive energy, consumes huge quantities of natural resources along with releasing huge quantities of CO_2 emissions [5, 91, 94]. The manufacture of Portland cement consumes about 5.6 GJ of energy and requires approximately 1.5 tonnes of raw materials along with the production of about 7% of CO_2 emission in the atmosphere [49, 95]. Additionally, the production of stabilised clay-based construction materials contribute to larger water depletion that needed for curing process and lower consumption of fossil fuels relative to fired clay-based construction materials [91].

In comparison with the aforementioned production techniques, the production of clay-based construction materials through geopolymerisation consumes much less energy and releases considerably lower quantities of greenhouse gases [5]. Therefore, the environmental burden of the geopolymer clay-based construction materials are generally lower than the fired or stabilised clay-based construction materials [96]. However, the production of geopolymer clay-based construction materials is also associated with some environmental impacts that mainly attributed to the utilisation of alkali activators [97]. The manufacture of the alkali activators require intensive energy: (i) sodium hydroxide that is processed by electrolysis of salt water and (ii) sodium silicate from the melting of soda ash and sand at about 1400^{o}C [97]. Additionally, in order to achieve reasonable strength for geopolymer clay-based construction materials, there is a need for curing at elevated temperatures (40^{o}C-80^{o}C) that means extra energy consumption [5, 97].

3.3.2 Economic assessment

The feasibility of different production techniques should be evaluated in order to produce sustainable products with competitive financial cost. The parameters included in the economic assessment are the cost of raw materials and the energy required in the production.

The cost of raw materials can vary significantly among the production techniques. Poinot et al. [96] reported that the cost of raw materials for fired clay-based construction materials could be as small as 2% of the total cost of the final product, while in the case of geopolymer clay-based construction materials most of the cost is attributed to the alkaline activators. The highest cost (about 60%) associated with the production of clay-based construction materials through firing is attributed to the consumption of large quantities of energy [96]. However, the unfired clay-based construction materials required smaller amount of energy to power the hydraulic pressure compressed machines and for curing at elevated temperatures (for geopolymer clay-based construction materials)[5, 96].

As overall, the evaluation of the environmental impacts and economic feasibility of different production techniques depends on considerations included in the assessment criteria and all of these considerations should be evaluated and compared to provide accurate evaluation of the performance of different clay-based construction materials. According to the evaluated criteria and from production point of view, the production of clay-based construction materials through geopolymerisation is seen to be the best production technique taking into consideration the low environmental impacts and the potentially competitive financial cost relative to other production techniques.

3.4 Future trends

The sustainability index of different clay-based construction materials could be significantly improved by employing cheaper and eco-friendly materials and manufacturing processes along with concentrate on improving the mechanical and durability performance. The following are some suggestions to improve the sustainability of different clay-based construction materials:

- As the utilisation of cement and/or lime in the production of stabilised clay-based construction materials reduced the sustainability index of the final products, therefore, replacing these materials with viable alternatives, could significantly improve the sustainability performance of this manufacturing technique. The use of industrial, agricultural and natural waste and/or by-products as partial or full replacement to traditional binders (cement and/or lime) can lead to the production of stabilised clay-based construction materials with superior environmental, financial and technical benefits. Marcelino-Sadaba et al. [94] stated that replacing the cement and/or lime partially by GGBS in the production of stabilised clay bricks resulted in reduced environmental impacts and superior technical performance.
- Generally, the production of geopolymer clay-based construction materials have lower environmental impact, relatively similar cost to other production techniques and with relatively high mechanical and durability performance. However, the alkaline activators used in the production of geopolymer clay-based construction materials are considered as the main contributor to environmental impact and cost of this production technique. Therefore, the viability of this production technique could be further enhanced by; firstly, reduce the molar concentration of the alkaline activators, secondly,

the utilisation of clay materials with a minimum Si/Al molar ratio of 2 to decrease the use of alkaline activator solutions and finally, utilisation of some waste materials with high alkaline content as alternative to traditional alkaline activators. Additionally, heat curing is essential for geopolymer clay-based construction materials to achieve adequate mechanical and durability performance, however, the use of conventional ovens is not an energy efficient technique as it takes a long time and consumes energy along with the negative environmental impact associated with it. Therefore, the use of microwave as an alternative source of heat can significantly reduce the cost and environmental impact of this technology, as the microwave heating is uniform and volumetric, reducing energy consumption and curing temperatures, with very rapid heating rates and significantly reduced processing times, thus improving physical and mechanical properties, and lowering environmental hazards.

4. Conclusion

Based on the review of the research studies on the production of clay-based construction materials, the following conclusions have been drawn:

- A wide variety of clay types were investigated in the production of different clay-based construction materials.
- The techniques studied for the production of clay-based construction materials were: blending and stabilising, alkali activation and the use of microwave heating as an innovative sintering, curing and drying technique. The method of blending and stabilising is based on replacing clay partially with some waste or by-product materials and adding cementing materials such as cement or lime. The technique of alkali activation is based on the chemical reaction between clay materials representing the alumina-silicate source and a high alkaline solution. The use of microwave heating is

based on volumetric heating that directly penetrates the material significantly reducing the processing time.

- A detailed comparison between different production techniques were conducted in terms of environmental and economic aspects along with suggestion for future trend to improve the sustainability of different production techniques.
- In order to maximize the commercial production of clay-based construction products using the techniques discussed in this work, more research needs to be conducted on the environmental and economic benefits along with public education and standardisation.

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