Utilisation of nut shell wastes in Brick, Mortar and Concrete: A review

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Abstract

Currently, growing activities in the construction sector have resulted in a rapid depletion of natural resources for building material production. On the other hand, agricultural industries generate a huge amount of residues/by-products every year around the world creating environmental concerns since most of these residues are burnt or disposed to the landfill. However, several current studies have presented the potential application of agricultural wastes in building material production owing to good physical and mechanical properties. Moreover, utilisation of such waste materials can contribute to reducing environmental impacts by proving alternative waste management strategies worldwide. This paper reviews some of the nut shell wastes (Argan nut, Brazil nut, Cashew nut, Groundnut, Hazelnut, Pistachio, Shea nut and Walnut) for the production of three groups of materials i.e. brick, mortar and concrete. Different properties of brick, mortar and concrete when admixed with nut shell wastes are discussed and compared with related standards. The review of literature exhibited an obvious potential of the nut shell waste as a partial replacement of conventional materials since most of the developed materials comply with the standards. However, a lack of studies on durability and thermal properties is observed. Besides, existing studies are inadequate to ascertain the potentiality of these wastes for reuse in building materials production. Therefore, extensive research is required to enhance the existing knowledge in this domain to achieve sustainable objectives in the construction industry.

Keywords: Brick, Concrete, Mortar, Nut shell waste, Replacement.

1. Introduction

The world population is predicted to grow significantly and hit 9.70 billion in 2050 and 11.20 billion by the end of the century [1] which will eventually lead to a major increase in housing demand. Consequently, the building construction industry will face a growing challenge to meet the additional demand and there will be a rise in building materials production like brick, concrete, steel, aluminium etc. The conventional manufacturing processes of fired brick and concrete masonry involve high energy [2, 3] and one of the key sources of global CO_2 emissions (around 6-7%) [4, 5] has been reported as cement production, which contributes to 60% global warming along with other greenhouse gases [6]. This concerning environmental issue has offered an incentive to the researchers for developing sustainable materials in the construction industry.

At the same time, it has been reported that the current annual global waste generation amounts approximately 1.30 billion tons and are projected to reach nearly 2.20 billion tons by 2025 [7]. The major population of the developing countries still depend on the agriculture-based economy, where a large amount of agricultural wastes are generated and left unmanaged every year. Inefficient management of these huge quantities of agricultural wastes ultimately causes a threat to the environment both in many developed and developing countries [8, 9]. Such agricultural wastes are locally available, low-cost and have the ability to act as an effective means of CO_2 processing [10, 11]. Therefore, the use of agricultural wastes in the building construction industry has gained global significance [12-14]. Researchers have made considerable efforts to develop different types of building materials from various types of agricultural wastes aiming to reduce environmental pollution as well as to protect the raw materials from depletion. Numerous agricultural wastes are already employed in brick and concrete production as alternative replacement materials for clay, aggregate, sand and cement. Jannat et al. [15] reported unfired earth brick production incorporating agricultural wastes whereas Al-Fakih et al. [16] reviewed fired brick manufactured with different organic wastes. Besides, Prusty and Patro [17] and Prusty et al. [18] reported the utilisation of agricultural wastes as fine and coarse aggregate replacement in concrete.

Every year million tons of nuts are produced around the world (Fig. 1) and a significant amount of by-products from the nut processing industry are discarded [19-21] However, several studies have been conducted on the use of these by-products/residues in different forms to produce building materials [22-24]. This paper aims to introduce some of the certain nut shell wastes (Argan nut, Brazil nut, Cashew nut, Groundnut, Hazelnut, Pistachio, Shea nut and Walnut) in different compositions to develop three types of building materials i.e. brick, concrete and mortar. The selection of these materials is based on their extensive use in building construction industry. The study presents the chemical and physical properties of the different nut shell wastes and underlines several properties of waste blended samples. Besides, it summarises the standards followed by different authors for the tests and compares the findings with the related standards. Nevertheless, existing studies are still inadequate and more extensive investigations are

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required to establish the suitability of these wastes for building material production.

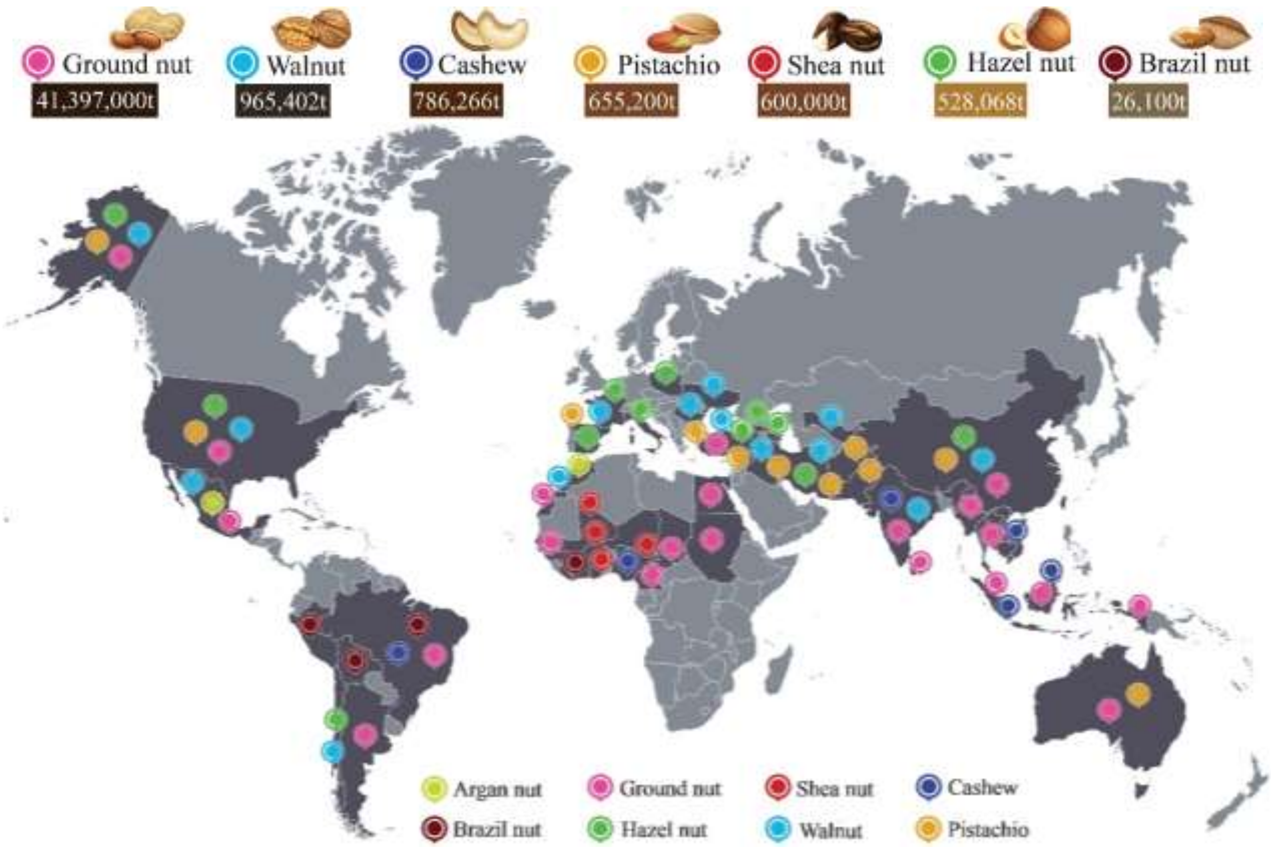

Fig. 1. Global annual nut production [25] and top nut-producing countries [26].

2. Previous reviews

Several review articles have already been published on the utilisation of numerous forms of shell wastes in concrete manufacture. Sujatha and Balakrishnan [22] presented an overview of the physico-mechanical and durability characteristics of concrete with ground coconut shells. Hamada et al. [23] and Alengaram et al. [27] reported the use of oil palm shells to replace lightweight aggregates in concrete. The studies discussed different physico-mechanical as well as durability behaviours of the waste incorporated concrete. In addition, the findings were compared with conventional normal-weight and lightweight concrete. Furthermore, Mo et al. [24] reviewed various durability properties (shrinkage, chloride penetration, resistance to chemical and high temperature) of oil palm and coconut shell concrete. Prusty and Patro [17] summarised some of the agricultural seeds (corn cob, date and rubber seed) and shell wastes (coconut, cockle, oil palm and periwinkle shell) as a substitute for aggregate in concrete production. The study discussed and compared the physical, mechanical and thermal properties of waste-blended concrete and waste-free concrete.

The previous review studies indicate that most of the work have been done on the incorporation of oil palm shell and coconut shell wastes in concrete. Therefore, this present article reviews the potential utilisation of several other nut shell wastes (Argan nut, Brazil nut, Cashew nut, Groundnut, Hazelnut, Pistachio, Shea nut and Walnut) in brick, mortar, and concrete production.

3. Nut shell wastes

Table 1 and Table 2 respectively present the physical properties and chemical compositions of different nut shell wastes. These properties generally vary based on the origin of the nut as well as the treatment process.

3.1 Argan Nut Shell (ANS)

Argan tree is one of the most common trees in the Moroccan region. A large argan forest of about 830000 ha covers the South-West of Morocco [28] and the amount of discarded ANS in Morocco is approximately 60 thousand tons per year [29]. The local people make use of almost all parts of the Argan tree including wood and woody fruit shells for heating, the fruit for edible argan oil production and fruit pulp from the oil production for cattle [30, 31]. The ANS which accounts for about 86% of the argan fruit weight has an elliptical cross through a slot in the longitudinal direction containing small fibres mainly composed of cellulose (25.70%), hemicelluloses (34.30%), lignin (34.50%) and ash (5.40%) [31, 32]. Studies revealed that the water content of Argan Nut Shell Powder (ANSP) is 5.43% and 24h water absorption is 26.30%, where the absolute and apparent densities are found as 1040 kg/m^3 and 0.74 kg/m^3 respectively. Besides, the thermal conductivity of ANSP is reported as 0.16 W/mK [33, 34]. Scientists have investigated the mechanical properties of ANS aiming to find new applications of this material and some research have already been conducted incorporating ANS in the development of bio-composite [30-36].

3.2 Brazil Nut Shell (BNS)

Brazil nuts commonly grow in a large area of South America mainly in Brazil, Peru, Colombia, Venezuela and Ecuador [37]. The nut-based industries in the Amazonian region generate a large amount of residues from the nut shelling process [38-40]. It is estimated that for each ton of clean nut, 1.40 tons of residues are produced [41]. These residues are commonly used as bio-fuel by the local people [42] which produces significant quantities (80–150 tons/year) of Brazil Nut Shell Ash (BNSA) [43]. The main inorganic components of BNSA are K_2O (33%), CaO (11%) and SO_3 (7.89%). The chemical analysis of the BNSA shows various phases including $CaCO_3$, $Ca_3(PO_4)_2$, K_2CO_3, K_2SO_4, $K_2Ca(CO_3)_2$, MgO, quartz etc. [43] which indicates a remarkable variety of minerals compared to other organic ashes. Research showed that brazil nut seed contains 65–70% of oil and the mesocarp of the nut has great potential for developing bioinspired impact-resistant materials [44]. BNS was also investigated as biosorbent [37] and stabiliser in porous brick production [43].

Table 1
Physical properties of the nut shell wastes.

	ANSP [33, 34]	CNSP [45, 46]	CNSA [47-49]	GSP [50]	GSA [51-55]	PSP [56]	PSA [57]	WSP [58, 59]
Fineness (%)	-	2.00	1.95-8.10	-	17.45	2.58	-	-
Specific gravity (g/cm^3)	-	0.58-3.10	2.98-3.10	0.60	1.81-3.20	0.12	-	0.96-1.25
Specific surface area (m^2/kg)	-	-	605	-	-	-	1630	-
Bulk density (kg/m^3)	-	-	772.92	257.78	254.55-445	-	-	-
Natural water content (%)	5.43	-	-	-	1.42	-	-	-
Absolute density (g/cm^3)	1.04	-	-	-	-	-	-	-
Apparent density (g/cm^3)	0.74	-	-	-	-	-	-	-
Water absorption (%)	26.30	-	-	-	1.61	-	-	10
Conductivity (W/mK)	0.16	-	-	-	-	-	-	-
pH	-	-	13.35	-	-	-	-	-
Colour	-	-	light yellow	-	-	-	-	brown

3.3 Cashew Nut Shell (CNS)

Cashew nut is found in Africa, Brazil, India, Vietnam and Central America as a cash crop. CNS represents around 67% of the fruit weight [60]. CNS is a waste by-product produced by the nut processing industry which is disposed of or incinerated extensively [21, 61]. Hence, CNS residues act as a major source of environmental contamination in the cashew nut processing areas when it is not efficiently utilised. On the other hand, the Cashew Nut Shell Ash (CNSA) is the waste from the boiler grid, resulted from the burning of the rind of nuts. This waste is used as compost in planting cashew and a little part of it is dumped in landfills [19]. The CNSA has a specific gravity of 2.98 to 3.10 [47, 49] specific surface area is 605 m^2/kg and fineness of 1.95% [47]. A number of studies examined the properties of brick and concrete [19, 46, 48, 49, 62-64] incorporating CNS wastes to evaluate their applications in diverse sectors.

3.4 Groundnut Shell (GS)

Groundnut comes originally from Brazil in South Africa and then spread to other areas of America and Asia. [50]. GS is an agricultural by-product constituting almost 20-30% of the total pod. Every year around 11,000,000 tonnes of GS are produced in the world which are often burnt or left to decompose naturally [65]. GS mainly consists of hemicellulose (62%), cellulose (18.10%), lignin (5.60%) and ashes (4.70%) [66]. The Groundnut Shell Powder (GSP) has a specific gravity of 0.60 and a density of 257.78 kg/m^3 [50]. On the other hand, Groundnut Shell Ash (GSA) has cement properties that are considered as a beneficiary to the brick production to enhance the binding properties. The specific gravity of GSA is found 2.10 to 3.20 [53, 54, 67, 68]. The total amount of oxide (62.83-76.39) and the higher CaO content (24.10%) in GSA also show that it has some self-cementing properties [69, 70]. Many researchers reported that GS waste possessed unique characteristics which make it competitive among other construction materials. GS is already used for developing bricks [53, 66, 71], sandcrete blocks [67] and a replacement material in concrete [48, 50, 51, 70] which are reviewed in this article.

3.5 Hazelnut Shell (HS)

Hazelnuts mainly grow in the Mediterranean Sea region. It is originally from Anatolia and Greece, but it spread through Europe in the nineteenth century [72]. Turkey, USA and Azerbaijan [73] are the world's leading producers of hazelnuts, where Turkey grows about 500,000-650,000 tons a year alone representing 75% to 80% of the world total production [74]. Since HS constitutes more than 50% by weight of the total nut abundant biomass residues are generated by the hazelnut processing industry [75, 76]. Hazelnut Shell Powder (HSP) mainly contains 99.37% CO_2, 0.27% Na_2O_5, 0.19% K_2O and 0.17% CaO [75]. Cimino et al. [77] found out that HS shows good efficiency in removing toxic ions from aqueous solutions. Çöpür et al. [78] investigated the possibilities of utilising husk and shell of hazelnut in medium-density fibreboard production where Gürü et al. [79] developed particleboard from HS and assessed the improvement of its fire and water resistance. Moreover, Demirbaş and Aslan [80] examined the effects of ground HS on the mechanical properties of cement. Studies were also conducted on the incorporation of HS waste in brick [75] and mortar production [81, 82].

3.6 Pistachio Shell (PS)

The pistachio is native to the Asia Minor region (Mediterranean island to India). According to FAOSTAT data [26] Iran, Turkey and US produce around 1,239,007 tons of pistachio per year which is almost 90% of the global production. PS comprises 51% to 69% of the fruit weight [83] and is usually disposed to landfills or used as fuel [84, 85]. Studies presented that Pistachio Shell Powder (PSP) has fine a modulus of 2.58 and specific gravity of 0.12 [56] whereas the Pistachio Shell Ash (PSA) contains calcite, graphene, quartz and alumina-based compounds with a high specific surface area of 1630 m^2/kg [57]. Scientists have proposed to utilise these abundant solid wastes for the preparation of activated carbons [86-88], for the production of low-cost adsorbent [89] and mortar [56, 57] because of their high carbon and low ash content.

3.7 Shea Nut Shell (SNS)

Shea trees are indigenous to semi-arid and sub-humid savannas of sub-Saharan Africa and the production of shea nut is in the African continent only [90, 91]. SNS is a by-product of the shea butter processing industry which is currently used as fuel to sustain the industry. The expected annual production of SNS waste would amount to approximately 30,000 tons as the demand grows rapidly [92]. Some studies have been conducted to use SNS waste in the production of activated carbons [93-95]. Other studies used it as a partial cement replacement in concrete [96, 97] and mortar [98].

3.8 Walnut Shell (WS)

The walnut trees grow widely in the Asian belt extending from the Balkans to China [99, 100]. In Europe it was grown as far back as 1000 BC. and later, it spread to the Mediterranean regions [101]. Global walnut production was recorded around 965,402 tons in 2019 where China, USA and Iran were the top producers [25, 26]. WS attributes to 67% of the total weight of the fruit [102, 103]. The principal feature of WS microstructure is high lignification stone cells which are relatively short-sized and isodiametric sclereids. The cell walls which possess high strength and stiffness account for almost 90% of cell volume [104, 105]. WS can be crushed or ground into different grits that range from coarse grits to fine powders. Because of the high hardness, WS is used as an abrasive to blast clean [106] and render cementitious surfaces [107]. Besides, WS finds its place in the building construction industry as it has sound technical features such as lower water absorption, better strength and bio-resistance [108]. Researchers used WS in the production of particle boards [109-111], as a substitute for fine and coarse aggregate in concrete [59, 112-115] and alternative material for load-bearing wall [116].

Table 2
Chemical compositions of the nut shell wastes.

Chemical Compounds (%)	BNSA [43]	CNSP [45]	CNSA [19, 47-49]	GSP [71]	GSA [52, 53, 55, 67-70, 117-121]	HSP [75]	HSA [81]	SNSA [96, 97]
SiO_2	6.38	53.50	54.85-65.02	5.92	16.21-51.54	-	4.89	29.01 -41.50
Al_2O_3	1.94	2.10	2.01-16.28	2.41	1.75-22.45	-	0.77	20.05 -22.50
Fe_2O_3	0.67	4.30	4.20-12.51	6.05	0.50-14.21	-	1.83	9.05-1.13
CaO	10.84	35.90	0.86-35.67	2.10	8.69-24.27	0.17	50.48	1.81 -5.18
MgO	5.36	1.56	1.53-1.85	0.30	1.20-7.00	-	1.67	1.04-1.48
K_2O	32.86	0.50	0.49-0.52	1.55	4.42-21.90	0.19	27.73	0.95-1.70
Na_2O	0.82	0.35	0.34-0.80	0.11	0.04-13.27	-	2.98	0.26
Na_2O_5	-	-	-	-	-	0.27	-	-
SO_3	7.89	1.00	0.80-1.32	-	0.94-6.97	-	3.20	2.10
TiO_2	0.93	-	0.01	-	0.13-2.00	-	-	-
P_2O_5	3.79	-	0.01	-	0.60-2.80	-	-	-
MnO	0.76	-	-	-	0.05-0.42	-	-	-
P_2O_3	-	-	-	-	-	-	0.29	-
Na_2O_3	-	-	-	-	10.00	-	-	0.81
Na_2O_{eq}*	-	-	-	-	-	-	21.23	-

SrO	-	-	-	-	0.30-0.50	-	-	-
ZnO	-	-	-	-	0.12-0.50	-	-	-
BaO	-	-	-	-	0.05-0.57	-	-	-
Cl^-	-	-	-	-	-	-	1.00	-
CO_2	-	-	-	-	-	99.37	--	-
LOI	27.50	0.80	2.65-2.95	80.56	2.65-28.99	-	-	4.25-9.55

* Equivalent Na_2O = Na_2O+0.658K_2O

4. Review of studies

Researchers examined different properties of brick, mortar and cement incorporating various percentages of nut shell wastes according to different relevant standards. Table 3 presents the studies on the development of brick where Table 4, Table 5 and Table 6 summarise mortar and concrete with nut shell wastes. Moreover, Table 7 lists the relevant standards followed by the researchers to investigate the different physical and mechanical properties of nut shell-blended samples.

4.1 Nut shell wastes in unfired brick

The effects of ANSP (2, 4 and 6%) and cement (5%) on the mechanical and thermal performances of the Compressed Earth Block (CEB) were examined by Tatane et al. and Akhzouz et al. [33, 34, 36]. The test results showed that thermal conductivity decreased with increasing ANSP content from 0-6% in the sample blocks and the conductivity values for the cement-free blocks (0.87 W/mK to 0.75 W/mK) were found higher than cement stabilised blocks (0.64 W/mK to 0.48 W/mK). This decrease is attributed to the low thermal conductivity of the ANSP (0.16 W/mK) compared to the clay matrix (0.30 W/mK). Besides, the addition of cement in the blocks further limited the manoeuvrability of the mixture which ultimately reduced the good compaction. This resulted in additional air inside the blocks which increased the porosity and decreased the thermal conductivity. Also, tensile strength slightly reduced for both cement-free (0.75 MPa to 0.65 MPa) and cement stabilised blocks (0.90 MPa to 0.68 MPa) with the increase of ANSP content from 0-6%. Moreover, dry compressive strength indicated a decreasing trend from 2.21 MPa to 1.89 MPa for the same amount of ANSP due to poor adhesion between the clay matrix and ANSP. However, cement in the block developed some rigid connections between the soil particles which induced a little improvement in the strength. But for the cement stabilised blocks the optimum compressive strength was achieved at 2% waste content (3.12 MPa) since it adhered well to the clay matrix and above this amount, the cement content became inadequate to bind the ANSP. Moreover, due to the non-absorbing characteristics of ANSP (absorption=26.3%), the water absorption coefficient declined from 16.92% to 10.10% as ANSP was added (0-6%) which was below the limit stated in XP 13-901 standard [122] (20%).

Miron et al. [116] developed CEB incorporating a various percentage of WS (5-20%). It can be observed that the introduction of WNS negatively affected the properties of CEB. Only the control samples satisfied the compressive strength value specified by the Mexican Standard: NMX-C-404-ONNCCE-2005 [123] (6 MPa) and WS mixed samples showed a drop up to 94% in strength. In order to improve the properties of the WS blended samples lime (7%) and gypsum (3%) were incorporated in the mixture which demonstrated a decrease of up to 65% in strength. Besides, the control sample exceeded the water absorption (30%) allowed by the standard (21%). Furthermore, the samples with 5% WS and 10% cement exhibited water absorption of 23.8% while lime and gypsum stabilised samples containing 20% WS (18.55%) and 10% WNS (19.39%) showed lower values.

4.2 Nut shell wastes in fired brick

Escalera et al. [43] produced lightweight porous ceramic bricks by sintering diatomaceous earth and BNSA (10, 20 and 30%) at different temperatures (750-950°C). The results revealed that shrinkage decreased from 11.60% to 6.80% for samples containing 10-20% BNSA which was less than the control sample. This can be explained by the formation of small voids in the mixture filled with gas (CO_2 and SO_2) by the sulfates and carbonates decomposition from the BNSA as they reacted with SiO_2. Moreover, the bulk density increased but the open porosity decreased for all samples with increasing the temperature as well as increasing BNSA content. Density ranged between 850 kg/m^3 to 1440 kg/m^3 (750°C), 1060 kg/m^3 to 1840 kg/m^3 (850°C) and 1340 kg/m^3 to 1860 kg/m^3 (950°C) for varying BNSA content from 10-30%. On the other hand, open porosity varied between 57.50% to 23.75% (750°C), 49% to 7.50% (850°C) and 37.50% to 6.25% (950°C) for the same BNSA content. Furthermore, the thermal conductivity increased (0.20 W/mK to 0.76 W/mK) than the control sample (0.22 W/m K) with the incorporation of BNSA. Besides, most of the samples displayed an improvement in compressive strength with increasing the temperature and BNSA percentage except the sample containing 30% BNSA at 950°C showed a substantial drop (33%) in strength. This significant reduction in strength is due to the development of $(K_{0.7}Na_{0.3})Cl$ salt phase by the surplus BNSA in the mixture which later decomposed into two individual phases under the phase separation temperature making the blend very brittle. The highest compressive strength was recorded as 24 MPa at 20% BNSA (950°C), 18.75 MPa at 30% BNSA (850°C) and 8.75 MPa at 30% BNSA (750°C). In addition, all the samples but the samples with 0-20% BNSA at 750°C achieved the minimum compressive strength requirement (7 MPa) specified in Turkish Standard (TS EN 771-1) [124].

Santhoshkumar et al. [46] manufactured low-weight bricks (fired at 1100°C) utilising CNSP (10-60%). The results showed that the 10% waste-blended sample exhibited a compressive strength of 3.50 MPa and with the further addition of the waste to 50% the compressive strength decreased to 1.20 MPa. The reference sample obtained the highest compressive strength (7 MPa) and the lowest compressive strength was found at 60% of waste content which was within the threshold limit. The water absorption test revealed that with varying CNSP content from 10-60% water absorption increased from 18% to 43% which was above the reference sample (15%).

Table 3
Nut shell wastes in brick production.

Nut shell wastes	References	Brick type	Content (%)	Unit size (mm)	Firing temp. (°C)	Density (kg/m^3)	Porosity (%)	Max. Compressive Strength (CS), Flexural Strength (FS), Splitting Tensile Strength (STS) (MPa)	Water absorption/ Capillary water absorption coefficient (%)	Min. Thermal conductivity (W/mK)
ANSP	[33, 34, 36]	CEB	2,4,6% mass and 5% cement	14×29.50	-	1825-2062.50	-	CS:3.12 STS:0.80	10.10-11	0.48
BNSA	[43]	Fired Diatomaceous Earth Brick	10,20,30% wt	⌀35× 35	750	850-1440	23.75-57.50	CS:8.75	-	0.20
					850	1060-1840	7.50-49	18.75		
					950	1340-1860	6.25-37.50	24		
CNSP	[46]	Fired Clay brick	10,20,30,50,60%vol	225×100×75	1100	-	-	CS:3.50	18-43	-
CNSL	[62]	Soil-Cement brick	16.66g,8.33g	252×125×125	-	-	-	CS:2.45	-	-
GSP	[66]	Fired Clay brick	5,10,15%vol	70×40×18	950,1000	-	25.15-28.04	FS:7.03	-	-
GSA	[53]	Fired Clay brick	2,4,5,6,8,10%wt	1850×850×650	600-850	1225-1426	-	CS:17.00 FS:0.11	15.33-25	-
HSP	[75]	Fired Clay brick	2.50,5,7.50, 10%wt and 5-30% RM	⌀20×8.56 ⌀20×13.60	950	1410-1670	38-51.35	CS:32	22.50-36.10	0.45
					1000	1440-1700	36.25-48	30	21.25-33.33	0.47
WS	[116]	CEB	5, 10, 15, 20%wt and 10% cement, 7% lime, 3% gypsum	100×200×50	-	-	-	CS:6.00	18.50-30	-

de Araujo et al. [62] produced soil-cement bricks having Cashew Nut Shell Liquid (CNSL) as a constituent of the formulation. The samples were obtained from the mixture of pure CNSL, soil and cement (1:10). The results of the compression tests of the full brick presented average resistance of 2.70 MPa for the control sample which was in accordance with ABNT standard, NBR 8492/12 (2 MPa) but for the half brick, the average compressive strength was 1.30 MPa which was lower than that recommended by the standard. But with the inclusion of CNSL into the half brick samples, the compressive strength value was observed to double (average 2.30 MPa) which met the standard. Besides, CNSL caused an improvement in the impermeability of the samples.

Quaranta et al. [66] studied the possibility of using GSP (5, 10, 15%) as a raw material in the manufacture of ceramic bricks at 950°C. The results presented that increasing amount of GSP in the sample caused an increase in the porosity (25.15% to 28.04%) and decrease in flexural strength compared to the control sample (19.20% and 8.30 MPa). The lower degree of sintering of 15% waste-blended sample caused a comparatively greater decline in strength (5.49 MPa). Hence, 15% GSP sample was further treated at 1000ºC which presented a higher sintering degree as well as good properties (25.12% porosity and 9.10 MPa strength).

Fernando et al. [53] investigated the use of GSA (2-10%) as a partial substitution to produce lightweight clay bricks (fired at 600°C to 850°C). The findings exhibited that the average sample density steadily dropped (1500 kg/m^3 to 1225 kg/m^3) while the water absorption value increased (13% to 25%) with 0% to 8% replacement level and after that density sharply increased to 1384 kg/m^3 and water absorption decreased to 18% at 10% replacement. The compressive strength of the GSA blended samples ranged between 7 MPa (8% GSA) to 17 MPa (4% GSA) which satisfied the BS 3921 standard [125] requirement (>5.10 MPa). The greater quantity of SiO_2 in GSA helped to stabilise the brick clay, contributing to an increase in strength. Also, the flexural strength significantly decreased with increasing replacement levels. The maximum flexural strength (0.13 MPa) was obtained for the control sample whereas for GSA blended samples optimum strength (0.11 MPa) was found at 2% replacement.

Çam [75] incorporated 2.50, 5, 7.50, 10% by weight of HSP and 5-30% by weight of Red Mud (RM) waste to clay for the production of highly porous ceramic bricks (fired at 900°C and 1000°C). The test results showed that the addition of HSP and RM to the mixture increased the porosity and water absorption compared to the control sample but increasing the firing temperature there was a slight decrease observed both in porosity and density. The apparent porosity varied between 38% (2.50% HSP) to 51.35% (10% HSP + 30% RM) at 900°C and 36.25% (2.50% HSP) to 48% (10% HSP) at 1000°C. On the other hand, water absorption values were between 22.50% (2.50% HSP) to 36.10% (10% HNP + 30% RM) at 900°C and 21.25% (2.50% HSP) to 33.33% (10% HSP) at 1000°C. However, HSP and RM additives decreased the bulk density and compressive strength of bricks and increasing of firing temperature the bulk density and strength increased. Bulk density varied between 1410 kg/m^3 (10% HSP) to 1670 kg/m^3 (2.50% HSP) at 900°C and 1440 kg/m^3 (10% HSP) to 1700 kg/m^3 (2.50% HSP) at 1000°C. The maximum compressive strength for the waste blended samples were achieved as 32 MPa (2.50% HSP) and 30 MPa (2.50% HSP) at 900°C and 1000°C respectively. These values were lower than the control sample (65.47 MPa) but higher than the acceptable strength requirement specified by the Turkish Standard [124]. Moreover, thermal conductivity decreased for both increasing waste material quantity and firing temperature. The lowest thermal conductivity value was found as 0.45 W/mK (10% HSP + 30% RM) at 900°C.

4.3 Nut shell wastes in mortar

Thirumurugan et al. [19] examined the use of CSNA (20, 30%) and Chicken Feather Fibre (CFF) (2%) to replace cement in mortar. The compressive strength improved with the curing time for all the samples and up to 20% substitution of cement with CNSA achieved better strength results at 27-d (35.16 MPa) than the control sample (32.56 MPa). When CNSA was used up to 30% in concrete it gained lower strength (30.65 MPa).

Pandi and Ganesan [126] studied the water absorption properties of CNSA (5-50%) blended mortar following the mix design (1:3) according to IS 269: 1970 [127]. The water absorption increased from 2.12% (5% CNSA) to 4.16% (50% CNSA) which were greater than the control sample (2%). The minimum and maximum soprtivity values were achieved as 0.73 $mm/min^{0.5}$ (10, 25% CNSA) and 1.45 $mm/min^{0.5}$ (35, 40, 45% CNSA) respectively whereas for the control sample soprtivity value was 1.81 $mm/min^{0.5}$.

Baran et al. [81] replaced cement in mortar by different percentages of HSA (5-30%). The introduction of finer HSA (<1μm) increased the total surface area of the solid particles in the mixture which induced an increase in the water demand (up to 59%) for standard consistency and a decrease in the setting time (up to 96%). Moreover, the compressive and flexural strength values of the blended cement mortars decreased by HSA addition related to the control sample at all curing time and only 5% HSA blended samples showed the satisfactory compressive strength (>42.50 MPa at 28-d) recommended by BS EN 197-1 (2011) [128]. The highest flexural strength at 28-d was found 5.70 MPa at 5% HSA whereas flexural strength for the control sample was 7 MPa.

Restuccia and Ferro [82] analysed the utilisation of Hazelnut Shell Pellets (HSP) (0.50, 0.80, 1%) as carbon nano-aggregates in cement. The test results revealed that compressive strength decreased from 55.09 MPa to 36.95 MPa at 28-d curing period as the content of nanoparticles increased from 0.50-1%. However, these values were higher than the control sample (33.59 MPa). On the other hand, the Modulus of Rupture (MOR) substantially improved in comparison with the waste-free sample (2.74 MPa) with the incorporation of HSP and 0.80% waste blended sample displayed the optimum MOR (4.02 MPa) at 28-d. This increase in strength was attributed to the irregular shape and porous nature of the carbon-composed nanoparticles which generated toughening mechanisms within the cement-based composites.

Ketkukah and Ndububa [69] replaced OPC in the mortar by GSA (2-10%) adopting a mix proportion of 1:5. The inclusion of ash induced a delay in the setting time of the mortar which indicated its suitability in hot weather concreting. The density (2287 kg/m^3 to 2152 kg/m^3), water absorption (9.19% to 7.83%) and 28-d compressive strength values (3.31 MPa to 2.69 MPa) decreased with the addition of GSA. However, the strength values surpassed the minimum strength requirement for sandcrete blocks specified in the Nigerian Industrial Standard [129] (2.50 MPa). The decrease in density is due to the lighter nature of GSA.

Narayana Moorthi et al. [121] conducted experiments to determine the optimum percentage of cement replacement with GSA (15, 20, 30 and 40%). The results presented that the 7-d compressive strength reached the optimum value (16.71 MPa) at 15% replacement which was an 8.50% increase compared to the control sample. For further addition of GSA, the strength linearly dropped and reached 5.35 MPa at 40% replacement.

Tekin et al. [57] incorporated 5-30% PSA as a replacement material to modify Ordinary Portland Cement (OPC). The results revealed that with the increasing amount of PSA both the water requirement (up to 54%) and setting time (up to 300%) of the cement increased consistently. The improved total surface area of the cement by the finer PSA particles induced an increased water demand while the carbon-based composition of PSA disrupted the setting phase. The compressive strength of 5% and 10% PSA blended sample yielded a similar strength (around 22 MPa) as the control sample at 2-d age. However, with the advance of the curing time samples with 5-20% PSA replacement achieved acceptable strength values. Furthermore, the incorporation of 30% PSA substantially decreased the compressive strength at all curing periods. The maximum compressive strength was 42.50 MPa (5% PSA) at 28-d, 45 MPa (5% PSA) at 90-d and 67.50 MPa (10% PSA) at 400-d. Besides, porosity measurement showed no major influence up to 20% PSA addition while the 30% PSA blended sample exhibited around 67% increase in the porosity. Consequently, the low compressive strength of the 30% PSA containing sample could be justified by the high-porosity structure of the blend caused by the unbound PSA particles. The 28-d minimum porosity was recorded as 18% (5% PSA) where the maximum was 24% (20% PSA). In another study, Alsalami [56] studied the effect of utilising PSP (10-60%) as a partial replacement of sand on the properties of cement mortar. A water-cement ratio (w/c) of 0.48 and a mix proportion of 1:3 was used by the authors to obtain the samples. The findings revealed that both density and compressive strength reduced with the increase of PSP in the sample but increased with curing time. The 28-d density of the control sample was 2315.84 kg/m^3 and it decreased from 2207.97 kg/m^3 to 1000 kg/m^3 with the addition of 10% to 60% PSP. The reduction in density was attributed to the low density of PS compared to the fine aggregate used and the increase with age was due to the hydration process of cement which closed the pores and densified the mortar. The 28-d maximum compressive strength was 71.47 MPa for the control sample and significantly reduced from 51.54 MPa to 1.75 MPa for 10-60% PSP blended samples. The decrease in compressive strength with the rise in substitution levels might be due to the water absorption by the PSP which induced poor workability of the mixture. Water absorption increased from 0.80% (10% PSP) to 6.04% (60% PSP) which were higher than the control sample (0.47%). The study concluded that 50% to 60% replacement mixtures can be used as lightweight mortar in compliance with BS EN 998-2, 2010 standard [130] where 20% and below replacement is suitable for load-bearing purposes (ASTM C270, 2014) [131]. Furthermore, the mortar could be used for non-load bearing purposes with 30% or above replacement.

Tsado et al. [98] utilised SNSA to partly substitute cement up to 20% for mortar adopting a 1:6 (cement-fine aggregate) mix ratio and 0.60 water to binder ratio. The test results presented that setting time increased but compressive strength decreased gradually as the percentage of SNSA increased. Apart from the 20% waste-blended sample (2.05 MPa), the 28-d compressive strength of the samples containing 0-15% SNSA ranged between 4.50 MPa to 2.61 MPa which satisfied the Nigerian Industrial Standard [129]. Consequently, the study recommended 10-15% partial replacement of cement with SNSA to produce sandcrete blocks.

Table 4
Nut shell wastes in mortar and concrete production.

Nut shell wastes	References	Content (%)	Unit size (mm)	w/c ratio	Density (kg/m^3)	28-d max. Compressive Strength (CS), Flexural Strength (FS), Splitting Tensile Strength (STS) (MPa)	Water absorption (%)
CNSA	[19]	20,30%wt, 2% CFF	70.6×70.6×70.6	0.45	-	CS:35.16	-
CNSA	[126]	5,10,15,20,25,30,35,40, 45,50%wt	⌀ 80×50	0.45	-	-	2.12-4.16
GSA	[69]	2,4,6,8,10%wt	50×50×50	0.31-0.40	2133-2310	CS:3.31	7.83-9.19
GSA	[121]	15,20,30,40%	70.6×70.6×70.6		-	CS:17.05 (7-d)	-
HSA	[81]	5,10,15,20,25,30%wt	40×40×160	0.50-0.71	-	CS:40.67 FS:5.70	-
HSP	[82]	0.50,0.80,1%wt	20×20×75	-	-	CS:55.09 FS:3.96	-
PSP	[56]	10,20,30,40,50,60%wt	70.60×70.60×70.60	0.48	1000-2207.97	CS:51.54	0.80-6.04
PSA	[57]	5,10,15,20,30%wt	50×50×50	0.50-0.71	-	CS:42.25	-
SNSA	[98]	5,10,15,20%wt	50×50×50	0.60	-	CS:3.25	-
CNSP	[45]	4,8,12%, 1% CFF	⌀150×300 150×150×150 100×100×700	0.48-0.56	-	CS:35.02 FS:5.39 STS:2.90	-
CNSA	[47]	5, 10, 15, 20%wt	⌀150×300 150×150×150 150×150×600	0.62-0.77	-	CS:30 FS:4.40 STS:3.63	-
CNSA	[48]	5,10,15,20%wt	⌀150×300 150×150×150	0.42-0.60	-	CS:48 STS:4.14	-

CNSA	[49]	5,10,15,20,25,30%wt	⌀80×50	0.45	-	-	0.68-1.98
CNSL	[64]	20,30,40%wt	102×102×356	0.38	-	STS:846	-
GSP	[50]	10,20,30,40,50,60,70, 80,90,100%wt	-	0.75	1000-2000	CS:7	-
GSA	[51]	5,15,25,50,75%wt	150×150×150	0.50	1854.81-2533.33	CS:40.59	-
GSA	[52]	5,10,15,20%wt, 1, 2, 3% Sisal fibre	150×150×150 100×150×800	-	-	CS:33.95 FS:21.79	-
GSA	[54]	5,10,15%wt	-	0.45	-	CS:41.33 FS:4.70 STS:4.15	-
GSA	[55]	5,10%wt	-	0.50-0.56	-	CS:28.95 FS:14 STS:8.20	-
GSA	[67]	10,20,30,40,50%wt	-	0.52-0.59	-	CS:4.03	-
GSA	[68]	10,20,30,40%wt	150×150×150	-	2220-2301	CS:17.98	-
GSA	[70]	10,20,30,40%wt	100×100×100 40×40×160	0-0.37	-	CS:49	2.24-2.67
GSA	[117]	GNA+RHA 2.50,5,7.50,10,12.50 %wt	150×150×150	0.55	2237-2372	CS:27.01	-
GSA	[118]	5,10,15, 20,25,30,35%wt	⌀150×300 150×150×150 100×100×500	0.60	-	CS:23.15 FS:7.50 STS:3	-
GSA	[119]	1,2,3,4,5,6%wt	150×150×150	0.55	-	CS:33.50	0.46-0.84
GSA	[120]	10,20,30,40,50%	150×150×150	-	-	CS:20.68	-
GSA	[132]	10,20%wt, 10% CA, 10-30% FA	150×150×150 100×100×500	-	-	CS:34.88 FS:5.91	-
GSA	[133]	15,30,45,60,75%wt	-	0.55	1625-2125	CS:22.10	-
GSA	[134]	2.50,5,7.50,10,12.50,15%wt	150×150×150 100×100×500	0.45	-	CS:38.44 FS: 6.21 STS:4.80	-
GSP	[135]	10,20, 30%wt	150×150×150 500×500×300	-	-	CS:25.60	-
GSA	[136]	12%wt	150×150×150	0.68	-	CS:17.50	1.25-3.17
WS	[58]	20%wt	⌀150×300 150×150×150 100×100×500	0.45	-	CS:29.70 FS:3.80 STS:2.90	-
WS	[59]	5,10,15,20,25,30,35,40,45, 50%vol	100×100×100	0.36	1813-1990	CS:49	-
WS	[112]	5,10,15, 20,25%vol	⌀100×200 100×100×100 100×100×500	0.55	2000-2370	CS:34 FS:2.60 STS:3.10	1.50-2.70
WS	[113]	25,50,75%wt	100×100×100	0.48	1850-2050	CS:30 STS:3	-
WS	[114]	10,20, 30%	150×150×150	0.55		CS:30.90	-
WS	[115]	1.72,10,30,50,58.28% wt	150×150×150	0.38-0.52	2200- 2420	CS:40.73	0.73-1.20
WS	[137]	0.40, 0.60, 0.80, 1, 1.20, 1.40%wt	-	0.75	580-1350	CS:10	3.20
SNSA	[96]	10, 20%mass	150×150×150	0.50-0.56	-	CS:20.13	-
SNSA	[97]	10, 20, 30%mass	150×150×150	0.60	-	CS:28.22	-

4.4 Nut shell wastes in concrete

The effect of CNSP (4%, 8%, 12%) with CFF (2%) in concrete was investigated by Pavithra et al. [45]. The study used a mix design ratio of grade 30 MPa concrete. The results indicated that compressive and flexural strength improved steadily and reached the maximum value with 8% CNSP. After this replacement level strength dropped for 12% CNSP. The 28-d optimum compressive and flexural strengths were 35.02 MPa and 5.39 MPa respectively which were approximately 3.60% and 30.77% higher than the control sample. Besides, splitting tensile strength gradually increased from 1.88 MPa to 2.90 MPa with increasing CNSP content from 4% to 12%.

Moreover, from the cost comparison analysis, it can be observed that 12% CNSP replacement level showed the minimum cost. However, the study recommended 8% replacement as it increased the strength while cut the cost by 2.90%.

McIsaac et al. [64] investigated the effect of biobased resin (Cardolite NC-513) derived from CNSL as a partial substitute (20-40%) of epoxy on the bond strength between concrete and fibre reinforced polymer (FRP) (glass and carbon fibre). The bond strength of CNSL samples ranged between 38 MPa to 40 MPa for both types of fibre reinforced samples. Nevertheless, the splitting tensile strength values were higher for carbon fibre reinforced samples (522 MPa to 840 MPa) than glass fibre reinforced samples (293 MPa to 424MPa).

Pandi and Ganesan [49] determined the potential replacement level of cement in concrete by CNSA (5-30%). The mix design was carried out for grade 20 MPa concrete using 1:1.44:3.19 proportions based on IS: 10262-2009 [138]. The results showed that 28-d water absorption and sorption value increased from 0.68% to 1.98% and 1.45 mm/min$^{0.5}$ to 4.35 mm/min$^{0.5}$ respectively when CNSA was added from 5 to 30%. However, up to 25% replacement level showed water absorption and sorptivity value lower than the control sample.

Oyebisi et al. [47, 48] replaced Portland Limestone Cement (PLC) by CNSA at 5% to 20% employing grade 25 MPa concrete mix design ratio according to the procedures specified in the BS EN 206 [139]. It was noticed that the incorporation of CNSA from 0% to 20% caused an increase in compacting factor (0.85 to 0.89) and slump (30 to 75mm) [47]. The results may be due to the particle shape of CNSA which increased the rate of workability. Also, the strength showed an increasing trend by 5 % to 15% replacement and beyond this replacement level strength slightly declined. A higher filling capacity of the CNSA and the presence of additional portlandite and alkalis in the blended mix observed from the micromorphological analysis can explain this increase in strength. The maximum compressive, flexural and splitting tensile strength values were obtained as 30 MPa, 4.40 MPa and 3.63 MPa respectively. In addition, the CNSA concrete showed more resistant to sulfate attacks than the control sample. Therefore, this study suggested up to 15% replacement of PLC by CNSA for the application of load-bearing concrete.

The utilisation of GSP in concrete was evaluated by Tata et al. [50] (10-100%) and Mohamad et al. [135] (10-30%). The results of Tata et al. [50] showed that as the ratio of GSP increased from 10-100% there was a subsequent decrease in both density (1000 kg/m^3 to 2000 kg/m^3) and compressive strength (7 MPa to 0.70 MPa) but increase in water absorption (3.25% to 35.25%). The study concluded that GSP blended concrete is suitable for insulating concrete due to its low strength. However, 30-70% replacement had suitable strength (3.67 MPa to 0.80 MPa) and density (1890 kg/m^{3}to 1330 kg/m^3) for use as non-load bearing partition walls.

Mohamad et al. [135] developed an artificial reef with different volume of GSP (10-30%). It was observed that the highest compressive strength (31.30 MPa) was achieved for the control sample and the increased percentage of GS in the concrete caused a reduction (25.60 MPa to 18.10 MPa) in strength. A higher water absorption characteristic of GSP generated more voids in the concrete and created poor bonding between the cement and aggregates which ultimately decreased the strength of the concrete.

Besides, Mujedu and Adebara [133] (15-75%), Lakshmi and Sagar [118] (5-35%), Alabadan et al. [120] (10-50%), Mahmoud et al. [67] (10-50%), Nwofor and Sule [68] (10-40%), Buari et al. [70] (10-40%), Kanchidurai et al. [52] (5-20%), Reddy et al. [54] (5-15%), Shubham and Khandelwal [134] (2.5-15%), Kumar and Lemessa [55] (5,10%), Ikumapayi [136] (12%), Wazumtu and Ogork [119] (1-5%) replaced cement where Sada et al. [51] replaced fine aggregate (river sand) in concrete by GSA (5-75%).

Reddy et al. [54] demonstrated that 28-d optimum compressive strength (41.33 MPa) was found at 10% replacement and the strength showed a decreasing trend beyond 10% replacement of cement by GSA. The result was similar for Lakshmi and Sagar [118] (23.15 MPa), Buari et al. [70] (49 MPa), Kumar and Lemessa [55] (28.95 MPa), Kanchidurai et al. [52] (29.84 MPa), Nwofor and Sule [68] (17.98 MPa) and Alabadan et al. [120] (20.68 MPa). On the other hand, Mahmoud et al. [67] developed sandcrete block and found the highest compressive strength as 4.03 MPa at 10% of cement replacement. On the other hand, Mujedu and Adebara [133] and Shubham and Khandelwal [134] found the highest 28-d compressive strength as 22.10 MPa and 38.44 MPa for 15% GSA and 7.5% replacement, respectively whereas for Wazumtu and Ogork [119] (33.50 MPa) and Sada et al. [51] (40.59 MPa) 4% replacement showed the optimum compressive strength. The highest flexural strength was found as 4.70 MPa (10% GSA) [54], 7.50 MPa (15% GSA) [118], 6.21 MPa (7.5% GSA) [134] and 14 MPa (10% GSA) [55] whereas the highest splitting tensile strength was recorded as 4.15 MPa (10% GSA) [54], 3 MPa (10% GSA) [118], 4.80 MPa (7.5% GSA) [134] and 8.20 MPa (10% GSA) [55]. The variance in the strength value of different studies may be attributed to the chemical compositions and physical properties of GSA used by the different authors. GSA having fewer cementing properties led to less hydration in the mixture which induced lower strength in concrete [68, 119]. Besides, the w/c ratio may affect the strength as increasing the w/c ratio can increase the strength [118]. Moreover, the density of the concrete decreased varying between 2125 kg/m^3 (15% GSA) to 1625 kg/m^3 (75% GSA) [133] 2301 kg/m^3 (20% GSA) to 2220 kg/m^3 (40% GSA) [68] and 2533.33 kg/m^3 (5% GSA) to 1854.81 kg/m^3 (75% GSA) [51] as the ash percentage increased. This can be explained by the lower specific gravity of GSA (2.02) compared to cement (3.07) [133] which created more voids in the mixture. Mahmoud et al. [67] and Sada et al.

[51] explained that because of a higher water absorption ability of GSA, the workability of mixture decreased as the GSA content was increased. It was also noticed that GSA addition decreased both slump and setting time [67, 119]. However, the water absorption gradually decreased from 0.84% (1% GSA) to 0.46% (6% GSA) [119], 2.67% (10% GSA) to 2.24% (40% GSA) [70] with the addition of GSA.

Kumar and Sharma [132] mixed Fly Ash (FA) (10, 20, 30%), Coconut Ash (CA) (10%) and GSA (10, 20%) with cement and examined the strength properties. The peak compressive and flexural strength were achieved as 34.88 MPa and 5.91 MPa respectively for 10% CA + 20% GSA + 10% FA sample which was 8.19% and 4.05% increase in strength related to the control sample.

Kumari et al. [117] used Rice Husk Ash (RHA) with GSA (2.50-12.50%) to replace cement in concrete. It was observed that slump decreased by 35.70% and density decreased from 2372 kg/m^3 to 2237 kg/m^3 as the replacement level was increased to 12.50% in the mixture. Compressive strength also decreased compared to the control mix (27.51 MPa) but increased with the addition of ash up to 10% (27.01 MPa) and then decreased at 12.50% (21.33 MPa).

Ikumapayi [136] investigated the properties of GSA blended concrete sample in water and NaCl solution. The results showed that the water absorption values of the samples in salt were higher (3.27%) than the samples in water (1.25%). But the compressive strength values of the samples in the salt solution (15 MPa) were found lower compared to the samples in water (17.50 MPa).

Tsado et al. [97] and Zievie et al. [96] used different replacement amounts (up to 30%mass) of cement by SNSA. The results showed that the setting times gradually increased while the workability of the concrete decreased with an increase in the SNSA content. This is due to the low calcium content (1.81%) present in SNSA as hydraulic reactivity in ash declines with decreasing calcium content. The slump test values showed a decreasing trend from 115 mm (0% SNSA) to 57 mm (20% SNSA) while the water content increased (5% for each replacement) with increasing SNSA quantity [96]. Besides, the compressive strength dropped when the replacement percentage was increased. Tsado et al. [97] reported that the compressive strength of the control sample was 33.62 MPa and the highest compressive strength for SNSA blended sample was obtained for 10% replacement (28.22 MPa) at 28-d curing period. Also, Zievie et al. [96] found the mean compressive strength ranging from 18.77 MPa to 10.37 MPa at 14-d, 22.61 MPa to 17.44 MPa at 28-d and 26.73MPa to 30 MPa at 90-d for 0-20% cement replacement level. There was a high decrease in strength of 21% (10% SNSA) and 45% (20% SNSA) over the control sample at 14-d curing period while the drop lowered to 12% (10% SNSA) and 23% (20% SNSA) at 28-d. However, at 90-d there was a substantial increase in strength of 21% (10% SNSA) and 11% (20% SNSA) over the control sample which indicates that SNSA is suitable for use in the places where long term strength is required.

Cheng et al. [113], Venkatesan et al. [58], Khadykina and Meretukov [137], Hilal et al. [59, 112] Husain et al. [114] and Kamal et al. [115] assessed the effects of WS integration in concrete production. Various percentages of WS that were used as replacement material in concrete were as follows:
25-75% [113], 20% [58], 0.40-1.40% [137], 5-50% [59], 10-30% [114], 1.72-58.28% [115].

The analysis illustrated that WS incorporation caused the Slump Flow Diameter (SFD) to decrease from 800 mm (0%) to 510 mm (50%) [59] and 120 mm (0%) to 90 mm (75%) [113]. The key reasons for such a decrease were the irregular shape and absorption potential of WS. The thin concave and convex shells of WS generated framework of aggregates in the mixture which resisted the flow and decreased the slump [59, 113]. Besides, the addition of WS reduced the strength and the optimum compressive strength was found for the lowest amount of WS blended samples as 30.90 MPa (10%) [114], 40.73 MPa (10%) [115], 49 MPa (5%) [59], 30 MPa (25%) [113], 4.25 MPa (0.40%) [137] due to the poor bonding between the WS particles and cement. Kamal et al. [115] also showed that compressive strength decreased with increasing w/c ratio. Moreover, in the study of Cheng et al. [113], the splitting tensile strength linearly decreased up to 68.80% in comparison with the control sample. Furthermore, the density results showed that added WS decreased both fresh and dry densities from 1990 kg/m^3 (5% WS) to 1813 kg/m^3 (50% WS) [59], 2050 kg/m^3 (25%) to 1850 kg/m^3 (75%) [113], 1350 kg/m^3 (0.40%) to 580 kg/m^3 (1.40%) [137]. The low density of the WS as well as the creation of voids in the mixture through the irregular shape of the WS was responsible for such a decrease. The increasing amount of WS also caused a drop in water absorption (from 1.20% to 0.73%) [115] and in UPV (4.28 km/sec-3.27 km/sec) [59]. In another study Hilal et al. [112] replaced both fine and coarse aggregate to analyse the effects of WS particle size in the mixture. The analysis was carried out in three series i.e. group 1 (replacing the fine aggregate), group 2 (replacing the coarse aggregate) and group 3 (replacing both the coarse and fine aggregate). The results revealed that a significant reduction in density occurred in group 2 samples, followed by group 3 and group 1. The larger particle size in group 2 than the other groups contributed to the formation of additional voids in the mixture that induced the reduction. In addition, group 3 samples obtained the optimum strength where different fine and coarse WS led to the formation of smaller amounts of voids providing a good interface with other elements in the blend.

Khadykina and Meretukov [137] examined the use of WS as replacement material (0.40, 0.60, 0.80, 1, 1.20, 1.40%) in concrete to develop structural and insulating lightweight concrete. The test results demonstrated that WS inclusion from 0.40% to 1.40% in the concrete caused a gradual reduction in density (1350 kg/m^3 to 580 kg/m^3) and compressive strength (4.25 MPa to 3.10 MPa). Hence, the study further used various additives [$Ca(NO_3)_2$, $NaNO_2$, Na_2SiO_3] in the 0.60% WS composition to improve its properties. The greatest increase in strength (4.10 MPa to 10 MPa) was observed by the $NaNO_2$ additive at the minimum dosage. The thermal conductivity and the water absorption of the that sample were found 0.30 W/mK and 3.20% respectively which indicates a lightweight insulating concrete characteristic.

Venkatesan et al. [58] employed steel slag (0-50%) and WS at a constant proportion of 20% to produce M30 grade concrete. The results presented that WS replaced sample exhibited slightly lower strength (CS: 29.70 MPa, FS: 3.80 MPa, STS: 2.90 MPa) but steel slag incorporated sample had slightly higher strength (CS: 38.20 MPa, FS: 5.10 MPa, STS: 3.90 MPa) than the control sample (CS: 31.40 MPa, FS: 4.10 MPa, STS: 3.20 MPa). Moreover, the durability tests such as salt (NaCl) resistance, acid resistance (HCl) and sulphate resistance ($MgSO_4$) showed that the sample containing 40% steel slag with WS had better resistance than the control sample.

Table 5
Setting time of nut shell blended mortar and concrete.

Nut shell wastes	References	Type of cement used	Setting time (min)		
			Content (%)	Initial	Final
GSA	[67]	OPC	0-50	95-436	155-812
GSA	[69]	OPC	0-10	140-200	190-260
GSA	[119]	OPC	0-6	90-152	150-211
HSA	[81]	OPC (CEM I 42.50R)	0-30	136-5	254-40
PSA	[57]	OPC (CEM I 32.50R)	0-30	100-300	250-720
SNSA	[96]	OPC	0-20	125-218	366-580
SNSA	[98]	OPC	0-20	71-274	183-411

Table 6
Slump value of nut shell blended concrete.

Nut shell wastes	References	Type of cement used	Design strength	Content (%)	Slump (mm)		
GSA	[51]	OPC		0-75	52-5		
GSA	[54]	OPC 53	M30	0-15	24-27		
GSA	[55]	OPC 43	M20	0-12.50	82-45		
GSA	[67]	OPC		0-50	15-20		
GSA	[70]	OPC Type I		0-40	708-630		
GSA	[118]	OPC 53	M15	0-35	25-20		
GSA	[119]	OPC		0-6	38.50-29		
GSA	[134]	OPC 43		0-15	50-90		
GSA	[136]	OPC		0-12	45-40		
SNSA	[96]	OPC		0-20	115-57		
SNSA	[97]	OPC		0-30	30-20		
WS	[58]	OPC 53	M30	0-50	69-47		
WS	[59]	OPC Type I		0-50	800-510		
WS	[113]	OPC 42.50		0-75	120-90		
CNSP	[45]	OPC 53	M30	0-12	15-25		
CNSA	[47]	PLC (3×42.50R)	M25	0-20	30 -75		
CNSA	[48]	PLC (3×42.50R)	M25, M30, M40	0-20	M25	M30	M40
					75-47.50	72.50-42.50	62.50-35

5. Discussion

Section 4 reveals that several nut shell wastes were used in brick, mortar and concrete production to evaluate their properties. In the following section, the findings of the selected reviewed articles are discussed according to the related standards.

5.1 Effects of nut shell wastes on the properties of unfired brick

From section 4.1 it can be seen that researchers used ANSP [33, 34, 36] and WS [116] to produce unfired brick. The results showed that density, compressive strength and water absorption decreased with the incorporation of nut shell wastes. Poor adhesion between the clay matrix and the nut shell waste particles induced the decrease in strength and the decrease in water absorption can be explained on the basis of the non-absorbing characteristics of nut shell particles. However with the addition of 5% cement with ANSP and 7% lime + 3% gypsum with WS improved the compressive strength to 3.12 MPa (2%

ANSP) and 6 MPa (5% WS) which met the requirements for unfired earth block construction specified in Sri Lankan Standard: SLS 1382 (2.80 MPa) [140], Brazilian Standard: NBR 8492 (2 MPa) [141] and Turkish Standard: TS 2514 (1 MPa) [142] (Fig. 2). The water absorption coefficients of ANSP blended samples were 10.10% to 11% which were lower than the minimum limit stated in XP 13-901 Standard [122] (20%). Conversely, water absorption values of WS mixed samples were above (18.50 % to 30%) the threshold level specified in Indian Standard: IS 1725 (15%) [143], Sri Lankan Standard: SLS 1382 (15%) [140] and Brazilian Standard: NBR 8492 (20%) [141]. The density ranged between 1825 kg/m^3 to 2062.50 kg/m^3 for ANSP samples which met the Indian Standard: IS1725 [143] and Sri Lankan Standard: SLS 1382 [140] of 1750 kg/m^3 (Fig. 3).

5.2 Effects of nut shell wastes on the properties of fired brick

Section 4.2 shows that BNSA [43], HSP [75], CNSP [46] and GSA [53] were used to produce fired brick. It was observed that the density increased for increasing BNSA and HSP percentage and firing temperature. The density varied between 1440 kg/m^3 to 1860 kg/m^3 and 1410 kg/m^3 to 1700 kg/m^3 at different temperatures for BNSA and HSP respectively. Also, the average maximum density of the GSA brick was obtained as 1426 kg/m^3 which met the minimum requirement as per BS 3921 (1300 kg/m^3 to 2200 kg/m^3) [125] (Fig. 3). This increase in density is related to the good compactness between the materials that creates less voids in the samples. Besides, the highest compressive strength of BNSA and HSP brick varied between 8.75 MPa to 24 MPa and 30 MPa to 32 MPa respectively at different temperatures. Moreover, GSA improved the compressive strength and the value ranged between 7 MPa to 17 MPa. These values fulfilled the minimum compressive strength requirements for building applications by Turkish Standard: TS EN 771-1 [124] (7 MPa), Indonesian Standard: SNI 15-2094-2000 (5 MPa) [144] and British Standards: BS 3921 [125], BS 5628 [145] (5 MPa) (Fig. 2). However, the CNSP brick exhibited the highest compressive strength of 3.50 MPa which was below the recommended value. The porosity and crystallisation process completed by the firing temperature generally affect the compressive strength of the brick. The firing temperature contributes to sealing the open pores leading to an increase in the compressive strength whereas the flabby nature of the waste particles allows the open pores to increase and hence, decreases the compressive strength. Furthermore, water absorption increased for waste addition and the values ranged between 21.25% to 33.33% (HSP) which were above the value stated in BS 5628 [145] (12% to 20%) and Indonesian Standard SNI 15-2094-2000 [144] (20%). On the other hand, minimum water absorption of CNSP (18%) and GSA (15.33%) satisfied both the above standards. Water absorption is directly related to the porosity and inversely linked to density. Hence, higher porosity and lower density cause greater water absorption.

Table 7
Standards followed by the reviewed articles.

Brick
Compressive strength test
American Standard: ASTM C67-05 [53]; European Standard: NF XP P13-901-2001 [33, 34]; Mexican Standard: NMX-C-404-ONNCCE-2005 [116]; Brazilian Standard: NBR 8492-2012 [62]; Sri Lankan Standard: SLS 39-1978 [53]
Flexural strength test
American Standard: ASTM E72-15 [53]; Sri Lankan Standard: SLS 39-1978 [53]
Density test
American Standard: ASTM C20-00 [43, 75], ASTM C67-05 [53]
Porosity test
American Standard: ASTM C20-00 [43, 75]
Water absorption test
American Standard: ASTM C67-05 [53] ASTM C20-00 [75]; European Standard: NF XP P13-901-2001 [33, 34]; Mexican Standard: NMX-C-404-ONNCCE-2005 [116]
Mortar
Compressive strength test
American Standard: ASTM C 109 -16 [57, 69, 98]; British Standard: BS 1881-Part 4-1989 [56]; European Standard: EN 196-1-16 [81]
Flexural strength test
European Standard: EN 196-1-16 [81]
Density test
American Standard: ASTM C642-06 [56]
Porosity test
American Standard: ASTM C 642-13 [57]; Argentinian Standard: IRAM 12510 [66]
Water absorption test
American Standard: ASTM C 642-06/13 [56, 57]; British Standard: BS 1881-Part 122-1983 [69]

Concrete
Compressive strength test
American Standard: ASTM C618 -92 [67]; British Standard: BS EN 12390_3-2009 [47, 48, 119], BS 1881-Part 116-1983 [50, 59, 112, 115, 118, 133]; Chinese Standard: GB/T 50081-2002 [113]; Indian Standard: IS 516-1959 [45, 54, 132, 134], BIS 516-2004 [52]
Flexural strength test
American Standard: ASTM D7958/D7958M -17 [64], ASTM C78-84 [45]; British Standard: BS EN 12390_5 [47, 48], BS 1881-Part 117-1983 [112]; Indian Standard: IS 516-1959 [132, 134], BIS 9399-2013 [52]
Splitting tensile strength test
American Standard: ASTM C496-90 [45, 112]; British Standard: BS EN 12390_6 [47, 48], BS 1881-Part118-1983 [112]; Chinese Standard: GB/T 50081-2002 [113]; Indian Standard: IS: 5816-1999 [54]
Slump test
American Standard: ASTM C143-15 [52]; British Standard: BS EN 12350_2-2009 [47, 48, 119], BS 1881-125-1986 [96]; Indian Standard: IS 1199–1959 [58]
Density test
American Standard: ASTM C 138-86 [112]
Water absorption test
American Standard: ASTM C-642-06 [70]; British Standard: BS 812: Part 2-95 [70, 119]
Ultrasonic pulse velocity test
American Standard: ASTM C597-09 [59]; Indian Standard: IS 13311-Part 1-1992 [134]

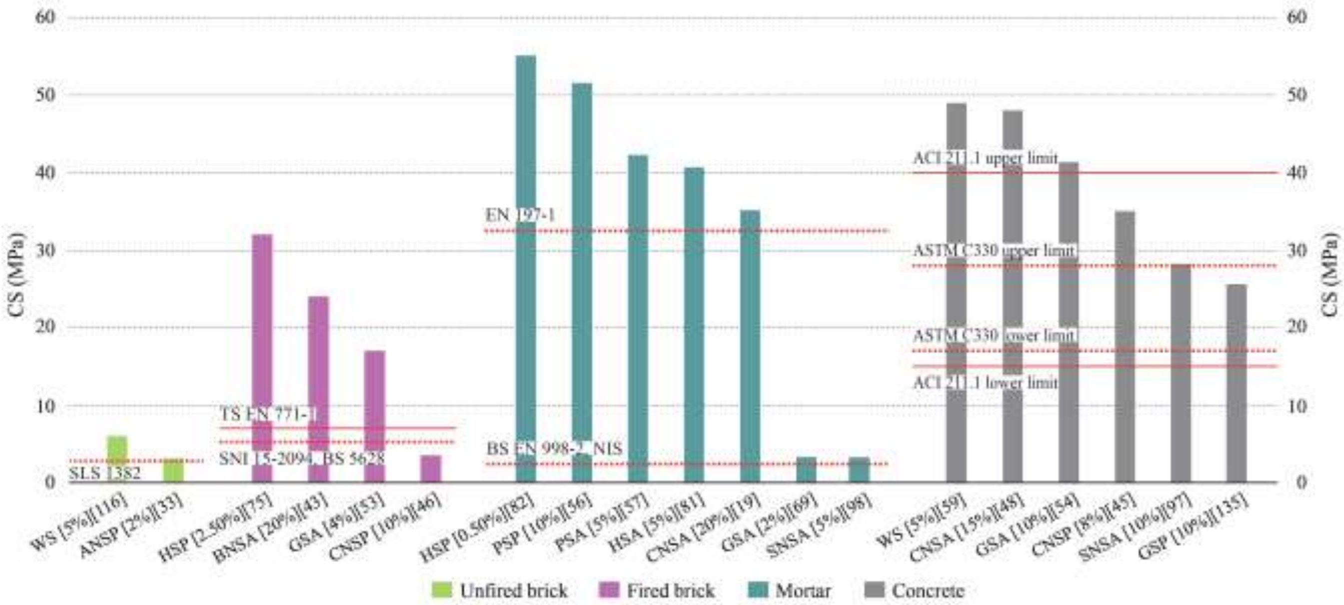

Fig. 2. Maximum compressive strength of nut shell waste-blended samples.

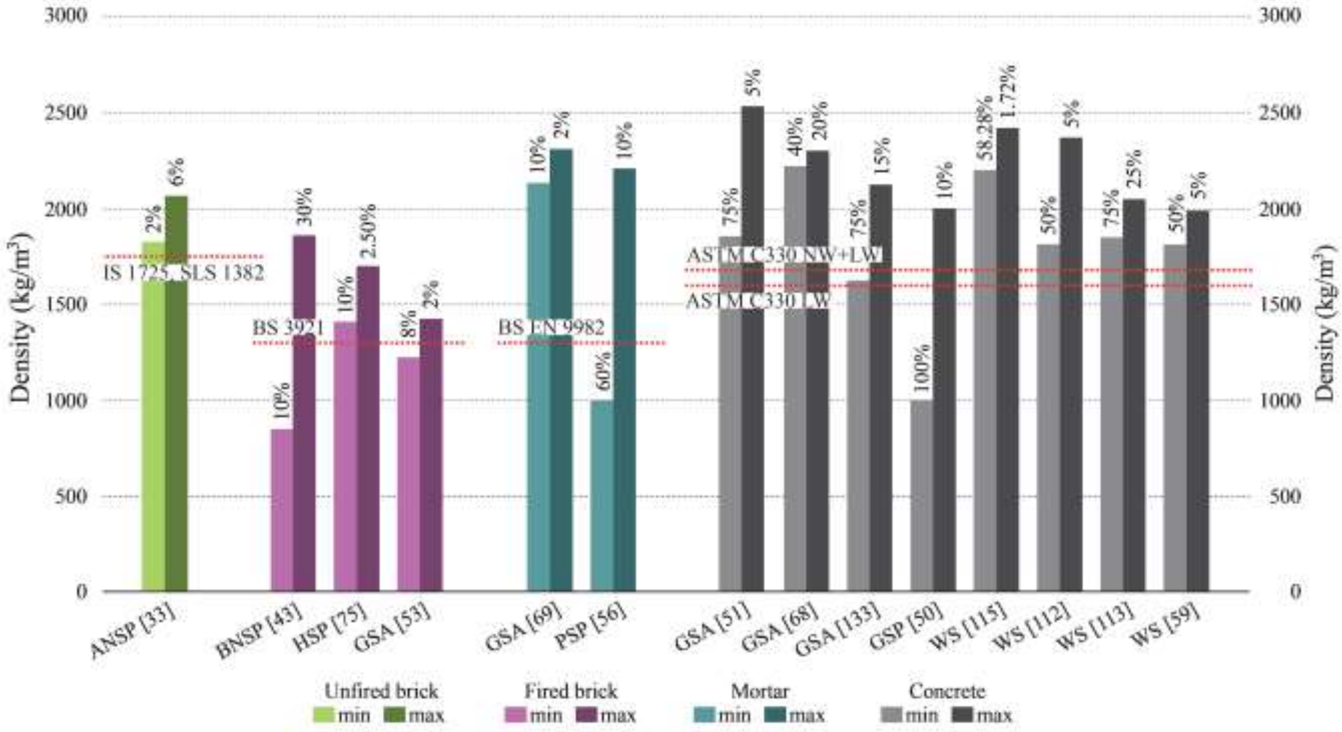

Fig. 3. Density of nut shell waste-blended samples.

5.3 Effects of nut shell wastes on the properties of mortar

SNSA [98], PSA [57], PSP [56], HSA [81], HSP [82], CNSA [19, 126] and GSA [69, 121] were used by several investigators to replace cement in mortar. For SNSA, PSA and GSA [69] mortar setting time increased as the replacement percentage increased (see Table 5) which were above the EN 197-1 (2011) [128] requirement (≥45 min). Ketkukah and Ndububa [69] explained that the less tricalcium illuminate (C_3A) generated by the ash material is responsible for this increase in setting time. On the contrary, with the increase of HSA percentage, the setting time of the mortar reduced which did not satisfy the standard requirement. This is because HSA acted as a set accelerator in the mixture decreasing the setting time by transitioning the blend from plastic to a rigid state. The maximum 28-d compressive strength for CNSA, HSA, PSA, PSP, HSP mortar were 35.16 MPa, 40.67 MPa, 42.50 MPa, 51.54 MPa and 55.09 MPa respectively which were higher than the minimum compressive strength requirement (≥32.5 MPa for 28-d) stated in EN 197-1 (2011) [128] (Fig. 2). The finer waste particles enhanced the interactions between the particles and the surrounding matrix by increasing the surface area to volume ratio in the mixture, thereby improving the strength. However, the compressive strength of mortar with GSA (3.31 MPa) [69] and SNSA (3.25 MPa) did not conform to the above-mentioned standard but satisfied the Nigerian Industrial Standard [129] (2.50 MPa) and BS EN 998-2 for M1 and M2.50 mortar classes (1 MPa to 2.50 MPa) [130]. The decrease in compressive strength may be attributed to the poor workability of the blend resulted from the water absorption by the waste materials. In addition, an inadequate amount of oxide and a low density of waste particles can lead to a reduction in strength. Furthermore, BS EN 998-2 specifies the density of lightweight masonry mortars to be less than or equal to 1300 kg/m³. The density of PSP and GSA mortar were found ranging between 1000 kg/m^3 to 2207.97 kg/m^3 and 2152 kg/m^3 to 2287 kg/m^3 [69] (Fig. 3). Besides, water absorption varied between 0.80% to 6.04% (PSP), 2.12% to 4.16% (CNSA) [126], 7.83% to 9.19% (GSA) [69]. The lower density of the nut shell particles caused to decrease the density while the porous nature and higher absorption capacity of the waste particles may induce an increase in water absorption.

5.4 Effects of nut shell wastes on the properties of concrete

The chemical composition analysis indicated that the CNSA, GSA and SNSA fulfilled the chemical pozzolanic requirements specified by the ASTM C 618-9 [146] BS EN 450_1 [147] and BS EN 8615_2 [148] in that the sum of SiO_2, Al_2O_3 and Fe_2O_3 met the minimum requirement of 50-70% (see Table 2). The results of the studies showed that the setting times delayed with an increase in the SNSA [96] and GSA content [67, 119] in the mixture. This delay was caused by the low calcium substances in the nut shell ashes which declined the hydraulic reactivity in the mixture. According to the ACI [149], the slump should not exceed 100 mm whereas BS EN 12350-2 [150] and IS 456 [151] specify maximum slump up to 150 mm. From Table 6 it can be seen that slump of SNSA 115 mm to 57 mm [96], WS 120 mm to 90 mm [113], GSA 82 mm to 80 mm [55] were within the limit stated in the standards. The reason for the reduction in slump can be related to the finer particle size, higher carbon content and higher specific surface area of waste particles than the cement used. Such features are responsible for an increment in the water requirement that renders concrete impermeable and highly cohesive. Besides, the highest 28-d compressive strengths of WS blended samples were 40.73 MPa [115], 49 MPa [59] and for GSA it was 41.33 MPa [54], 49 MPa [70], 38.44 MPa [134], 40.59 MPa [51] which met the ASTM C 330 (17 MPa to 28 MPa) [152] and ACI 211 (15 MPa to 40 MPa) [149] (Fig. 2). On the other hand, peak compressive strength of GNP 25.60 MPa [135], SNSA (28.22 MPa) [97] and CNSA (30 MPa) [47] did not satisfy the standards. The filling capacity of the nut shell waste particle in the mixture can explain the increase in strength. Also, the findings differed in literature with similar waste incorporation due to the variations in chemical and mineralogical compositions of the waste particle used. A higher C_2S/C_3S ratio present in the waste particle improved the compressive strength while the poor fluidity caused a lower compressive strength by producing an increased void ratio in the blend. The maximum densities of different nut shell waste blended concrete were 2420 kg/m^3 (WS) [115], 2000 kg/m^3 (GSP) [50], 2533.33 kg/m^3 (GSA) [51], 2125 kg/m^3 (GSA) [133], 2301 kg/m^3 (GSA) [68] which were above the values stated in ASTM C 330 (1600kg/m^3 to 1840 kg/m^3) [152] for normal weight (NW) and lightweight aggregate (LW) (Fig. 3). The decrease in density can be explained by the lower specific gravity of the waste particles and the formation of voids due to the particle size and shape. Moreover, the water absorption of WS concrete was found 1.20% to 0.73% [115] whereas for CNSA it was 0.68% to 1.98% [49]. The hygroscopic nature of the waste particles increased the water absorption of the mixture.

6. Conclusion

The present article has studied the utilisation of certain nut shell wastes (Argan nut, Brazil nut, Cashew nut, Groundnut, Hazelnut, Pistachio, Shea nut and Walnut) in making brick, mortar and concrete. Different properties of the produced samples are discussed in accordance with relevant standards and the following conclusions can be drawn based on the review:

- In contrast to concrete manufacturing, there has been an insufficient number of studies carried out on the use of nut shell wastes in brick production. Besides, the most examined physico-mechanical properties of manufactured materials were density, compressive strength and water absorption. The assessment of the durability properties of any building material is crucial prior to its practical application. Though, it has been observed that limited research addressed the durability of nut shell waste-based materials i.e. the effect of sulphate, salt and acid attack test and depth of chloride penetration test. Moreover, the thermal properties of the waste-blended samples were rarely investigated. In addition, very few studies analysed the cost comparison of the developed materials with conventional materials. However, an extensive review of various studies presented that the effects of incorporation of nut shell wastes on the properties of brick, mortar and concrete depend on the mixture proportions and replacement level as well as on the physical and chemical properties of the nut shell particles.
- The density, water absorption and thermal conductivity of unfired bricks were found to decrease with the addition of ANSP and WS due to the low density, non-absorbing and low thermal conductivity characteristics of the nut shell. Besides, the weak bond between the nut shell particles and clay matrix led to a drop in brick strength. The studies suggested that the optimum percentages of ANSP and WN to produce unfired brick should be 2% and 5% respectively.
- It has been observed that in the production of fired brick, the densities increased with increasing the percentage of BNSA and HSP which refers to the good compaction between the materials in the mixture minimising the voids. However, incorporation of CNSP increased the water absorption of the brick sample due to its high absorption potential. On the other hand, high-level SiO_2 content in GSA particle induced an increase in strength and its soft nature contributed to decreasing the open pores in the samples which lowered the water absorption value. It was revealed that 10% BNSA, HSP and CNSP can produce brick with acceptable physical and mechanical properties while for GSA the optimum percentage was found 4%.
- The CNSA, GSA and SNSA met the standard-specified chemical pozzolanic requirements for mortar and concrete production. The literature findings with the identical waste incorporation differed because of variations in the chemical structure and physical characteristics of the utilised nut shell. For example, nut shells with lower specific gravity reduced the density of the mortar and concrete. A reduction in density can also be caused by particle size and shape, which are linked to void formation in the mixture. Besides, the strength was improved by the increased filling capacity of finer waste particles (CNSA, HSP, HSA, PSP and PSA). But there was a decrease in strength due to the poor workability of the blend which was caused by a higher water absorption quality of the nut shell particles (SNSA, GSP and GSA). Moreover, the lack of oxide and lower density of the nut shell particle may also be associated with this reduction. Furthermore,

inadequate calcium content in the nut shell particle (SNSA and GSA) resulted in longer setting times and decreased the workability of the concrete. Also, the shape (concave and convex) of WS caused to develop frameworks of aggregates in the blend which resisted the flow and decreased the slump value. It was noticed that 10-25% WS, 15% CNSA, 8% CNSP, 10-15% GSA, 10% SNSA and 10% GSP achieved the optimum strength for cement replacement in concrete. In mortar 5% cement replacement by HSA, PSA and SNSA obtained the highest strength while for PSP, GSA and CNSA the optimum percentages were 10%, 15% and 20% respectively.

The partial substitution of conventional aggregate by the nut shell wastes can contribute considerably to cost-effectiveness as well as provide an efficient solution to global waste management. Consequently, the enhancement of current knowledge on the utilisation of potential agricultural wastes for building material production is essential to make the construction sector environmentally sustainable. Therefore, this study will assist to create a database in the development of brick, mortar and concrete incorporating different potential nut shell waste materials which will be supportive of the building material manufacturers.

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