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Production of Synthetic Lightweight Aggregates Using Sand Wash Fines and Other Waste Materials for Masonry

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ABSTRACT

Local aggregate sources in Kuwait are scarce and quarrying for coarse aggregates has been stopped completely. The construction industry now is entirely dependent on imported aggregates. In an effort to look for alternative sources, research has been carried out at Kuwait Institute for Scientific Research (KISR) to explore suitable indigenous raw materials for the production of synthetic lightweight aggregate (LWA) to serve and support sustainable construction projects.
The paper reports the investigation of rotary kiln manufactured lightweight aggregates (LWA) using sand wash fines obtained from the sand washing plant of the National Industries Company (NIC) in Kuwait in addition to other waste materials acting as gas generating and fueling agents such as used lube oil and municipal sewage sludge. The physical and mechanical properties of the sand wash fines and other ingredients, synthetic LWA were assessed as well as the engineering properties of the lightweight aggregate concrete (LWAC) made from the LWA. The physical properties of the concrete masonry units made from the LWA were then measured. The investigation revealed the sand wash fines contain all the necessary elements to enable the bloating and calcining processes within the commercial kiln. When exposed to the high heat, this material undergoes dramatic changes, developing a hard ceramic shell and a porous core comprised of non-interconnected capillaries. The LWA produced from the kilning process meet the requirements of Standard Specification for Lightweight Aggregates for Concrete Masonry Units ASTM C331.

1. INTRODUCTION

The construction industry is very demanding for natural raw materials. The concrete production consumes huge quantities of aggregates. The local aggregate sources in Kuwait are scarce and quarrying for coarse aggregates has been stopped completely. The industry now is entirely dependent on imported aggregates. Therefore there is a need to look for alternative sources. Manufactured or synthetic aggregates are used as a source for aggregates, specially light weight aggregates.

Synthetic aggregates are usually characterized by their low density. According to ASTM specifications (C 330-05, 1989; C 331-05, 1994; and C 332-05, 1994), the bulk density of lightweight aggregates used in structural concrete, heat insulating concrete and concrete masonry units should be in the range of 0.88 to 1.12 g/cm3.

Synthetic aggregates are produced from a number of raw materials including clay, shale, slate, perlite, vermiculite, blast furnace slag, and pulverized fuel ash. The production of synthetic aggregate from clay involves heating suitable raw material at a sufficiently high temperature so that it melts to a viscous, pyroplastic mass. The entrapped gases in the viscous mass cause the expansion (bloating) of the mass and subsequently a porous structure with low density is obtained on cooling.

Riley (1951) showed that the chemical composition of unfired raw material indicates whether or not it can develop the proper viscosity at the melting point needed for gas entrapment, and thus, reduce bloating. His research showed experimentally that the viscosity requirement can be satisfied if the chemical composition of the raw material is such that there is a proper ratio of fluxing oxides (CaO, MgO, FeO, Fe_2O_3, Na_2O and K_2O) to silica (SiO_2) and alumina (Al_2O_3). The compositional relationship for satisfying the viscosity requirement in clays are demonstrated in the Riley triangle.

The production of synthetic aggregate from clay involves heating suitable raw material to a sufficiently high temperature to melt it into a viscous, pyroplastic mass. The entrapped gases in the viscous mass cause the expansion (bloating) of the mass, and subsequently, a porous structure with low density results on cooling. Some basic requirements for raw material to be used in synthetic aggregate production are as follows:

- The raw materials should melt at a temperature not exceeding 1300^0C.
- The raw materials should contain sufficient gas-forming ingredients for bloating, and the gases should be evolved at the temperature at which melting occurs.
- The viscosity of the melt should neither be too high nor too low. A viscosity that is too high results in thick wall formation in the finished product, whereas a viscosity that is too low results in insufficient bloating.

The melting temperature is mainly controlled by the mineralogical composition of the raw material. When clay is subjected to heat treatment, liquefaction starts with the melting of minerals requiring the lowest temperature. Once such minerals begin to melt, they act as a fluxing or dissolving agent and tend to lower the melting point of the minerals in contact with them. Some low-temperature fluxing minerals include sodium and potassium salts, and silicates. Feldspar provides fluxing action over a wide range of temperatures.

The constituents necessary for gas evolution at a temperature coincident with the molten state are reported to be pyrite, hematite, and dolomite. The various gases generated from these minerals or other sources that bloat the viscous mass include oxygen, sulphur dioxide, sulphur trioxide, carbon monoxide and entrapped air. The evolution of oxygen from the dissociation of ferric oxide at high temperatures is considered to be very significant in the bloating of clays.

In Kuwait, preliminary studies were started at KISR in 1981 (Parks, 1981) in which silty marine clay from Sulaibikhat Bay, was used for laboratory production of synthetic aggregate. Trials indicated that aggregates with a bulk density of 700 to 800 kg/m^3, as compared to 350 kg/m^3 for lightweight expanded clay aggregate (LECA), could be

produced by firing silty marine clay in a rotary kiln at 1100 to 1150^{o}C. Such production was shown to be uneconomical (Parks, 1981).
In Singapore, where geographical limitations, insufficient natural resources and huge quantities of municipal and industrial waste drive the need to find alternatives to reduce the importation of raw materials, Laursen et al. (2004) conducted a study on recycling of industrial sludge and marine clay as LWA. To produce LWA, the researchers use marine clay and CaF_2-rich semiconductor-industry sludge, utilizing a bench-scale rotary kiln with three clay-to-sludge loadings (90/10, 70/30 and 50/50). All three mixtures produced good bloating during firing and low densities as required for LWAs.
In Spain, Gonzalez-Corrochano et al. (2008) studied the "Production of Lightweight Aggregates from Mining and Industrial Wastes". To do this, they used AW sludge from a gravel pit and SS from a wastewater treatment plant. Mixtures were formed into pellets, preheated, sintered in a rotary kiln at different temperatures, and the products obtained were LWAs that met the specifications of standard UNE-EN-13055-1(2003), and low apparent particle density, low water absorption and high compressive strength. Gonzalez-Corrochano et al. (2008) were able to establish three groups of LWAs on the basis of their properties that were compareable to Arleta G3, F3 and F5, commercially available LWAs manufactured in Spain at the time. The synthetically produced LWAs could be used for same applications (horticulture, prefabricated lightweight structures and building) as the commercial products.
In Kuwait, research has been conducted by Al-Bahar and Bogahawatta (2000, 2004, and 2008) at KISR gave initial promising results that were followed through by extensive and comprehensive research out of which some results are presented in this paper.

2. Raw Materials

For the production of synthetic aggregate, different locally available raw and waste materials were used. The natural clay (RC) and GC) was dug up and transported from an area northeast of Kuwait City. The aggregate wash (AW) was obtained from the sand washing plant of the National Industries Company. The sewage sludge (SS) was collected from a local sewage treatment plant, while the waste lube oil (LO) was collected from petrol stations around Kuwait.
Utilization of AW would minimize the avoidable environmental impact of the daily dumping of 60 to 70 m^3 of this waste material in the Amgharah area in south western Kuwait, which is being dumped by NIC alone(Figure). This number could increase four folds if other sand washing facilities are taken into account. Utilization of AW in for such purposes, would eliminate the wasted expenses of sand washing and the transport of sand wash for dumping in the desert; added to that the costs of energy to run the washing plant and the labour employed. It is estimated that the yearly production of AW waste (at NIC facilities only), is 250,000 m^3.

3. Pre-Production Investigation

3.1 Chemical and Mineralogical Analyses

To determine the raw materials suitability for LWA production and to adjust their melting behavior and bloating characteristics, representative samples of raw materials and subsequent raw mixtures were subjected to chemical analysis using the X-ray fluorescence (XRF) method. The presence of an appreciable Al_2O_3 content in any sample indicates that it is clay of an acceptable quality for bloating as the approximate limit is 10 to 17% (Table 1). Also, the presence of CaO and MgO indicates that the sample consists of materials such as calcite, dolomite or magnesite, which that will liberate CO_2 at a temperature at which a glassy phase forms. The presence of fluxes such as Fe_2O_3, CaO, MgO, K_2O and Na_2O ensures the development of a high-temperature glassy phase of sufficient viscosity to allow for good bloatability.

Table 1. XRF Analysis of Raw Materials and Raw Material Mixtures

Sample Designation	SiO_2	Al_2O_3	CaO	Na_2O	MgO	Fe_2O_3	K_2O	TiO_2	P_2O_5	MnO
AW	63.1	18.20	3.42	1.09	3.85	3.83	1.52	0.26	0.05	0.03
RC	59.2	20.80	0.50	3.94	5.43	6.895	2.91	0.54	0.28	0.12
GC	65.3	18.70	1.20	2.07	3.30	5.05	2.98	0.47	0.27	0.04
50%AW-50%RC	60.4	20.00	1.69	2.07	4.94	5.75	2.10	0.42	0.21	0.08
SS	8.93	4.34	0.00	1.39	3.68	ND	0.00	0.00	2.15	0.00

Riley's diagram for the raw materials shows that according because of the raw materials' chemical compositions, at the melting point, they could develop the viscosity, necessary for gas entrapment, which, in turn, is required for bloating to occur. Hence, LWAs could be produced from these raw materials. The raw materials assessed in this study were superimposed on Riley's (Fig. 1).

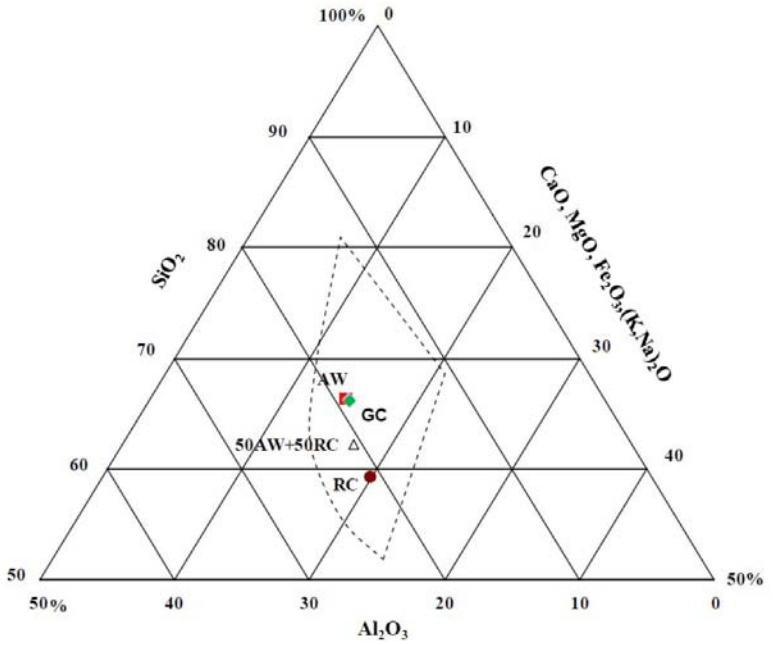

Figure 1. Raw materials and mixtures positioning in Riley's composition diagram of major oxides.

3.2 Heating Microscope

The bloating ranges of the raw materials and their mixtures were evaluated using a heating electron microscope and confirmed the acceptability of their bloating characteristics by simulating a kiln-heating environment on a micro scale. With the heating microscope technique, samples are heated at a temperature ranging from 25 to 1600^{o}C. A monitoring camera captures the images of the melting of the raw materials at different temperatures. Temperature peaks representing a variety of melting stages related to each sample can be obtained, such as the sintering temperature at which the specimen starts to shrink; the deformation temperature at which the specimen starts to soften, indicating the start of gas liberation; the sphere temperature at which gas liberation is maximum; the hemisphere temperature at which the specimen forms hemisphere shape, indicate the end of gas liberation; and the flow point temperature, indicating the mass collapse and gas escaping from the melted structure. Between the deformation and the hemisphere temperatures, gas release takes place, causing the material mass to bloat. From the measurements collected, accurate bloating temperatures can be determined.The plots for all of the materials and mixtures assessed indicated their ability to bloat under firing temperatures. The RC and AW samples have both exhibited maximum bloating at 1260^{o}C a typical plot is shown in Figure 2.

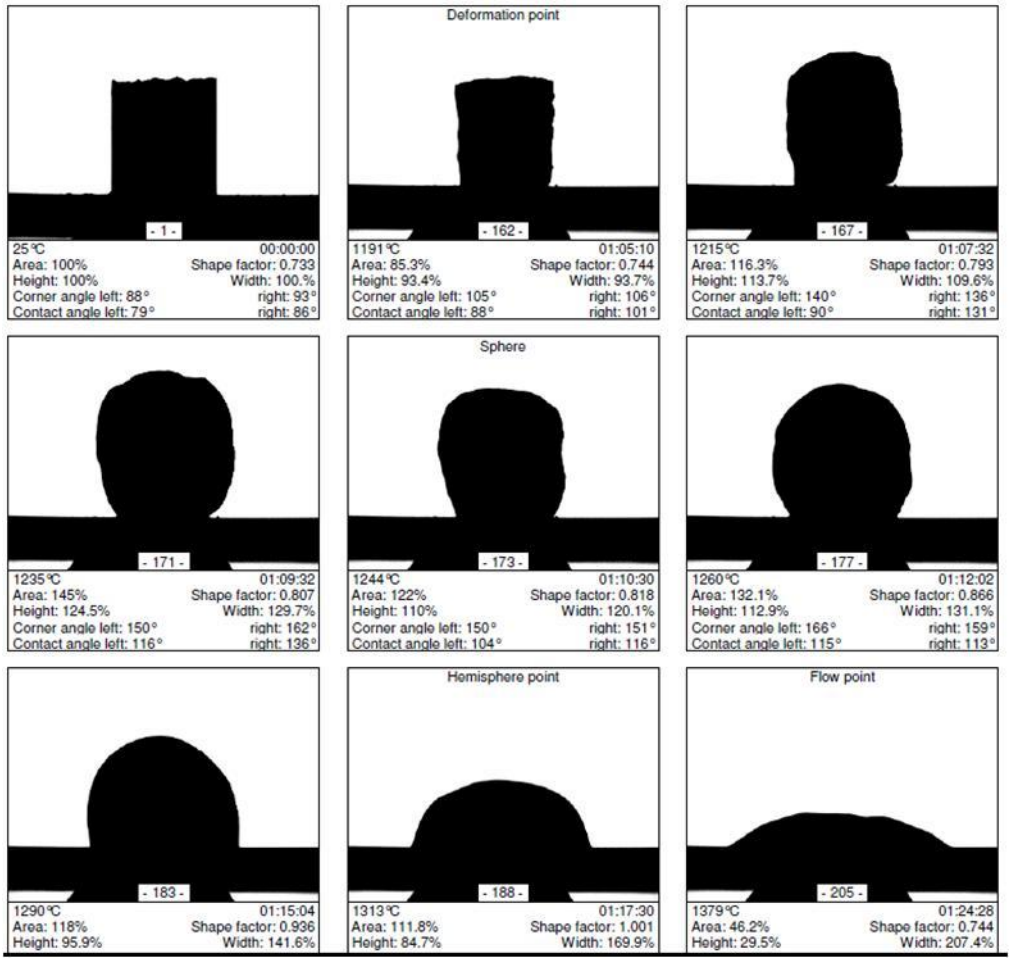

Figure 2. Heating Microscope Results for Aggregate Wash

3.3 Burnability and Heat Treatment

Susceptibility for bloating was further confirmed by actual firing trials of green pellets in a double-muffle furnace. Prepared and dried green pellets of each material and mixture were fired in a muffle furnace at 650^{o}C (i.e., calcinations temperature) for 3 min, then removed and placed instantly in another muffle furnace where they were subjected to bloating temperatures ranging from 1000^{o}C to 1200^{o}C (i.e., bloating temperatures). At each bloating temperature, the holding time (soaking time) was maintained for 1, 3, and 5 min, before the sample was removed from the second furnace and allowed to cool (Figure 3).

The quality of the resulting pellets was assessed in terms of its bloating ratio, surface texture, and bulk density (Table 2). The higher the bloating ratio, the better the quality of the fired pellets. The surface texture of the fired specimens was evaluated mainly on the basis of the presence of glass melts on the specimen surface. The presence of excessive glass on the surface is undesirable in industrial production as it causes rings to form within the rotary kiln at high temperatures.

Figure 3. Mixing, Pelletizing and Firing

Table 2. Assessment Criteria for the Evaluation of the Fired Pellets

Bloating Ratio*	Assessment	Meaning
1.6-2.0	Excellent	Thin reddish brown oxidized mat skin layer
1.4-1.6	Very Good	
1.2-1.4	Good	Dark brown oxidized skin layer with slightly glossy appearance
1.0-1.2	Fair	
1.0	Poor	Grey-greenish or dark grayish skin layer with very glossy appearance, cracks and burst

*Bloating Ratio = Diameter of Fired Pellet/Diameter of Unfired Pellet Surface texture

After completing the firing of the green pellets, according to the procedure described above a bloatability assessment was carried out for each batch of fired pellets. Bloating has been defined as the ratio of the diameter of the fired product to the diameter of the unfired pellet. The quality of the finished products was assessed in terms of bloating ratio, surface texture, specific gravity and bulk density. Bloatability ratio assessment, based on the bloating quality, An example of the Assessment Display Sheets is shown in Figure 4, which present the firing temperature, holding time, bloating ratio, pellet diameter size, density, and mixture composition.

4. Selecting Light Weight Aggregate Mixtures

According to the results of the assessment of the firing trials carried out over more than six months, a selection was made of the best options for raw materials, firing temperatures, and calcination and bloating holding times stages. The firing trials indicated that AW and RC were promising raw materials for synthetic aggregate production. The effect was more profound in clay samples containing LO and SS as bloating additives. Nevertheless, due to the difficulty in accessing the clay reserves in the desert, relying on natural clay sources alone would be impractical. Therefore, AW waste materials were determined to be the most suitable and most reliable sustainable source of raw materials for the production of synthetic aggregate, in combination with natural RC and other additives, such as LO and SS. For the pilot production, the following were considered:

- AW without LO calcined at 650^0C for 5 min and fired at 1200^0C for 15 min.
- AW with 1.12% LO calcined at 650^0C for 5 min and fired at 1200^0C for 15 min.
- 50% AW and 50% RC with 1.12% LO calcined at 650^0C for 5 min and fired at 1200^0C for 15 min.
- AW with 4% SS calcined at 650^0C for 5 min and fired at 1200^0C for 15 min.

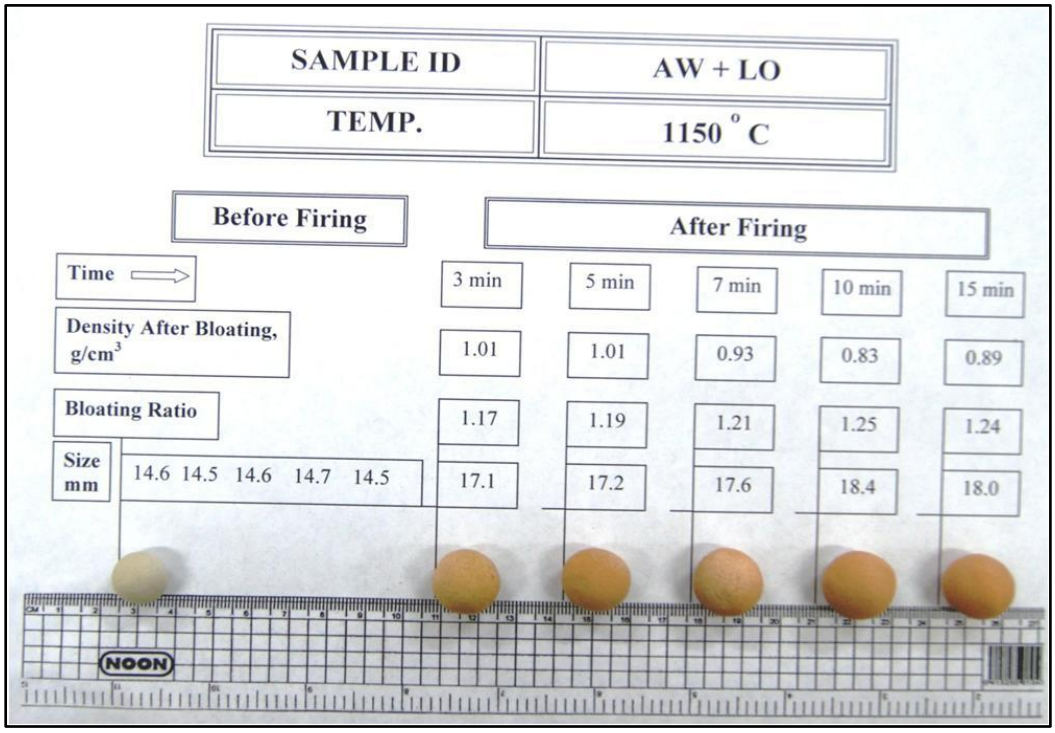

Figure 4 Typical Bloating Assesment Sheet

5. Pilot Scale Production

Production of lightweight expanded clay aggregate (LECA) on pilot-plant scale started with green-pellet productions of every selected mixture combination, as optimized previously. Raw materials were stockpiled, dried, crushed, and powdered. Then, the powdered materials were liquefied, screened, press-filtered reduce moisture, extruded into strands, and pelletized into green pellets. The green pellets then dried and conditioned, in preparation for rotary kiln firing (Figure 5).

Firing was done in stages. The first was the calcination stage, in which the green pellets were fired at 650 ^{o}C for 3 to 6 min. The second was the bloating stage in which the calcined pellets were subjected to a temperature of about 1200 ^{o}C for 10 to 20 min. As the materials passed through the kiln, the heating stage was designated. mechanical moisture or drying period, hygroscopic or colloidal water dehydration period, chemical or molecular water dehydration period, oxidation period, dissociation-reduction period, vitrification period which involves the first glass formation melting, and pyroplastic conditioning which is a period of bloating for clays so that all of the gases present in the material can be completely liberated, sealed and entrapped within the bloated pellet. Firing was done with graduated increases of temperature to avoid thermal shocks, which can cause pellets to shatter into small pieces.

Figure 5. Pilot rotary trefoil kiln.

The pilot plant at the Kuwait Institute for Scientific Research (KISR) was able to produce and approve five different types of LWA (Table 3). As an example, resulting LWA produced from AW is shown in Figure 6.

Table 3. Details of the Tested KISR-LWAs

Aggregate No.	Mix Details
1	AW-LO(1.12%)
2	50AW-50RC-LO(1.12%)
3	AW-SS(4%)
4	AW

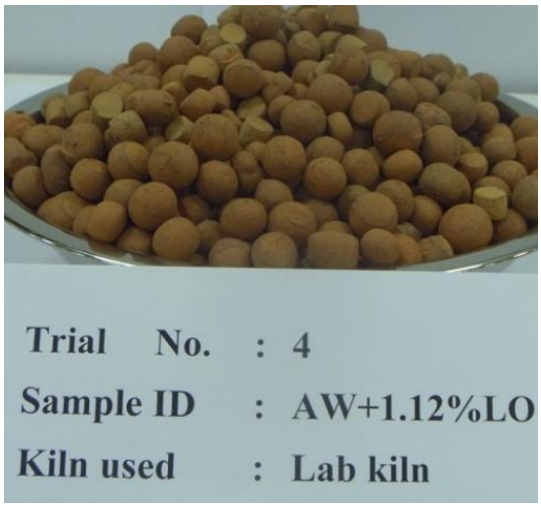

Figure 6. LWA produced from AW with 1.12% LO with light brown colour.

6. Light Weight Aggregate Concrete

Concrete specimens containing KISR-LWA were prepared and evaluated against the performance of concrete specimens containing commercial LWA. The evaluation included shrinkage, compressive strength, thermal conductivity, density and absorption (Table 4).

Table 4. Concrete tests and Concrete Specimen Size

Test	Standard Test Method	Concrete Specimen Size
Shrinkage	ASTM C331-05 & C157 (2005)	50 x 50 x 285 mm
Density & Water Absorption	BS 1881-122 (1983) & BS 1881-114 (1983)	300 x 300 x 50 mm
Compressive Strength	ASTM C39 (2005)	100 mm Ø x 200 mm
Thermal Conductivity	ASTM C518 (2002)	300 x 300 x 50 mm

The concrete mixes were prepared using one part Portland cement to six parts combined aggregate, measured in loose dry volume. The water content was adjusted to produce a slump of 50 to 75 mm (2 to 3 in). Different sizes of concrete specimens were produced and tested.

6.1 Drying Shrinkage

The drying shrinkage results for concrete specimens made using fired LWA and commercial LWA are presented in Table 5. Drying shrinkage should not exceed 0.10%, as specified in ASTM C331-05 (2005). No samples showed drying shrinkage that exceeded 0.10%; the samples containing commercial LWA showed similar results to the concrete specimens containing fired KISR-LWA.

Table 5. Drying Shrinkage Results for Concrete Specimens containing LWA

Mix Using Aggregate Type	Drying Shrinkage (%)	
	7 d	28 d
1	0.02	0.09
2	0.04	0.08
3	0.03	0.10
4	0.03	0.06
Commercial	0.01	0.09

Density and Absorption of Hardened Concrete

The density and water absorption of hardened concrete samples were evaluated, and the results are tabulated in Table 6. The density of the concrete produced using KISR-LWA ranged between 1342 and 1584 kg/m^3; KISR-LWA 2 produced the lightest concrete, while KISR-LWA 4 had the lowest water absorption value (13.3%). Concrete produced using commercial LWA showed comparable results to the concrete specimens made using KISR-LWA.

Thermal Conductivity

The thermal conductivity of the concrete samples was evaluated by means of measurements of steady-state thermal transmission using a heat flowmeter apparatus. The K-value expressed in (W/m K) was measured and results are presented in Table 6. No measurable difference was noticed among the K-values of the concrete samples produced using the five types of KISR-LWA (i.e., between 0.45 and 0.55). The commercial LWA concrete samples had comparable K-values to the KISR-LWA concrete being particularly close to the K-value of KISR-LWA 3. The thermal conductivity of KISR-LWA concrete was comparable to that of other conventional insulation materials used in building walls and roofs, which makes it an economically competitive alternative insulation material.

Table 6. Density, Water Absorption, Thermal Conductivity and Compressive Strength of Concrete Specimens containing LWA

Parameter	Mix containing LWA Type				
	1	2	3	4	Commercial
Density (kg/m^3)	1419	1342	1536	1584	1520
Water Absorption (%)	18.5	17.4	17.5	13.3	14.65
K-Value (W/m K)	0.5	0.48	0.55	0.45	0.62
28-d Compressive Strength (MPa)	8.58	7.59	9.43	12.75	10.48

Compressive Strength

The 28 d compressive strength are presented in Table 6. Although compressive strength is not a crucial property in this particular investigation, nevertheless, it is an indication of the minimum strength required for handling and transport of stockpiled blocks. The results showed no noticeable deviation in the compressive strength of the concrete mixes produced using the four types of KISR-LWA concrete. The average 28-d compressive strength values ranged between 7 and 12 MPa, the highest value with concrete made using KISR-LWA 4 (AW). All of the concrete mixes produced using the four types of KISR-LWA showed comparable values of compressive strength to the commercial LWA concrete samples.

7. CONCLUSIONS

- Synthetic LWA was successfully produced, on a pilot scale that complies with standard specifications and satisfies the requirements of thermal efficiency.
- The inclusion a by-product material of sand washing (AW) as an alternative raw material for the production of LWA, has been demonstrated to be highly successful and beneficial.
- AW was found to be the most suitable and reliable raw material for use in the production of synthetic LWA, in combination with natural clays and other additives, such as LO and SS.
- Its utilization would minimize the environmental impact of the daily dumping of this waste material in the desert.
- The thermal conductivity of concrete containing KISR-LWA was comparable to that of other conventional insulation materials used in building walls and roofs.

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