Advances in Materials Research, *Vol. 11*, *No. 2* (*2022*) *147-164*
https://doi.org/10.12989/amr.2022.11.2.147

Potential use of local waste scoria as an aggregate and SWOT analysis for constructing structural lightweight concrete

A.B.M. Saiful Islam*, Walid, A. Al-Kutti, Muhammad Nasir, Zaheer Abbas Kazmi and Mahmoud Sodangi

Department of Civil & Construction Engineering, *College of Engineering*, *Imam Abdulrahman Bin Faisal University*, *31451*, *Dammam*, *Saudi Arabia*

(*Received June 12*, *2021*, *Revised November 22*, *2021*, *Accepted January 3*, *2022*)

Abstract. This study aims to investigate the influence of scoria aggregate (SA) and silica fume (SF) as a replacement of conventional aggregate and ordinary Portland cement (OPC), respectively. Three types of concrete were prepared namely normal weight concrete (NWC) using limestone aggregate (LSA) and OPC (control specimen), lightweight concrete (LWC) using SA and OPC, and LWC using SA and partial SF (SLWC). The representative workability and compressive strength properties of the developed concrete were evaluated, and the results were correlated with non-destructive ultrasonic pulse velocity and Schmidt hammer tests. The LWC and SLWC yielded compressive strength of around 30 MPa and 33 MPa (i.e., 78-86% of control specimens), respectively. The findings indicate that scoria can be beneficially utilized in the development of structural lightweight concrete. Present renewable sources of aggregate will preserve the natural resources for next generation. The newly produced eco-friendly construction material is intended to break price barriers in all markets and draw attraction of incorporating scoria based light weight construction in Saudi Arabia and GCC countries. Findings of the SWOT analysis indicate that high logistics costs for distributing the aggregates across different regions in Saudi Arabia and clients' resistant to change are among the major obstacles to the commercialized production and utilization of lightweight concrete as green construction material. The findings further revealed that huge scoria deposits in Saudi Arabia, and the potential decrease in density self-weight of structural elements are the major drivers and enablers for promoting the adoption of lightweight concrete as alternative green construction material in the construction sector.

Keywords: eco-friendly concrete; lightweight concrete; renewable; Saudi scoria waste; silica fume; SWOT analysis

1. Introduction

During the recent years, the Kingdom of Saudi Arabia has seen a rapid escalation of infrastructure development. Widely available waste scoria in the western region of the Kingdom can be a substantial resource to compensate the rising demand of construction material in producing effectual concrete. The concrete produced by utilizing waste scoria is lighter in weight and a potential alternative of traditional normal weight concrete (NWC). The lightweight concrete (LWC) is continuously being a popular choice in the construction sector due to its low density

*Corresponding author, Ph.D., E-mail: asislam@iau.edu.sa

http://www.techno-press.org/?journal=amr&subpage=5 ISSN: 2234-0912 (Print), 2234-179X (Online)

(less than 2000 kg/m^3) and numerous other benefits over normal weight concrete (NWC). The reduced self-weight of structural LWC allows the engineers to design smaller structural elements (Islam *et al*. 2018b). Allowance of greater span to depth ratio in LWC aids in designing smaller beam cross- sections (Chandra and Berntsson 2002, Islam and Al-Kutti 2018, Shannag 2000). Based on reduced self-weight and sizes of the structural elements, it is fair to claim that LWC has significant sustainable and economic advantages over NWC (Hosen *et al*. 2019, Khan *et al*. 2021, Lopez *et al*. 2006).

The LWC with compressive strength of more than 20 MPa is known as structural lightweight concrete (BS8110 1997). The LWC which is manufactured by lightweight aggregate (LWA) is being employed for structural purpose and its application has been seen worldwide in various constructions such as buildings, precast members, bridges, and offshore structures (Chandra and Berntsson 2002, Raithby and Lydon 1981, Saif *et al*. 2019). Al-Azzawi and Al-Aziz (2018) investigated the behavior of reinforced lightweight aggregate concrete hollow-core slabs. Bideci *et al*. (2017) studied the LWA coated with colemanite. The effect of accelerators with lightweight waste material on the properties of cement paste and mortar was investigated by Devi *et al*. (2018), (Marthong 2019). The performance of improved concrete using lightweight waste material has been investigated in different aspects (Mazloom *et al*. 2018a, Palaskar and Vesmawala 2020, Yaragal and Ramanjaneyulu 2016). Similarly, some other studies have been conducted to investigate the effect of fine and coarse LWA on strength and settlement of self-compacting LWC (Mazloom *et al*. 2018b, Mazloom and Mahboubi 2017). Mazloom *et al*. (2020) introduced the long-term quality control of self-compacting semi-LWC using short-term compressive strength and combinatorial artificial neural networks. Tang (2017) assessed the effect of presoaking degree of LWA on the properties of LWC.

Generally, the LWC made from clay, shale, and pumice are largely used in the western countries. However, its use is limited in the GCC countries due to the lack of sufficient research (Islam *et al*. 2018a). The shallower depth of the earth's crust in the KSA is comprised of loose dune or beach sand with soluble salts. The generous conduct of salt bearing soil, fluctuation of ground water table, and extreme environmental conditions offer a variety of geotechnical problems influencing safety and serviceability of the infrastructure (Kazmi 2020, Kazmi and Sodangi 2021). Furthermore, limestone sedimentary rocks are the main source of coarse aggregate, called limestone aggregate (LSA). LSA are relatively soft and porous resulting in poor strength and durability of concrete (Zein-Alabideen 2001).

Considering the aforementioned facts, LWC is a potential alternative of traditional NWC. The availability of waste material like scoria, pumice, and calcined clay in the mountainous region of western Saudi Arabia are considered a great reserve of supplying LWA to produce LWC. Therefore, the study investigates the potential use of Saudi local waste scoria in developing structural lightweight concrete for construction applications.

2. Light weight concrete

Concrete remains one of the leading construction materials used all over the world. Its major structural significance in construction industry is primarily rooted to its technical attributes as well as to its economic advantage over other related materials. More so, concrete enjoys greater advantage due to the wide availability of its principal components like coarse aggregate, fine aggregate, water, and Portland cement. Concrete is generally grouped into three distinct categories namely lightweight, normal, and heavy weight concrete.

The incessant high demand of normal concrete in construction projects significantly decreases the natural stone deposits, which has adversely resulted into ecological imbalance (Al-Kutti *et al*. 2019a, b). Thus, it is paramount to shift focus to appropriate construction materials that will replace the natural aggregate. The LWC is a good alternative option. The most popular way of producing LWC is by making use of LWA.

The density of Lightweight aggregate concrete (LWAC) is quite less than the NWC, maintaining good quality as a construction material.

Remarkably, several replacements for conventional aggregates have been identified in the construction industry. These include artificial and natural LWA, which offer significant reduction in the size of structural members (Ahmmad *et al*. 2014, Huda *et al*. 2015, 2016, 2017).

2.1 Benefits of light weight concrete

The advantages of LWC include reduction in dead load, steel reinforcement, and substantial reduced costs of foundation, transportation, formwork and scaffolding. Other notable advantages include enhanced thermal insulation, sound absorption, reduced tendency to buckle due to differential temperature gradients, improved anti condensation attributes, durability, enhanced fire resistance, heat isolation, and resistance to frost (Düzgün *et al*. 2005, Jumaat *et al*. 2015).

The LWC retains large voids and not forming laitance layers or cement films when it is placed on walls. It offers low density, good thermal conductivity, faster construction, and lower transport and handling costs. It also offers increased service life, reduction of noise, better fire resistance and it makes the structural design more flexible.

Usually, the density of structural LWAC ranges from 1440 to 1840 kg/m^3 while the density of NWC ranges from 2240 to 2400 kg/m^3. Thus, the major advantage of using LWC is the potential construction cost savings and sustainability by minimizing the consumption of raw material.

2.2 Need for LWC in coastal region of KSA

The coastal regions have several problems like shallow water table, salt concentration, as well as poor bearing capacity of the soil. Furthermore, the available normal and traditional aggregate in KSA is limestone, which is highly porous, soft, and poor in quality. Therefore, the Saudi Arabian construction demands alternative concrete having lower density and good structural properties. The lightweight concrete using local waste of Saudi Arabia could compensate the radical demand.

In the coastal regions of KSA, a huge land is not suitable for construction because of low bearing capacity of soil. The replacement cost of the soil layer is pricy. So, instead of going to that approach, a workaround solution is to use lighter weight material.

2.3 Scoria light weight concrete in Saudi Arabia

Several lightweight aggregates are available in Saudi Arabia such as Scoria, Calcined clay, expanded clay, Shale, Pumice as well as artificial aggregates like Expanded blast-furnace slag, Vermiculite, Clinker Aggregate etc. In this study, locally available LWA, Scoria aggregate (SA), has been chosen along with silica fume to produce the sustainable LWC. In the Kingdom of Saudi Arabia (KSA), the LWAC can be used as potential building materials instead of NWC due to the limited soil bearing capacity (less than 100 KN/m^2) in its many areas around the Eastern Province.

The locally available SA in the Western Province in the KSA is a good alternative. Scoria is highly vesicular fine to coarse fragments, dark colored volcanic rock that can or cannot include crystals. It is naturally dark in color (usually dark brown, black, or purplish red). Competitively, scoria is low in density due to its various macroscopic ellipsoidal vesicles (Moufti *et al*. 2000). Scoria reserves are widespread in the western part of KSA, but no considerable studies have been published on exploring the magnitude or quality of these reserves. The approximated deposits available in four different locations inspected within central Harrat Rahat, namely Jabal Halat Ash Shaykh, Jabal Al Hala, Jabal Suwah and Jabal As Sahiliyah amount about five million cubic meters (Sabtan and Shehata 2000). Fig. 1 shows scoria rock fields located in KSA.

Sabtan and Shehata (2000) suggested that the attributes of scoria aggregate in its normal condition are more appropriate as a LWA, satisfying most of the ASTM specifications of structural concrete. Fares *et al*. (2014) determines the compressive strength at 7 and 28 days of curing by varying percentages of scoria. The results satisfy the minimum requirement of compressive strength at 28 days with 50% SA replacement. The modulus of elasticity of concrete is highly influenced by the stiff nature of the coarse aggregates. The low density, specific gravity of more

Fig. 1 Locations of Scoria fieldsin Harrat, Saudi Arabia
(Courtesy: http://www.saudicaves.com/lava/harra.jpg)

than one, and porous nature of SA directly influences the stiffness of concrete. Consequently, we end up with a concrete that has a lower modulus of elasticity.

Due to the dynamic loading like earthquake, wind, and vibration, huge lateral forces and accelerations are applied on the concrete structures leading to tremendous damage. Therefore, the strength of the structure needs to be augmented to prevent such structural damages. However, enormous increase in the strength is practically not possible. The use of LWAC remarkably reduces self-weight of the structure, thereby decreasing the lateral forces, and thus the structural damages under dynamic loading. Pardakhe and Nalamwar (2015) analyzed and compared traditional RC and lightweight RC structure with and without considering the dynamic loading (earthquake). It has been established in their study that adaptation of lightweight concrete reduces overall construction cost, which proves it to be a safe and economical solution.

2.4 State of the art problem

Though several studies have been conducted to devise new alternatives of eco-friendly structural concrete, the use of Saudi local waste in production of LWC has rarely been explored. Most of the coastal land is salvaged with exceedingly poor geotechnical properties, further worsened by the fluctuating ground water table and presence of soluble salts. The low bearing capacity of the soil and heavy dead weights of the structures require massive foundation system at the cost of capital, material, and time. Hence, an alternate eco-friendly construction approach, in terms of LWC, is required to be developed and studied in detail.

To meet the objective, this study investigates the properties of scoria based LWC and compares it with the NWC. The scoria aggregate for the LWC is obtained from the western part of Saudi Arabia.

3. Materials and methods

3.1 Materials

3.1.1 Cementitious material

In this study, Type I - ordinary Portland cement (OPC) with a specific gravity of 3.15 was used as the binder material in all concrete mixtures. Silica fume (SF) having specific gravity of 2.10 was used as a 7% partial replacement of OPC in SLWC mix. Table 1 shows the chemical composition of OPC and SF.

3.1.2 Aggregate

The dune sand was used as fine aggregate. In the NWC, crushed limestone aggregate (LSA) was used as coarse aggregate. For lightweight concrete mixes, crushed scoria, collected from local mountain wastes of Saudi Arabia, was employed as coarse aggregate. The aggregate grading was in accordance with ASTM C33, sieve size no. 8. According to that, 10 mm and 5 mm aggregates were used as 85% and 15%, respectively. Typical coarse aggregates are shown in Fig. 2.

In the recent years, scoria rock (SR) is being used as lightweight aggregate to replace the traditional normal weight aggregate (NWA) in structural elements as well as in road construction. The mechanical and structural properties of scoria-based concrete are compared with normal weight concrete (NWC) in some studies (Islam *et al*. 2018a, b). The modulus of elasticity of scoria-based concrete is governed by the stiffness of the coarse aggregates. The low density,

Fig. 2 Limestone aggregate (left) and scoria aggregate (right)

Table 1 Chemical composition of Type I cement and silica fume

Parameter	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	K_2O	Na_2O	Na_2O + (0.658K_2O)	Loss on ignition
OPC %	20	3	63	6	1.5	0.5	0.5	1	0.73
SF %	92.5	0.96	0.48	0.72	1.78	0.84	0.5	1.34	1.55

Table 2 Physical properties of aggregate

Aggregate properties	Specific gravity	Water absorption	Unit weight	Water content	Fineness modulus
	(SSD)	(%)	(kg/m^3)	(%)	
Coarse aggregate (Limestone)	2.46	2.58	1458.1	1.06	-
Coarse aggregate (Scoria)	1.7	15.8	932.8	13.7	-
Fine aggregate (Sand)	2.66	0.6	-	2.5	2.51

specific gravity of more than one, and porous nature of SA directly influences the stiffness of concrete. Thus, the scoria concrete has low modulus of elasticity which is a major key point to select it in this study. Table 2 shows the physical properties of both fine and coarse aggregates.

3.1.3 Super plasticizer (SP)

Water reducing concrete admixture, Sikament NN, was employed to enhance the workability of concrete. SP had density of 1.2 kg/l and it complies with ASTM C-494 Type A & F and EN 934-2:2001.

3.1.4 Water

Potable water was used for all concrete mixes and to cure the specimens. It was ensured that water is free of dirt and other elements that may affect cement hydration process. The curing water was changed every week to avoid excessive dirt.

3.2 Mixing and testing

3.2.1 Mix parameters

Based on the outcomes of the trial mixes, three types of concrete were prepared namely NWC using limestone aggregate (LSA) and ordinary Portland cement (OPC) (referred as control

Table 3 Mix design details

Mix	Cement (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	w/cm ratio	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)
NWC (control)	466.6	-	186.6	0.4	933.4	685.5
LWC	567.4	-	227	0.4	367.8	1003.4
SLWC	527.7	39.7	227	0.4	367.8	1003.4

Fig. 3 Concrete casting view: (a) mixing; (b) compaction; (c) finished specimens; (d) curing under water tank

specimen), LWC using SA and OPC, and LWC using SA and SF (SLWC). The physical and chemical properties of aggregates and cementitious materials were first determined to prepare mix designs. The design details of all three mixes are shown in Table 3. The performance of all the concrete mixes was evaluated by the specimens prepared were evaluated by determining workability, density, compressive strength, and modulus of elasticity along with non-destructive pulse velocity and Schmidt rebound hammer tests. The concrete casting operation is depicted in Fig. 3.

3.2.2 Testing of concrete

The details of the experimental testing program including test method, age of testing, specimens size/shape and applicable standard is summarized in Table 4.

Table 4 Summary of test methods, specimen type and standards

Test method and age	Specimen type	Standard
Workability by slump test on fresh concrete	Slump cone	ASTM C 143
Density of concrete: at 28 days	100 mm diameter and 200 mm high cylinder	-
Compressive strength: at 3, 14 and 28 days of water ponding		ASTM C 39
Ultrasonic pulse velocity: at 3, 14 and 28 days of water ponding		ASTM C 597
Rebound number: at 28 days of water ponding		ASTM C 805
Modulus of elasticity of concrete: at 28 days		ACI 318-14M

4. Results and discussions

4.1 Workability

With a fixed water-cement ratio of 0.40, the workability of LWC was expected to be lower due to high water absorption capacity of scoria aggregate. Thus, and adequate quantity of superplasticizer was added to get the desired workability of 50 ± 25 mm. In the LWC, a slump of 50 mm was recorded by adding 1% superplasticizer by the weight of cement. On the other hand, a similar workability was achieved in NWC by adding 0.5% plasticizers.

4.2 Concrete density

The concrete density for NWC and LWC after 28 days of curing was evaluated. The results ensure that the mix water was not evaporated and the object of curing was obtained. The average density in NWC was found to be 2357 kg/m^3 compared to 1850 kg/m^3 and 1950 kg/m^3 recorded in the case of LWC and SLWC, respectively. These results indicate that a 15% reduction in the density be achieved by using scoria based LWC as compared to the limestone based traditional NWC. The results are encouraging in minimizing the self-weight of the structure on poor bearing capacity of the soil up to some extent.

4.3 Compressive strength

Fig. 4 shows the development of compressive strength of all concrete specimens from 3 to 28 days. As expected, the compressive strength increased with increased curing time in all concrete specimens. The compressive strength of NWC was best followed by SLWC and LWC specimens at all test ages. The 3-day average compressive strength of NWC specimens was about 26.8 MPa. The compressive strength of LWC and SLWC specimens could reach up to 74% and 82.8%, respectively, of that of NWC. Similarly, the 28-day average compressive strength of NWC specimens was about 37.9 MPa whereas the LWC and SLWC specimens gained a compressive strength of 78% and 86.1%, respectively, of that of NWC. The higher compressive strength development in SLWC compared to LWC is attributed to the pozzolanic or secondary hydration reaction of silica fume which enables formation of extra C-S-H gel. This argument is in agreement with other studies wherein pulse velocity was used as an indicator of the density and microstructure of the concrete (Khan *et al*. 2021, Nasir *et al*. 2016). However, in those studies, a 28-day compressive strength of NWC and SF-based NWC was 47.1 and 50.4 MPa, respectively. The results of this study indicate that the scoria light weight aggregates can be used in the production of structural lightweight concrete in Saudi Arabia. For structural applications requiring

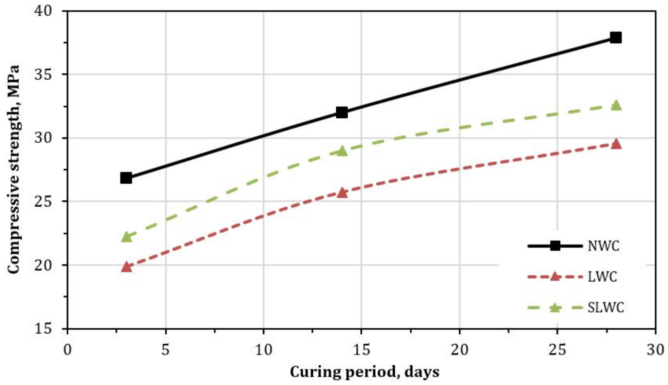

Fig. 4 Compressive strength development in SLWC and LWC specimens

medium compressive strength, LWC can be used by incorporating OPC-alone. However, for structural applications requiring high compressive strength, 7% blend of silica fume could be used.

4.4 Pulse velocity

Fig. 5 shows the development of ultrasonic pulse velocity in all concrete specimens. It is reported that the pulse velocity values highly depend on the mix constituent and exposure conditions (Tchamdjou *et al*. 2018). The pulse velocity also increased with age in all concrete specimens of the present study. The 3-day average pulse velocity of NWC specimens was about 4605 m/s whereas the LWC and SLWC specimens gained 86% and 92.7%, respectively, of that of NWC. Likewise, the 28-day average pulse velocity in NWC specimens was about 4765 m/s whereas the LWC and SLWC specimens gained 89.5% and 95.3%, respectively, of that of NWC. The trend of pulse velocities in all types of concretes is similar to that evident in the compression test data, which validates both the test results. The high pulse velocity in the SLWC compared to LWC also affirms that the pores were filled by the finer silica fume particles and the gel products. By observing the comparable pulse velocities of NWC and SLWC at 28-day, it can be posited that the microstructure of both the specimens would have significantly densified. Therefore, the scoria

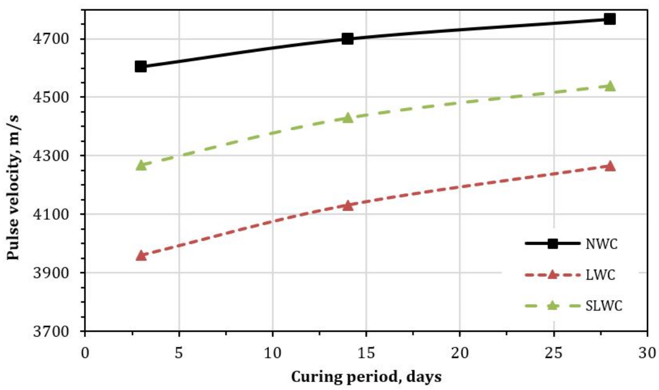

Fig. 5 Pulse velocity development in SLWC and LWC specimens

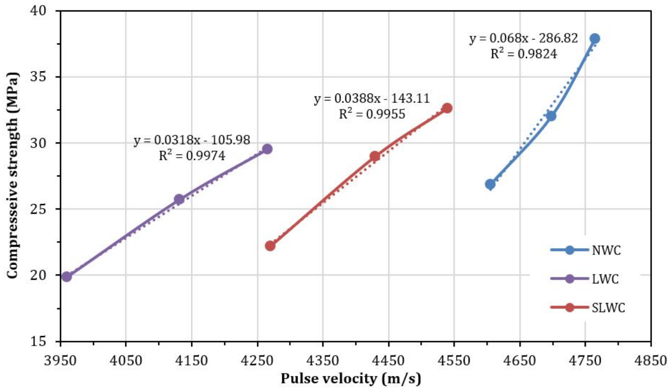

Fig. 6 Compressive strength vs pulse velocity after 28 days of curing

can be beneficially valorized by SLWC ascribed to its pore-filling and crack-bridging capabilities leading to higher strength development with respect to LWC counterpart.

4.5 Rebound number

Digital Schmidt hammer was used to determine the rebound number of hardened concretes after 28 days of water curing. The average rebound number in NWC was noted to be 30 while it was 24 and 28 in LWC and SLWC specimens, respectively. This further strengthen the contentions derived from the compressive strength and pulse velocity data.

4.6 Relationship between compressive strength and pulse velocity

Correlation equations have been developed between the destructive compressive strength and non-destructive pulse velocity data among NWC, LWC and SLWC. The R^2 value was found to be more than 0.9 indicating an excellent correlation, as shown in Fig. 6. Three empirical formulas (1), (2) and (3) were developed to predict the compressive strength based on ultrasonic pulse velocity test. These linear statistical relationships will offer the concrete technologists to predict the compressive strength of concrete based on the non-destructive pulse velocity test provided that the specimens are prepared in same conditions and having same mix proportions and material characteristics. These numerical relationships are user-friendly and more accurate as compared to those employing artificial intelligence (AI) or second-order models (R-square value in the range of 0.87 – 0.98) in the literature (Khan *et al*. 2021, Nasir *et al*. 2020).

$$f_c' = 0.068\,V - 286.82\,MPa \quad for \quad SLWC \tag{1}$$

$$f_c' = 0.0388\,V - 143.11\,MPa \quad for \quad LWC \tag{2}$$

$$f_c' = 0.0318V - 105.98\,MPa \quad for \quad NWC \tag{3}$$

4.7 Modulus of elasticity

Modulus of elasticity is one of the most important characteristics of concrete. The modulus of elasticity of the NWC, SLWC and LWC was calculated in accordance with the ACI recommendations. All the normal weight and lightweight concretes follow the ACI 318M-14 empirical formula in section 19.2.2.1a due to its applicability for the density ranging between 1440 and 2560 kg/m^3 (ACI Committee 2014). The formula in SI unit (Ali 2018; Moravia 2010) proposed by the ACI 318M-14 is mentioned in Eq. (4). Such relationship seems to be suitable as it offers the modulus of elasticity of concrete from the concrete compressive strength as well as the material density, which is a vital property for light weight concrete.

$$E_c = 0.043 * {\rho_c}^{1.5} * \sqrt{{f_c}'} \tag{4}$$

Where ρ_c is the density in kg/m^3 and ${f_c}'$ is compressive strength of concrete in MPa give the value of modulus of elasticity, E_c in MPa. The NWC has shown the modulus of elasticity as 30291 MPa. However, the elastic modulus of SLWC and LWC are found as 21141 MPa and 18584 MPa, respectively. Thus, the value of E_c reduces to 69.80% and 61.35% for corresponding SLWC and LWC as per the materials used.

4.8 SWOT analysis

This study adopts the renowned SWOT analysis technique in which the strengths, weaknesses, opportunities, and threats factors were examined and utilized to provide comprehensive insight for adopting lightweight concrete as an alternative to the normal weight concrete in the construction sector (Fig. 7). The authors recently published SWOT analysis of cementitious material (Nasir *et al*. 2021), however, such analysis for aggregates was not reported, hitherto. The technique was also used to develop effective strategies for promoting the implementation of lightweight concrete. The SWOT analysis was adopted for this study ahead of similar analyses like PEST (Political,

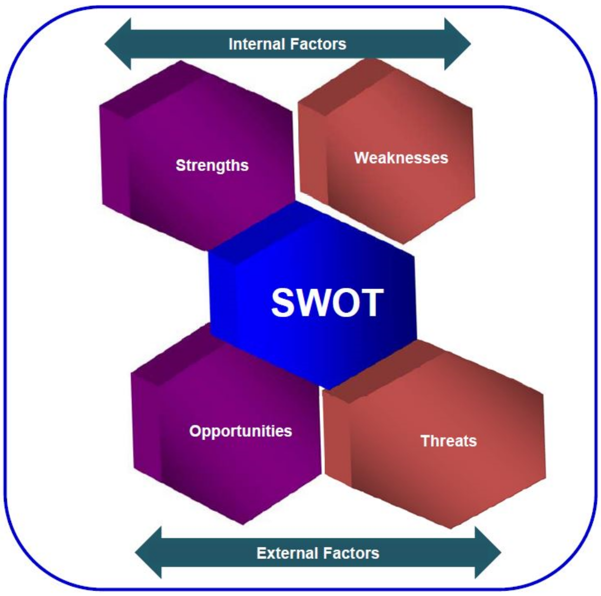

Fig. 7 SWOT analysis technique

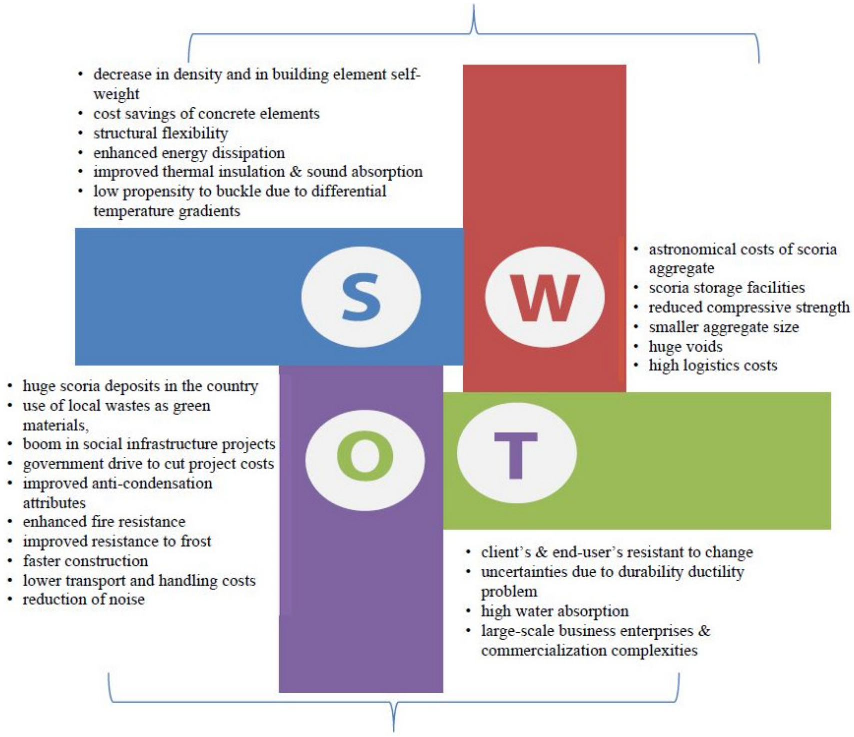

Fig. 8 Outcomes of the SWOT Analysis

Economic, Social and Technological) and RBV (Resource-Based View) analyses considering its intertwined interplay of the internal and external factors (Bell and Rochford 2016, Jiang *et al*. 2018).

4.8.1 Outcomes of the SWOT analysis

The outcomes of the SWOT analysis as presented in Fig. 8 were categorized basically into two, the internal and external factors. The internal factors captured the strengths and weakness that affect the production and use of lightweight concrete are investigated using the SWOT analysis. Conversely, the external factors predominantly focused on the opportunities and threats that influence the production and adoption of lightweight concrete as green construction material.

4.8.1.1 The internal factors

The findings of the analysis reveal that "substantial decrease in density and in building element self-weight", "cost savings of concrete elements", "structural flexibility", "enhanced energy dissipation", "improved thermal insulation and sound absorption", and "low propensity to buckle due to differential temperature gradients" are the major factors that strengthen the adoption of lightweight concrete. In essence, these factors are considered the primary enablers that can substantially help to promote the production and adoption of lightweight concrete in sustainable construction. On the other hand, the key factors that characterize the weaknesses of lightweight concrete adoption were equally investigated. These factors include "high logistics costs for distributing the aggregates across different regions in Saudi Arabia", "astronomical costs of scoria aggregate", "scoria storage facilities", "reduced compressive strength", "smaller aggregate size", and "huge voids". These weaknesses present formidable constraints to the production and adoption of lightweight concrete as green construction material. These constraints must be overcome by policy makers, practitioners, and all other key stakeholders in the industry in order to reap the full potentials of using the green building material and ensure its full utilization across the construction industry.

4.8.1.2 The external factors

The results of the SWOT analysis further indicated the opportunities and threats that influence the adoption of lightweight concrete as green construction material. These opportunities and threats are known as the external factors. The opportunities simply refer to the driving factors that support the production and adoption of lightweight concrete as green construction material. Thus, this technique was deployed to investigate the opportunities that abound the implementation of lightweight concrete as an alternative to the normal weight concrete in the construction sector. Prominent among these opportunity factors are "the use of local wastes as green materials, "boom in social infrastructure projects", "huge scoria deposits in the country", "government drive to cut project costs", "improved anti-condensation attributes", "enhanced fire resistance", "improved resistance to frost", "faster construction", "lower transport and handling costs" and "reduction of noise", among others. In contrast, threat related factors like "client's and end-user's resistant to change", "uncertainties due to durability", "ductility problem", "high water absorption", and "large-scale business enterprises and commercialization complexities" were similarly examined to ascertain the critical barriers that impeded the production and use of lightweight concrete as an alternative green construction material to the normal weight concrete.

Remarkably, the outcomes of the SWOT analysis have indicated that the factors related to strengths and opportunities are helpful in promoting the production and adoption of lightweight concrete as green construction material in the construction while the weaknesses and threats related factors seek to impede the successful production and adoption of lightweight concrete in sustainable construction. The practical implication of these findings is that policymakers, regulatory authorities, and practitioners are expected to pay close attention to these factors and establish policies and strategies that will overcome weakness and threats in order to encourage full utilization of lightweight concrete as green construction material.

4.9 Estimate of material costs

A salient goal of this paper is to ascertain the potential of utilizing lightweight concrete as a sustainable and eco-friendly alternative to the conventional normal weight concrete. Accordingly, it became vital to identify the main differences between normal weight concrete and the lightweight concrete with respect to cost, reactions, and design. Therefore, detailed specifications were adopted and used for each type of concrete. The detailed estimate of the required materials needs high degree of accuracy and inclusiveness. This is essential to ensure professional accountability of the cost estimator as well as reliability and validity of the estimate provided. The quantities of material to produce both lightweight concrete and normal weight concrete were obtained using the quantity take-off technique. The quantities of materials for this project were precisely calculated and presented in Table 5.

The quantity, unit, rates (in local currency and USD), and total amount of the constituent materials used for all mixes adopted namely, NWC, LWC, and SLWC were clearly provided in

Table 5 Comparison of the cost estimate for the various concrete mixes

Mix	Material	Quantity	Unit	Rate (SR/Kg)	Rate ($/Kg)	Amount	
						SR/m^3	US $/m^3
NWC	Cement	466.6	kg/m^3	0.34	0.091	158.644	42.4606
	Coarse aggregate (Gravel)	933.4	kg/m^3	0.25	0.067	233.35	62.5378
	Fine aggregate (Sand)	685.5	kg/m^3	0.15	0.040	102.825	27.42
						494.819	**132.4184**
LWC	Cement	567.4	kg/m^3	0.34	0.09	192.92	51.6334
	Coarse aggregate (Scoria)	367.8	kg/m^3	0.30	0.08	110.34	29.424
	Fine aggregate (Sand)	1003.4	kg/m^3	0.15	0.04	150.51	40.136
						453.77	**121.1934**
SLWC	Cement	527.7	kg/m^3	0.34	0.09	179.42	47.493
	Silica fume	39.7	kg/m^3	1.10	0.29	43.67	11.513
	Coarse aggregate (Scoria)	367.8	kg/m^3	0.30	0.08	110.34	29.424
	Fine aggregate (Sand)	1003.4	kg/m^3	0.15	0.04	150.51	40.136
						483.94	**128.566**

Table 5. As expected, the cost of SLWC mix is relatively 2.2% lower than the NWC despite the additional cost of using silica fume in the mix. This is remarkable because the addition of the silica fume reduced the cost of the SLWC mix while increasing the tensile, compressive and flexure strengths. Another notable result of the cost estimate and analysis is related to the cost of the LWC, which is considerably lower than the NWC by 8.3%. This was made possible by replacing the gravels (coarse aggregates) used in NWC with the locally available scoria in the LWC mix. It should be noted that while the estimate of materials required for this research involves the estimation of materials for both the lightweight concrete and normal weight concrete, this paper emphasizes on estimates obtained from the laboratory experiments.

5. Conclusions

This study presents the production of light weight concrete (LWC and SLWC) by using scoria aggregate. The performance of LWC and SLWC was compared with the NWC. The following conclusions have been drawn from the present study:

- ❑ A reduction of 15% in density was observed using scoria based LWC as compared to the limestone based NWC. This is encouraging finding in minimizing the self-weight of the structure on poor bearing capacity soil.
- ❑ In case of LWC, a slump of 50 mm was noticed with 1% superplasticizer by the weight of cement whereas NWC showed a similar workability using 0.5% plasticizer.
- ❑ The compressive strength of NWC of 3 to 28-day was in the range of 26 to 38 MPa. Incorporation of LWC and SLWC can yield up to 78 and 86% of the control NWC.
- ❑ The usage of silica fume based SLWC has potential to gain high strength development attributed to the pozzolanic or secondary hydration reaction which enables formation of

extra C-S-H gel. The comparable pulse velocities of NWC and SLWC revealed that the microstructural densification of both specimens would be same since the silica fume imparts pore-filling and crack-bridging capabilities.

- ❑ The results of non-destructive Schmidt hammer and pulse velocity tests affirm the findings of compressive strength data.
- ❑ An excellent correlation was found among the destructive compressive strength and non-destructive ultrasonic pulse velocity of all types of concrete having R-square value of more than 0.9.
- ❑ It is postulated that for structural applications requiring medium compressive strength, LWC can be used by incorporating OPC-alone, however, for structural applications requiring high compressive strength, 7% blend of silica fume could be used. The SLWC effectively valorizes the natural and industrial wastes such as scoria and silica fume leading to a sustainable construction.
- ❑ The cost of the LWC notable decreases compared to NWC by 8.3%. Moreover, SLWC mix reduced the expenses by 2.2% despite the additional cost of using silica fume offering higher tensile, compressive and flexure strengths.

The following recommendations are made based on the experimental findings:

- ❑ Thorough study for enhancing LWC properties and obtaining its optimal mix design is essential to be carried out.
- ❑ Carry out other tests on the developed LWAC such as thermal conductivity and acoustic insulation properties.
- ❑ Comparative study between NWC and LWC for different structural systems, lateral loads, and high-rise building needs to be performed.

Acknowledgments

The authors are thankful to the Deanship of Scientific Research (DSR) (Project 2017-212-Eng), Imam Abdulrahman Bin Faisal University (IAU) for assisting in the study.

References

ACI Committee (2014), Building code requirements for structural concrete (ACI 318M-14) and commentary (ACI 318RM-14).

Ahmmad, R., Jumaat, M.Z., Bahri, S. and Islam, A.B.M.S. (2014), “Effect of water-cement ratios on oil palm shell (OPS) lightweight concrete for ecofriendly construction”, *Int. J. Adv. Comput. Sci. Applicat.*, **4**(4), 246-249.

Al-Azzawi, A.A. and Al-Aziz, M. (2018), “Behavior of reinforced lightweight aggregate concrete hollow-core slabs”, *Comput. Concrete*, *Int. J.*, **21**(2), 117-126. https://doi.org/10.12989/cac.2018.21.2.117

Ali, T.K.M. (2018), “Modulus of Elasticity of Lightweight Concrete Containing Different Ratios of PET as an Aggregate and Fiber”, *J. Mater. Eng. Struct.*, **5**(1), 51-72.

Al-Kutti, W., Saiful Islam, A.B.M. and Nasir, M. (2019a), “Potential use of date palm ash in cement-based materials”, *J. King Saud Univ. – Eng. Sci.*, **31**(1), 26-31. https://doi.org/10.1016/j.jksues.2017.01.004

Al-Kutti, W.A., Islam, A.B.M.S. and Nasir, M. (2019b), US Patent No. 10,221,097 B1, United States Patent & Trademark Office.

Bell, G.G. and Rochford, L. (2016), “Rediscovering SWOT’s integrative nature: A new understanding of an old framework", *Int. J. Manag. Edu.*, **14**(3), 310-326. https://doi.org/10.1016/j.ijme.2016.06.003

Bideci, A., Bideci, O.S., Oymael, S., Gultekin, A.H. and Yildirim, H. (2017), "Lightweight aggregates coated with colemanite", *Comput. Concrete*, *Int. J.*, **19**(5), 451-455. https://doi.org/10.12989/cac.2017.19.5.451

BS8110 (1997), Structural use of concrete, Part I: Code of practice for design and construction, British Standards Institution, UK.

Chandra, S. and Berntsson, L. (2002), *Lightweight Aggregate Concrete*, Elsevier.

Devi, K., Saini, B. and Aggarwal, P. (2018), "Effect of accelerators with waste material on the properties of cement paste and mortar", *Comput. Concrete*, *Int. J.*, **22**(2), 153-159. https://doi.org/10.12989/cac.2018.22.2.153

Düzgün, O.A., Gül, R. and Aydin, A.C. (2005), "Effect of steel fibers on the mechanical properties of natural lightweight aggregate concrete", *Mater. Lett.*, **59**(27), 3357-3363. https://doi.org/10.1016/j.matlet.2005.05.071

Fares, G., Alhozaimy, A., Al-Negheimish, A. and Alawad, O.A. (2014), "Effect of Powdered Scoria Rocks on the Fresh and Hardened Properties of High Performance Concrete", *Proceedings of ATINER's Conference Paper Series CIV2014-0974*.

Hosen, M.A., Jumaat, M.Z., Alengaram, U.J., Sulong, N.H.R. and Islam, A.B.M.S. (2019), "Structural performance of lightweight concrete beams strengthened with side-externally bonded reinforcement (S-EBR) technique using CFRP fabrics", *Compos. Part B*: *Eng.*, **176**, 107323. https://doi.org/10.1016/j.compositesb.2019.107323

Huda, M.N., Jumaat, M.Z., Islam, A.B.M.S. and Soeb, M.R. (2015), "Ductility Performnce of High Strength Lightweight Concrete Produced from a Mixture of Oil Palm Shell and Palm Oil Clinker", *Proceedings of First International Conference on Advances in Civil Infrastructure and Construction Materials*, MIST, Dhaka, Bangladesh.

Huda, M.N., Jumat, M.Z.B. and Islam, A.B.M.S. (2016), "Flexural performance of reinforced oil palm shell & palm oil clinker concrete (PSCC) beam", *Constr. Build. Mater.*, **127**, 18-25 http://doi.org/10.1016/j.conbuildmat.2016.09.106

Huda, M.N., Jumat, M.Z.B., Islam, A.B.M.S., Darain, K.M.U., Obaydullah, M. and Hosen, M.A. (2017), "Palm oil industry's bi-products as coarse aggregate in structural lightweight concrete", *Comput. Concrete*, *Int. J.*, **19**(5), 515-526. https://doi.org/10.12989/cac.2017.19.5.515

Islam, A. and Al-Kutti, W.A. (2018), "Seismic response variation of multistory base-isolated buildings applying lead rubber bearings", *Comput. Concrete*, *Int. J.*, **21**(5), 495-504. https://doi.org/10.12989/cac.2018.21.5.495

Islam, A.B.M.S., Al-Kutti, W., Alsaidan, M.N., Alharbi, F.S., Nasir, M. and Anwar, F. (2018a), "Potential of volcanic waste Scoria as an eco-friendly aggregate to produce Lightweight Concrete", *Proceedings of Smart Cities Symposium 2018*, Bahrain, April.

Islam, A.B.M.S., Al-Kutti, W., Nasir, M., Alharbi, F.S. and Alsaidan, M.N. (2018b), "Development of lightweight concrete using Saudi Scoria aggregate — A preliminary study", *Proceedings of the Smart Cities Symposium 2018*, Bahrain, April.

Jiang, R., Mao, C., Hou, L., Wu, C. and Tan, J. (2018), "A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation", *J. Cleaner Product.*, **173**, 225-234. https://doi.org/10.1016/j.jclepro.2017.06.147

Jumaat, M.Z., Alengaram, U.J., Ahmmad, R., Bahri, S. and Islam, A.B.M.S. (2015), "Characteristics of palm oil clinker as replacement for oil palm shell in lightweight concrete subjected to elevated temperature", *Constr. Build. Mater.*, **101, Part 1**, 942-951. http://doi.org/10.1016/j.conbuildmat.2015.10.104

Kazmi, Z.A. (2020), "Improvement in shear strength characteristics of desert sand using shredded plastic waste", *Geomech. Eng.*, *Int. J.*, **20**(6), 497-503. https://doi.org/10.12989/gae.2020.20.6.497

Kazmi, Z.A. and Sodangi, M. (2021), "Integrated Analysis of the Geotechnical Factors Impeding Sustainable Building Construction—The Case of the Eastern Province of Saudi Arabia", *Sustainability*, **13**(12), 6531. https://doi.org/10.3390/su13126531

Khan, M.U., Nasir, M., Al-Amoudi, O.S.B. and Maslehuddin, M. (2021), "Influence of in-situ casting temperature and curing regime on the properties of blended cement concretes under hot climatic conditions", *Constr. Build. Mater.*, **272**, 121865. https://doi.org/10.1016/j.conbuildmat.2020.121865

Lopez, M., Kurtis, K. and Kahn, L. (2006), "Pre-wetted lightweight coarse aggregate reduces long-term deformations of high-performance lightweight concrete", *ACI Special Publication*, **234**, 661-680.

Marthong, C. (2019), "Effect of waste cement bag fibers on the mechanical strength of concrete", *Adv. Mater. Res.*, **8**(2), 103-115. https://doi.org/10.12989/amr.2019.8.2.103

Mazloom, M. and Mahboubi, F. (2017), "Evaluating the settlement of lightweight coarse aggregate in self-compacting lightweight concrete", *Comput. Concrete*, *Int. J.*, **19**(2), 203-210. https://doi.org/10.12989/cac.2017.19.2.203

Mazloom, M., Homayooni, S.M. and Miri, S.M. (2018a), "Effect of rock flour type on rheology and strength of self-compacting lightweight concrete", *Comput. Concrete*, *Int. J.*, **21**(2), 199-207. https://doi.org/10.12989/cac.2018.21.2.199

Mazloom, M., Soltani, A., Karamloo, M., Hassanloo, A. and Ranjbar, A. (2018b), "Effects of silica fume, superplasticizer dosage and type of superplasticizer on the properties of normal and self-compacting concrete", *Adv. Mater. Res.*, *Int. J.*, **7**(1), 45-72. https://doi.org/10.12989/amr.2018.7.1.045

Mazloom, M., Tajar, S.F. and Mahboubi, F. (2020), "Long-term quality control of self-compacting semi-lightweight concrete using short-term compressive strength and combinatorial artificial neural networks", *Comput. Concrete*, *Int. J.*, **25**(5), 401-409. https://doi.org/10.12989/cac.2020.25.5.401

Moravia, W.G. (2010), "Efficiency factor and modulus of elasticity of lightweight concrete with expanded clay aggregate", *Revista IBRACON de estruturas e materiais*, **3**(2), 195-204. https://doi.org/10.1590/S1983-41952010000200005

Moufti, M., Sabtan, A., El-Mahdy, O. and Shehata, W. (2000), "Assessment of the industrial utilization of scoria materials in central Harrat Rahat, Saudi Arabia", *Eng. Geol.*, **57**(3), 155-162.

Nasir, M., Al-Amoudi, O.S.B., Al-Gahtani, H.J. and Maslehuddin, M. (2016), "Effect of casting temperature on strength and density of plain and blended cement concretes prepared and cured under hot weather conditions", *Constr. Build. Mater.*, **112**, 529-537. https://doi.org/10.1016/j.conbuildmat.2016.02.211

Nasir, M., Gazder, U., Maslehuddin, M., Al-Amoudi, O.S.B. and Syed, I.A. (2020), "Prediction of properties of concrete cured under hot weather using multivariate regression and ANN Models", *Arab. J. Sci. Eng.*, **45**(5), 4111-4123. https://doi.org/10.1007/s13369-020-04403-y

Nasir, M., Al-Kutti, W., Kayed, T.S., Adesina, A. and Chernykh, T. (2021), "Synthesis and SWOT analysis of date palm frond ash–Portland cement composites", *Environ. Sci. Pollut. Res.*, **28**, 45240-45252. https://doi.org/10.1007/s11356-021-13957-9

Palaskar, S.M. and Vesmawala, G.R. (2020), "Performance of concrete modified with SCBA and GGBFS subjected to elevated temperature", *Adv. Mater. Res.*, *Int. J.*, **9**(3), 203-218. https://doi.org/10.12989/amr.2020.9.3.203

Pardakhe, P.K. and Nalamwar, M.R. (2015), "Comparative study of R.C.C structure for earthquake load using light weight building material", *Int. Res. J. Eng. Technol.* (*IRJET*), **2**(4), 1341-1350.

Raithby, K. and Lydon, F. (1981), "Lightweight concrete in highway bridges", *Int. J. Cement Compos. Lightweight Concrete*, **3**(2), 133-146. https://doi.org/10.1016/0262-5075(81)90007-5

Sabtan, A. and Shehata, W. (2000), "Evaluation of engineering properties of scoria in central Harrat Rahat, Saudi Arabia", *Bull. Eng. Geol. Environ.*, **59**(3), 219-225. https://doi.org/10.1007/s100640000061

Saif, M., Mullick, P. and Imam, A. (2019), "Analysis and structural design of various turbine blades under variable conditions: A review", *Adv. Mater. Res.*, *Int. J.*, **8**(1), 11-24. https://doi.org/10.12989/amr.2019.8.1.011

Shannag, M.J. (2000), "High strength concrete containing natural pozzolan and silica fume", *Cement Concrete Compos.*, **22**(6), 399-406. http://doi.org/10.1016/S0958-9465(00)00037-8

Tang, C.-W. (2017), "Effect of presoaking degree of lightweight aggregate on the properties of lightweight aggregate concrete", *Comput. Concr*, **19**, 69-78. https://doi.org/10.12989/cac.2017.19.1.069

Tchamdjou, W.H.J., Cherradi, T., Abidi, M.L. and Pereira-de-Oliveira, L.A. (2018), "Mechanical properties of lightweight aggregates concrete made with cameroonian volcanic scoria: Destructive and non-

destructive characterization", *J. Build. Eng.*, **16**, 134-145. https://doi.org/10.1016/j.jobe.2018.01.003
Yaragal, S.C. and Ramanjaneyulu, S. (2016), "Exposure to elevated temperatures and cooled under different regimes–a study on polypropylene concrete", *Adv. Mater. Res., Int. J.*, **5**(1), 21-34. https://doi.org/10.12989/amr.2016.5.1.021
Zein-Alabideen, H. (2001), "Concrete in the hot and severe environment of the Arabian Gulf Region", *Proceedings of the 26th Conference on Our World in Concrete & Structures*, Singapore.

CC