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RESEARCH

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Seawater-Mixed Lightweight Aggregate Concretes with Dune Sand, Waste Glass and Nanosilica: Experimental and Life Cycle Analysis

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Abstract

The use of alternative and locally available materials is encouraged in the construction industry to improve its sustainability. Desert regions with shortages in freshwater and river sand as fine aggregates in concrete have to search for alternative materials such as seawater, dune sand, and waste glass powder to produce lightweight concretes. The potential negative effects of adding these alternative materials can be reduced by adding nanosilica to the cementitious system at very low quantities. This study evaluates the feasibility of using these alternative materials and nanosilica (NS) in producing lightweight aggregate concretes (LWACs). A systematic study was carried out to understand the synergistic effect of nanosilica and seawater in improving the hydration characteristics of the developed cementitious systems. Also, the effect of these alternative materials on the fresh properties of the cementitious system was assessed by slump flow tests. The evolution of compressive strength at early ages was investigated after 2, 7, and 28 days of moist curing and an improvement in the strength development in concretes with seawater was observed. Furthermore, the integrity of the developed LWACs was analyzed using oven-dry density, thermal conductivity, water porosity and shrinkage measurements. Moreover, the capillary porosity and sorptivity measurements revealed the denser microstructure in the nano-modified seawater lightweight concretes. In the end, the life-cycle assessment study calculated the benefit of alternative materials in terms of carbon footprint and water consumption. As an outcome, a sustainable solution for producing LWACs containing seawater, dune sand or glass powder was proposed.

Keywords Lightweight concrete, Dune sand, Waste glass, Seawater, Shrinkage, Life cycle assessment

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1 Introduction

Freshwater is one of the most precious resources available on Earth to sustain ecosystems, biodiversity, economies, and society. United Nations (UN)—Water policy brief states that "improving the resilience of freshwater ecosystems is essential" to adapt to climate change (UN-Water Expert group on Water and Climate change, UN Water Policy Brief—Climate change and Water, September, 2019). The utilization of water in every stage of concrete production makes it a vital resource in large quantities. In near future, water scarcity and footprint analysis indubitably could become crucial for sustainable construction, which is addressed in UN Sustainable Development Goals such as SDG11 and SDG12 with special attention in dry regions. Concrete production accounted for 9% of the total freshwater consumption for industrial purposes. Also, futuristic estimates claim that 75% of the concrete production shall occur in the regions expecting severe stress on freshwater availability by 2040 (Miller et al., 2018).

On other hand, many developing nations face the scarcity of river sand for construction activities as a major challenge as there is a rapid increase in demand due to infrastructure development activities and stringent regulations on mining on river beds (Ioannidou et al., 2020). Torres et al., 2017 highlighted that a faster rate of extraction and consumption of river sand for construction can endanger biodiversity as well as sustainable growth in developing nations. Countries in South-East Asia and Africa are developing fast and the future requirement of river sand for construction in these countries can be multiple times higher than their current extraction rates (Ioannidou et al., 2020). Freshwater and river sand shortages can be tackled by reducing wastage during consumption and identifying suitable alternatives for freshwater and river sand in concrete production (Wesley & Puffer, 2019).

Among the available alternatives, seawater can potentially replace freshwater in concrete production. Ancient Romans developed durable "Roman concretes" (opus caementicium) that have been standing for more than 2000 years by mixing lime, volcanic ash, and seawater (Jackson et al., 2013). Among the 17 countries facing extremely high water stress as listed by the Water Resources Institute (WRI), Australia, Indonesia, Saudi Arabia, and the United Arab Emirates demonstrated the potential of making reinforced concretes with seawater and fiber-reinforced polymer (FRP) rebars (Dhondy et al., 2019; Xiao et al., 2017; Younis et al., 2018). A denser and stronger binding medium was developed with the addition of seawater in concrete when compared to the addition of freshwater due to faster early-age hydration (Wang et al., 2018a). Cement pastes made with seawater can acquire a more refined pore structure than the concretes made with freshwater (Montanari et al., 2019). Seawater-mixed concrete (SWC) is reported to have a significantly higher compressive strength than normal water concretes until 28 days (Dhondy et al., 2019; Khatibmasjedi et al., 2020; Montanari et al., 2019). Despite the better performance exhibited by seawater concretes, the proposed limits on total chlorides and sulfates to be present in raw materials for concrete production by EN 1008 and several other national standards prohibit practicing engineers to use seawater as mixing water for casting reinforced concretes as a measure to mitigate embedded-steel corrosion. However, limited works were carried out on understanding the role of seawater in producing lightweight aggregate concretes (LWACs).

Over one-fifth of the Earth's land area is desert, and the availability of dune sand is widespread across the different continents. The use of dune sand for construction activities, mainly in concrete production, is common in Middle-East and other countries with an abundant desert cover. The partial replacement (i.e., 50%) of conventional river sand with dune sand did not exhibit any negative effects despite dune sand not meeting the requirements of standard gradation mentioned in ASTM C 33 (Al-Harthy et al., 2007; Kog, 2020). Hence, dune sand shall be used as a partial replacement for manufactured sand or river sand, and such combinations can be economical and sustainable (Al-Harthy et al., 2007).

Besides the usage of natural resources, significant attention has been paid to recycling of post-consumer wastes as potential sources of aggregates such as rubber (Fiore et al., 2014; Gregori et al., 2019; Sgobba et al., 2015), plastics (Skibicki et al., 2022) or glass (Skoczylas & Rucińska, 2020). In 2018, data from the United States (US) showed that only a quarter of waste glass was recycled and more than half of the total waste glass generated was dumped in landfill (https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data). The crushed waste glass consists of broken pieces of glass containers and window glasses. Previous research articles demonstrated the suitability of waste glass as a partial replacement for the clinker and aggregate fraction (Ahmad et al., 2022; Ismail & Al-Hashmi, 2009). Waste glass can be crushed and milled to particle sizes at the micron level to produce a reactive pozzolan that can be used as a replacement for cement up to 20% by its weight (Ismail & Al-Hashmi, 2009; Nassar & Soroushian, 2012). In general, partial replacement of clinker with waste glass at an optimum level could improve the mechanical properties and can decrease the slump values slightly without affecting the workability due to their physical, chemical and mineralogical characteristics (Ismail & Al-Hashmi, 2009; Małek et al., 2020).

The combination of seawater, dune sand, and waste glass can improve the sustainability of concrete production by lowering the negative environmental impacts of the depletion of natural resources such as freshwater and river sand. Beyond the technical feasibility of using these materials in terms of cement chemistry and concrete workability, the reinforced concretes made with seawater and corrosion-resistant reinforcement proved to be a cost-effective solution based on the life cycle cost analysis (Younis et al., 2018). The water footprint for producing concretes can be reduced by up to 80% using alternative aggregates and seawater (Arosio et al., 2019). Furthermore, concrete made with 20% weight replacement (wt%) of cement with waste glass could decrease the environmental impact associated with repairs and maintenance due to improved resistance to chloride ingress of waste glass concrete (Guignone et al., 2022). More studies are needed to investigate the potential of using seawater and dune sand in producing reinforced concrete structures. However, the long service life exhibited by the Roman concrete demonstrates the potential of seawater and pozzolanic materials in producing concretes for non-reinforced and non-structural elements through proper mix proportioning (Jackson et al., 2013).

Lightweight aggregate concretes (LWACs) are ideal for producing non-structural and non-reinforced insulating blocks in buildings that require low density, good thermal insulation, and a satisfactory strength-to-weight ratio (Cheng et al., 2018). Moreover, along with coarse lightweight aggregates very fine (narrow) fraction of sand is used to ensure the target density of LWAC. Therefore, seawater and dune sand can be utilized in the production of LWAC. Lynda Amel et al. (2017) stated that lightweight aggregate concrete with dune sand exhibited better thermal performance than conventional lightweight concrete. Also, the compressive strength of lightweight aggregates concrete mixed with seawater can be enhanced significantly due to the acceleration in cement hydration at an early age (Cheng et al., 2018). Furthermore, the addition of waste glass in LWAC as a partial replacement of cement up to 10 wt% exhibited a higher strength and better resistance against alkali-silica reaction (ASR) (Ducman et al., 2002; Hooi & Min, 2017).

To date, limited research articles are available on lightweight aggregate concrete made by combining seawater, dune sand, and waste glass compared to the works related to conventional concretes made with normal-weight aggregates. Therefore, this study aims to fill the gap in the knowledge and presents a comprehensive study on the development of sustainable LWAC. Besides these alternative resources, the addition of nanosilica was explored. Furthermore, a Life Cycle Assessment (LCA) was employed to evaluate environmental impacts and identify cost-cutting opportunities. The conventional Life Cycle Impact Assessment (LCIA) methods consider water consumption but not availability in a specific region. This study used the Available Water Remaining (AWARE) method to analyze water use, as recommended by the United Nations Environment Program (UNEP) (WULCA), and to determine the impact of replacing freshwater in concrete production with seawater on water scarcity footprint (WSF) (Boulay et al., 2018).

2 Research Significance

This study investigates the fresh, mechanical, durability, and environmental-related properties of LWACs produced with seawater, dune sand, glass powder, and nano-SiO_2. Evaluating the properties of the proposed LWACs with nanosilica is necessary to explore the possibilities of making non-structural components for construction applications. A thorough investigation of fresh, early-age hydration, thermal, mechanical, shrinkage, and transport properties of the proposed lightweight aggregate concrete was carried out in this study. Also, this study can provide additional knowledge towards the design of sustainable LWACs containing seawater and dune sand or waste glass with desirable performance in terms of workability, strength, and durability through the AWARE approach suggested by UNEP instead of using conventional LCIA method.

3 Materials and Mixture Design

3.1 Materials

CEM III/A 42.5 N-LH conforming to EN 197-1 provided by HeidelbergCement (Leimen, Germany). Due to high volume of blast furnace slag in the cement, the hydration rate and the total hydration heat can be lowered and hence potential of micro-cracking in LWAC can be mitigated. Table 1 provides the chemical composition and physical properties of the cement used in this study.

Expanded glass (Liaver), complying with EN 13055 provided by Liaver GmbH, Ilmenau, Germany, was used as a lightweight aggregate. Three fractions of lightweight aggregates were used: 0.5–1, 1–2, and 2–4 mm. The physical properties of the used aggregates are given in Table 2. Three different materials were used as fine aggregate with the size range between cement and lightweight aggregate to compare their influences on the materials properties of concrete. As a reference material, fine quartz sand with particles size < 0.5 mm provided by Quarzwerke Gruppe (Frechen, Germany) was used. For comparison purposes, dune sand and crushed soda-lime waste glass were used. Natural dune sand collected from Egypt (Eastern Sahara Desert) was sieved to obtain the aggregate fraction with a maximum particle size of 0.5 mm and was used in the mixes.

Fine crushed brown soda-lime beverage waste glass received from a local recycling company (Szczecin, Poland) was used. Before use, waste glass was washed, dried, and crushed into small fragments. Afterward, a disc mill was used to grind the crushed glass into the desired fraction < 0.5 mm. Fig. 1 presents the particle size distribution (PSD) of the used fine materials. The dune sand (d50 of 248 μm) was slightly finer than quartz sand (d50 of 308 μm). The highest finesses were observed for waste glass (d50 of 160 μm) due to the milling process.

Table 1 Chemical composition of the used cement

Material	SiO_2 [wt.%]	CaO [wt.%]	Fe_2O_3 [wt.%]	Al_2O_3 [wt.%]	MgO [wt.%]	K_2O [wt.%]	Na_2O [wt.%]	SO_3 [wt.%]	LOI [wt.%]	Blaine [m^2/kg]	Specific gravity [g/cm^3]
CEM III/A 42.5 N-LH	29.1	49.1	1.1	8.8	4.9	0.7	0.18	3.4	2.7	386.5	3.06

Table 2 Properties of the used lightweight aggregate and filler materials

Material	Particle density [kg/m^3]	Crushing resistance [N/mm^2]	Water absorption [wt.%]
Liaver 2–4 mm	320	> 2.2	14.4
Liaver 1–2 mm	350	> 2.4	15.8
Liaver 0.5–1 mm	420	> 2.9	15.4
Fine quartz sand (< 0.5 mm)	2640	–	0.6
Dune sand (< 0.5 mm)	2670	–	0.8
Fine crushed glass (< 0.5 mm)	2530	–	0.2

Fig. 2 shows the morphology of the fine aggregates in this study obtained using optical microscopy. Both quartz and dune sand aggregates have comparable morphology with a round or slightly elongated shape. On the contrary, waste glass aggregate has flat-needled, long, and elongated shape particles.

To overcome the possible reduction in strength due to lightweight aggregate, nanosilica (NS) was used as an admixture in 3 wt.% of cement. A commercially available colloidal nanosilica suspension by Levasil CB8 (Bohus, Sweden) with a density of 1.4 g/cm^3, solid content of 50 wt.% and particle size distribution shown in Fig. 1 was used. To ensure proper homogeneity of mixtures and prevent fresh material from segregation and bleeding, methyl hydroxyethyl cellulose (Tylose MH 15000 YP4, SE Tylose GmbH & Co. KG, Wiesbaden, Germany), stabilizer (viscosity-enhancing admixture) in powdered form was used. Furthermore, due to the high sensitivity of fresh mixture to vibration and compaction, a polycarboxylate ether superplasticizer (Sika Viscocrete 1051) with a density of 1.04 g/cm^3 conforming to EN 934-2 was included.

In this research, in addition to tap water conforming EN 1008, artificial seawater (35.0‰ of salinity), prepared according to ASTM D1141-98 with main components including NaCl (24.53 g/dm^3), $MgCl_2$ (5.20 g/dm^3), Na_2SO_4 (4.09 g/dm^3), $CaCl_2$ (1.16 g/dm^3) and KCl (0.695 g/dm^3) was used for producing LWACs.

3.2 Mix Design and Mixture Composition

This investigation studies the development and characteristics of sustainable non-structural lightweight aggregate concrete with a target density of 1000 kg/m^3 (oven-dry density) and self-leveling ability (consistency class of F4/F5 according to EN 206-1). To optimize a mixture with such low density, the content of lightweight aggregate with low density should be maximized and the matrix volume with high density should be minimized. Therefore, the dense particle-packing concept has been applied to ensure a concrete mixture with homogenous distribution of the particles. The proper packing of aggregate particles is achieved by minimizing the volume of gaps between aggregate particles to be filled with the paste. Andreasen and Andreasen (1930) formula has been applied to formulate the grading of solid materials with maximum packing density as follows (Eq. 1):

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q}, \quad (1)$$

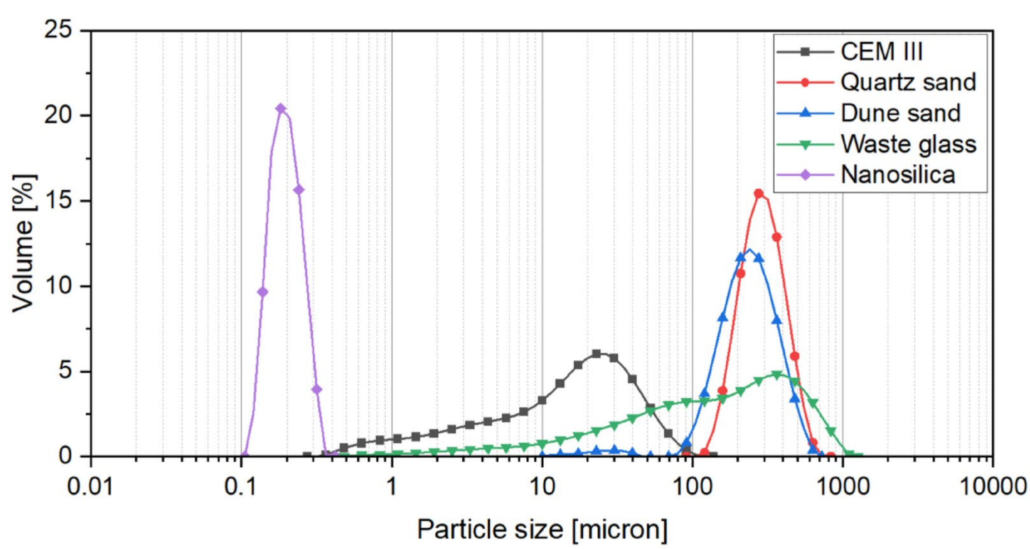

Fig. 1 Particle size distribution of the used fine materials

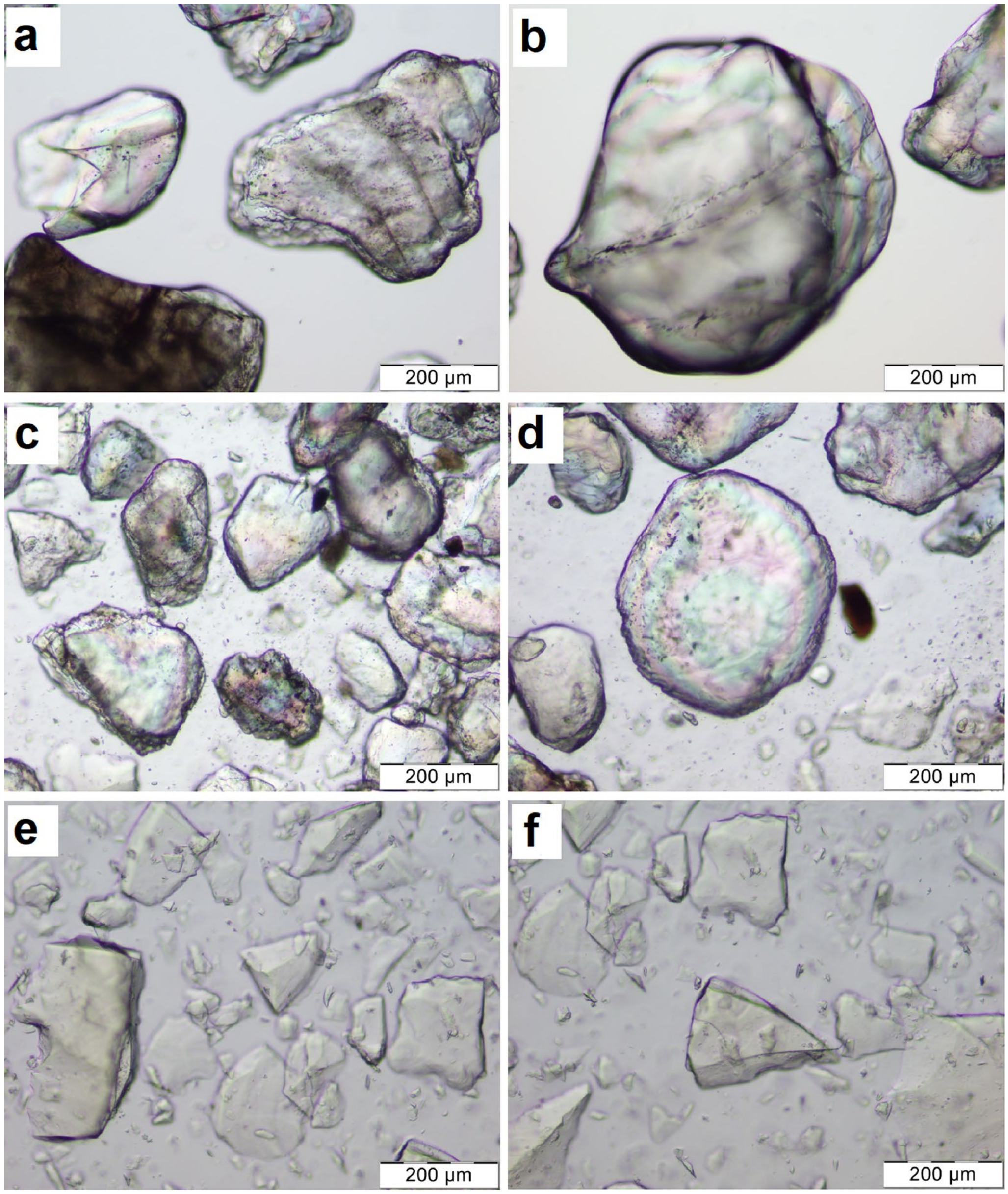

Fig. 2 Optical images of quartz sand (**a**-**b**), dune (desert) sand (**c**-**d**) and crushed glass (**e**–**f**)

where P(D): the total volume of particles passing through a sieve with size D, D_{max}: the maximum size of the particles, D_{min}: the minimum size of the particles, and q is the distribution factor (Abd Elrahman & Hillemeier, 2014).

To improve the strength and ensure better bonding between the binder and aggregates, colloidal nanosilica (NS) has been used with 3 wt.-% of cement (optimal content was determined in the previous study (Sikora et al., 2020a). For all mixtures, the aggregate grading is the same, and the binder content was kept constant at 500 kg/m^3 while the water–binder ratio (w/b) was fixed at 0.4. As NS was used in suspension form (50 wt.%), the mixing water was proportionally reduced to the amount of liquid content in the NS suspension. The stabilizer and superplasticizer contents have been adjusted during mixing to achieve a homogenous mixture with the appropriate consistency. The dosages of the chemical admixtures depend on the performance and characteristics of the concrete components as can be seen in Table 3. Due to the high capacity of water absorption of Liaver lightweight aggregates, the additional amount of water equals water absorption of aggregates has been added to the

Table 3 Composition of lightweight concrete mixes in kg/m^3

Mix	Cement	TW	SW	NS*	Liaver 0.5–1 mm	Liaver 1–2 mm	Liaver 2–4 mm	Quartz sand	Waste glass	Dune sand	SP	ST
QTW0	500	200		–	71.8	49.2	51	280	–	–	7.2	0.6
QSW0	500	–	200	–	71.8	49.2	51	280	–	–	8.4	0.6
QTW3	485	185	–	30	71.8	49.2	51	280	–	–	7.5	0.6
QSW3	485	–	185	30	71.8	49.2	51	280	–	–	9	0.3
GTW0	500	200	–	–	71.8	49.2	51	–	268	–	9.5	–
GSW0	500	–	200	–	71.8	49.2	51	–	268	–	10.8	–
GTW3	485	185	–	30	71.8	49.2	51	–	268	–	5	0.7
GSW3	485	–	185	30	71.8	49.2	51	–	268	–	6	0.7
DTW0	500	200	–	–	71.8	49.2	51	–	–	283	6	0.6
DSW0	500	–	200	–	71.8	51	51	–	–	283	6.5	0.5
DTW3	485	200	–	30	71.8	51	51	–	–	283	7.2	0.5
DSW3	485	–	200	30	71.8	51	51	–	–	283	7.5	0.5

TW tap water, *SW* seawater, *NS* nanosilica, *SP* superplasticizer, *ST* stabilizer

* nanosilica dispersion (50 wt.%); the water included in the NS dispersion is deducted from the mixing water

mixing water to prevent negative influences on concrete workability. Table 3 summarizes the mixture composition of the lightweight concretes in this study. Fig. 3 shows the graphical description of the framework adapted for providing designation to the mixtures in this study.

3.3 Sample Preparation

Twelve different lightweight concrete mixtures have been designed and prepared, as seen in Table 3. In the mixing process, a 60-L Zyklos concrete mixer (Pemat, Germany) has been implemented to mix the concrete components. The mixing procedure was as follows: (i) 30 s of dry mixing of lightweight aggregates, fine aggregate, and cement; (ii) addition of 2/3 of water (or water + NS) to the mixer and mix for 2 min; (iii) addition of superplasticizer and stabilizer with the rest of water to the mixer and mix for additional 2 min. After completing the mixing process, the fresh properties of the concrete were evaluated by measuring the diameter of the slump flow as specified in EN 12350-5. Afterward, the molds for hardened concrete tests were filled with fresh concrete without applying compaction energy or vibration. Concrete cubes with sizes 150 mm and 100 mm and prisms with dimensions of $40 \times 40 \times 160$ mm^3 were casted and demolded after 24 h. All concrete specimens have been cured in a controlled chamber with a temperature of 20 ± 1 °C and relative humidity of 99%.

3.4 Testing Methods

Section 3.4 summarizes the methodology of several tests carried out to assess lightweight concrete's physical properties, including isothermal calorimetry, dry-oven density, thermal conductivity, and drying shrinkage.

3.4.1 Calorimetry

The heat evolution rate of cementitious systems has been measured using TAM-Air (TA Instruments, USA) isothermal calorimeter with the external mixing procedure. For the measurement, a total of 12.6 g of cement paste containing 9 g of binder and 3.6 g of water was mixed using a vibration mixer and put immediately inside the calorimeter and the rate of hydration heat was measured

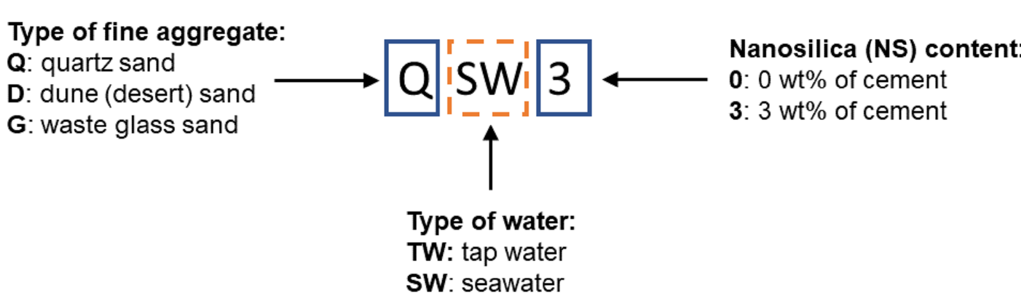

Fig. 3 Graphical description of specimens' designation

up to 168 h. The focus of this part is to compare the effect of the type of water and the presence of nanosilica on the hydration heat of cement pastes. Therefore, four specimens, including two cement pastes without nanosilica containing either tap water (TW0) or seawater (SW0) and two cement pastes containing 3 wt% of nanosilica with either tap water (TW3) or seawater (SW3), were evaluated.

3.4.2 Slump Flow Test

The slump flow test conforming to EN 12350-8 was used to assess the workability of the LWACs considered in this study. The freshly prepared concrete was filled in the Abrams cone placed on the steel platform. After filling the concrete, the surface was leveled and the Abrams cone was lifted to allow the concrete to freely spread on the surface of the platform. The spread diameter values of the LWAC mixtures were measured in two opposite directions and the average diameter of the spreading flow was reported for each mix.

3.4.3 Oven-Dry Density

After 28 days of curing, samples were taken for oven-dry density measurement as specified in EN 12390-7. Three cubical samples with an edge length of 150 mm from each mix have been dried at a temperature of 105 ± 5 °C till a constant mass. Then, the oven-dry density of each sample was calculated and the mean value of the three measurements was considered.

3.4.4 Thermal Conductivity

For thermal conductivity measurements, three concrete cubes with an edge length of 100 mm were dried completely till a constant mass between consecutive measurements was achieved and then, cooled down in moisture-free conditions to room temperature. After that, the Hot Disk TPS 2200 (Göteborg, Sweden), according to ISO 22007-2, was used to measure the thermal conductivity of the dried concrete samples using the transit plane source method (TPS). The measurements were carried out on three specimens, and the mean value was considered and reported in this investigation.

3.4.5 Drying Shrinkage

The Graff-Kauffmann method was used to measure the drying shrinkage in concretes according to DIN 52450. Three concrete prisms of dimension 40 × 40 × 160 mm were used in the measurement, which started directly after demolding and continued up to 28 d to initially assess the volumetric changes of different lightweight concrete mixes. The specimens were stored in the controlled temperature of 20 ± 1 °C and relative humidity of 65% throughout the test duration. The shrinkage measurements were carried out at 1, 2, 7, and 28 days.

3.4.6 Mechanical Properties

The compressive strength test was carried out on concrete cubes of edge length 100 mm according to EN 12390-3. Compressive strength was measured after 7 d and 28 d of curing using a standardized testing machine (Toni Technik, Berlin, Germany). In each test, three samples were tested, and the mean value was considered. The flexural strength test was performed on concrete prisms at 28 d according to EN 12390-5. The three-point bending method was applied to three samples and the mean value is considered in this investigation.

3.4.7 Transport Properties

In this investigation, open water porosity has been used to measure concrete porosity. It indicates the open (accessible) pores for water, which can be determined by the water displacement method (Abd Elrahman et al., 2019). To perform the measurement, concrete cubes with an edge length of 150 mm were immersed under water for more than 24 h until completely saturated (m_{sat}). Then the mass of saturated samples was measured under water (m_{sub}). The dry mass of the same sample has been determined after drying at 105±5°C till the specimen achieving a constant mass (m_{dry}). The open water porosity of the specimens was calculated using the equation given below (Eq. 2).

$$Open\ water\ porosity\ (\%) = \frac{m_{sat} - m_{dry}}{m_{sat} - m_{sub}} \times 100 \quad (2)$$

Moreover, according to EN ISO 15148, water sorptivity was tested by determining the increase in concrete mass (water uptake) by partial immersion up to 24 h. Three concrete samples from each mix were used and the measurement of mass increase was determined at different time intervals. From the differences in concrete masses with time, the water absorption coefficient of concrete has been calculated. Details of the measuring technique can be found elsewhere (Abd Elrahman et al., 2019).

3.5 LCA Methodology

Apart from desirable mechanical and durability characteristics, developing novel materials on an industrial scale requires an assessment of their environmental profile. The potential reduction in the environmental impact of the concrete mix designs was evaluated using the life-cycle assessment method in accordance with ISO 14040 (2006) and ISO 14044 (2006). Fig. 4 presents the procedure of LCA in this study.

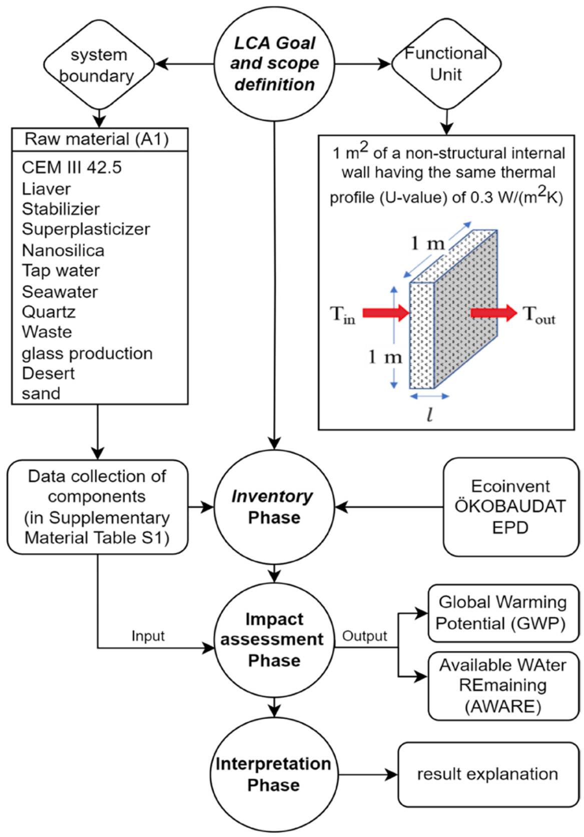

Fig. 4 The schematic figure for LCA in this study

3.5.1 Goal and Scope Definition

The primary goal of LCA as developed in this paper is to assess and compare the environmental impact of different mixtures for LWACs to produce non-reinforced insulating walls in buildings. The functional unit (FU) addressed in this research was 1 m^2 of a non-structural internal wall having the same thermal profile (Iuorio et al., 2019), and all the inputs and outputs are referred to the selected FU (Fig. 4). The wall thermal resistance for different mixtures in m^2K/W is calculated using the equation given below (Eq. 3) (Maddalena et al., 2018):

$$R = \frac{l}{\lambda}, \tag{3}$$

where l is the thickness of the material (m), and λ is the thermal conductivity ($Wm^{-1}\,K^{-1}$).

The minimum thickness of the wall was calculated to achieve a transmittance value (U-value) of 0.3 W/(m^2K) according to the UK building regulations standard (Maddalena et al., 2018), and the volume is adjusted accordingly for each mixture. A system boundary in this study is defined only for raw material (A1), which includes all processes and emissions from raw material extraction and processing. The information module of the raw material (A1) was assessed according to ISO 14025 (2006) and EN 15804:2012 + A2 (2019) to ensure that data harmonization approaches used in the construction sector are reflected. The analysis focuses solely on the raw material of the concrete mix designs, as this is the primary factor influencing the environmental impact of concrete mixtures. Therefore, other relevant life stages, such as the construction, use, end-of-life, and recycling stages, were not considered, as they have similar processes across all mixtures (EPD - InformationsZentrum Beton GmbH, 2018; Firdous et al., 2022; Nikravan et al., 2023).

3.5.2 Inventory Phase

The LCI (Life cycle inventory) phase quantifies all the unit processes' environmental inputs (energy and resources) and emissions (air, water, and soil) in a complete life cycle. The data collected for the LCI phase from the Ecoinvent and ÖKOBAUDAT databases, scientific literature, and industrial EPDs from companies. The cut-off modeling is used for Ecoinvent. Since the dune sand and seawater have been used in the mixture without any further processes and assumed to be locally available, both the dune sand and seawater are supposed to have no impacts. In addition, a widespread problem in nanomaterial LCAs is that detailed product system descriptions or emission inventories are not available for the nanomaterial (Alaviitala & Mattila, 2015) as well as well-known databases. So, the Environmental Product Declaration (EPD) report of the company has been employed to calculate the water consumption and carbon footprint for producing nanosilica. The life cycle inventory of components is provided in Additional file 1: Table S1.

3.5.3 Impact Assessment Phase

The LCA modeling was performed using openLCA modeling software (version 1.10.3). In that, two impact categories were evaluated in this study: Global Warming Potential (GWP) and Available WAter REmaining (AWARE). Global Warming Potential (GWP) 100a is a well-established methodology for calculating carbon emissions developed by the Intergovernmental Panel on Climate Change (IPCC). This study uses a time horizon of 100 years to assess the cumulative effects of GHG on the environment. For water use analysis, AWARE method was recommended by the United Nations Environment Programme (WULCA). AWARE was used to determine a catchment area's vulnerability to water stress and answer this question "What is the potential to deprive another user when using water in this region?" (Boulay et al., 2018). AMD (availability minus demand) is a variable that is used to calculate the characterization factors. It is composed of water availability minus human and environmental requirements in relation to the reference area (Boulay et al., 2018). Additionally, the AWARE characterization factor (CF) is inversely proportional to the remaining available water per unit of surface area and time in a region. The global average is consumption-weighted, and the indicator has a scale of 0.1–100. The value 1 denotes an area with the same amount of available water. The higher the AWARE scarcity index, the less available water in the country. For example, the CF value of 95.97 indicates that Egypt has 95.97 times less water than the global average (WULCA). Depending on the origin of products, CFs were adopted from the available online (www.wulca-waterlca.org) and scarcity footprint was calculated based on the following equation (Eq. 4) (Boulay et al., 2018):

$$\begin{aligned} &Water\ Scarcity\ Footprint\ \left(m^3_{waterequivalent}\right)\\ &= Water\ consumption\ inventory\ \left(m^3\right)\cdot CF_{AWARE} \end{aligned} \quad (4)$$

Finally, the direct consumption of water in mixtures and the indirect consumption of water from different life cycle stages were taken into account. Then, the total WSF was calculated as the sum of the water scarcity for all life cycle processes of every material considered. Since seawater has no AWARE characterization factor (Arosio et al., 2019), the water consumption used for mixtures with seawater had a water footprint solely due to other processes at different life cycle stages.

3.5.4 Interpretation Phase

This phase entails identifying significant issues, drawing conclusions, and making recommendations.

4 Results and Discussion

4.1 Calorimetry

Fig. 5 shows the heat of hydration at an instant and cumulative heat produced over a period of time (herein 168 h). Fig. 5a shows that the use of seawater increases the rate of hydration regardless of whether the samples were manufactured with NS (SW3) or without NS (SW0). In the case of paste without nanosilica (SW0), the inclusion of seawater accelerates the hydration rate and increases the peak height compared to paste with tap water (TW0). On the other hand, the addition of 3 wt% nanosilica has a significant influence on hydration heat rate and value at an early age. The combination of seawater and nanosilica (SW3) increases the value of the main silicate peak and accelerates the hydration process of the cementitious system. It is obvious from the results that the presence of seawater has a significant influence on accelerating the hydration, presumably due to the different cations in the seawater, which promote the hydration of cement at an early age (Sikora et al., 2020a). Therefore, more C-S-H is formed, and the setting time is shortened. With the addition of nanosilica, the rate of cement hydration is significantly increased due to the seeding effect of the silica nanoparticles leading to the formation of different hydration products. The presence of seawater accelerates cement hydration due to the existence of different cations, which accelerate the dissolution of C_3S (Ebead et al., 2022; Lu et al., 2021). Consequently, more calcium hydroxide (CH) is formed, which is consumed by nanosilica in the pozzolanic reaction to produce additional C-S-H. Based on the obtained experimental results, the use of seawater has an apparent influence on the rate of cement hydration at early ages and this effect is more noticeable by the incorporation of nanosilica.

Moreover, when compared to CEM I, blast-furnace slag cement (CEM III) could further accelerate the hydration process due to slag presence in the cementitious system (Ebead et al., 2022). A complex reaction between the Al-rich phases in slag and seawater can activate the slag, thus accelerating the hydration process of slag at an early age (Krivenko et al., 2022; Li et al., 2018a, 2018b). The second peak in the heat evolution process represents the acceleration effect in the results obtained from cement paste specimens mixed with seawater. The influence of acceleration in early age hydration of the proposed combination of materials on the other properties of the lightweight aggregate concretes are presented in upcoming sections.

The results of cumulative heat evaluation are presented in Fig. 5b. A discrepancy between cumulative heat values of pristine pastes and pastes containing nanosilica is visible. Due to the accelerating effect of nanosilica in the early stages of the hydration process, the 7 d cumulative heat values of TW3 and SW3 pastes were, respectively, ~6% and ~7% lower than the TW0 cement paste. On the contrary, SW0 exhibited comparable cumulative heat to that of TW0. The influence of water type on cumulative heat evolution is marginal. After 7 days, pastes with tap water and seawater exhibited comparable heat emission. However, at early ages, the influence of seawater is more pronounced since it accelerates the hydration rate as previously discussed.

4.2 Fresh Properties

Fig. 6 presents the experimental results of the flow diameter of different cementitious mixtures. QTW0 and QSW0 exhibited similar spread, and the seawater mix needs more superplasticizer to achieve this value (about 16% more than tap water). With the addition of nanosilica, a drop in the flow diameter took place, as

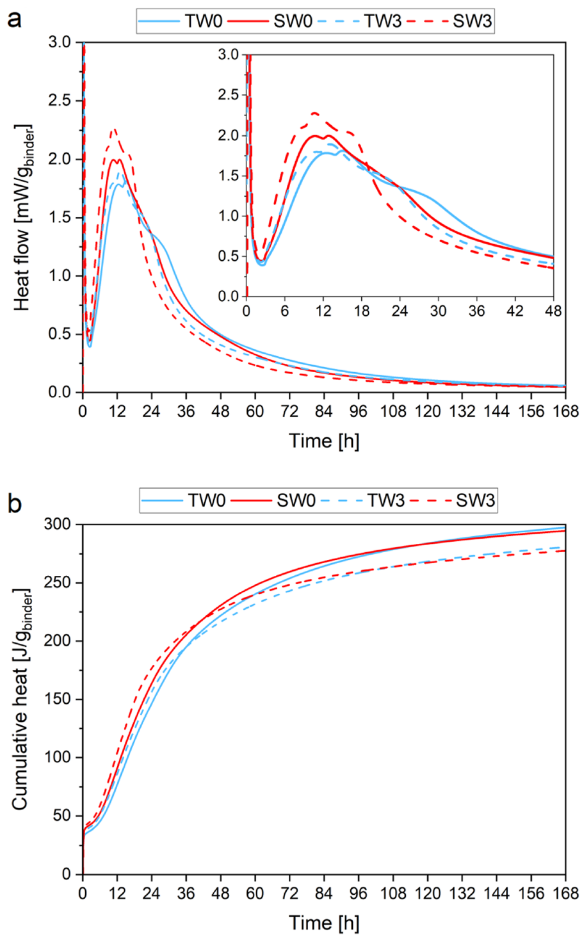

Fig. 5 Hydration heat (**a**) and cumulative heat (**b**) of cement pastes produced with and without seawater and nanosilica

can be recognized by comparing the results of QTW0 and QSW0 (without nanosilica) with that of QTW3 and QSW3. The role of the filler materials in the slump flow results is significant. Mixes prepared with finely crushed glass have slump values lower than reference mixes prepared with quartz sand though higher dosages of SP have been incorporated in mixes containing crushed glass. This can be attributed to the rough surface and angular shape of crushed glass particles compared to the spherical particles with a smooth surface in the case of dune sand (as shown in Fig. 2). On the other hand, the performance of dune sand is very similar to that of quartz sand. In all mixes, the addition of nanosilica resulted in a reduction in the workability of concrete. However, its performance depends a little bit on the type of water used: tap water or seawater, as well as on the type of filler material used. The use of seawater is similar to that of tap water in mixes without nanosilica addition. In contrast, with the addition of nanosilica, seawater mixes exhibited a slightly higher slump flow diameter in cases of quartz sand and finely crushed glass. Among the LWACs containing both dune sand and nanosilica, LWACs produced with seawater had a lesser slump flow diameter than the mix made with tap water.

4.3 Oven-Dry Density Results

Fig. 7 presents the experimental results of the measured oven-dry densities of different LWACs considered in this study. During the measurement, it was observed that the LWACs required more time than conventional concrete for complete drying due to the distribution of a high volume of pores with different sizes within the lightweight aggregate, which prolonged the drying process to achieve a constant mass (<0.2% wt.% between two measurements). The targeted theoretical density of LWAC in this study is 1000 kg/m^3 and as can be seen in Fig. 7, all mixes exhibited dry density in the range of 1000 ± 30 kg/m^3, which is in acceptable tolerance (up to ± 50 kg/m^3) (Abd Elrahman et al., 2021; Amran et al., 2015).

Fig. 7 shows the considerable influence of the type of fine aggregate on the dry density measurements. In the first four mixes prepared with quartz aggregate, the dry

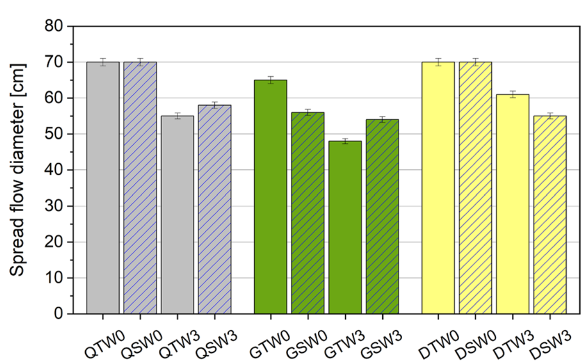

Fig. 6 Slump flow results of different concrete mixes according to EN 12350–5

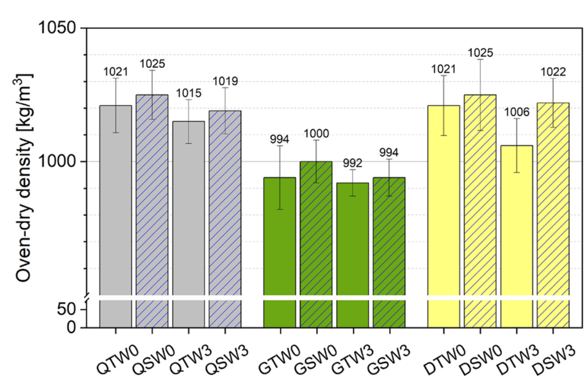

Fig. 7 Measured oven-dry density of different LWAC mixes

density is similar; however, in the group of mixes prepared with crushed glass, the dry density dropped. This can be attributed to the difference in the particle densities between quartz sand, crushed glass, and dune sand, as reported in Table 2. The effect of nanosilica on the dry densities is marginal as the amount of nanosilica is lesser than the amount of fine materials present in the concrete mixture. On the other hand, seawater-mixed concretes exhibited a marginally higher oven-dry density than the freshwater-mixed concrete in all LWAC groups since seawater has a higher density than freshwater due to the presence of salts or the higher degree of early-age hydration in seawater LWAC mixes.

Dry density is a material property that depends mainly on the volume of solid structure compared to the total volume of the sample. Hence, the influence of nanosilica and waste glass on the dry density variation in the concrete mixtures is secondary when compared to the effect of lightweight aggregate with low density occupying about 50% of the total volume of concrete, as reflected by the results reported in Fig. 7. The highest oven-dry density is recorded for mix QSW0 with 1025 kg/m^3, while the minimum dry density was for mix GTW3 with 991 kg/m^3; the difference is about 3.4%, which is rather not significant. From oven-dry density measurements, it is evident that all the LWAC mixes achieved the targeted design density of 1000 ± 50 kg/m^3 required for qualifying LWACs.

4.4 Thermal Conductivity

Fig. 8 shows the thermal conductivity (TC) values obtained for LWACs considered in this study. No substantial differences in the thermal conductivity of concrete specimens containing quartz and dune sand were reported and it could be attributed to the comparable density values of both, as reported in Table 2. Conversely, substantially lower thermal conductivity values were reported for mixes containing waste glass. GTW0 exhibited almost 30% lower TC when compared to QTW0. This effect is attributed to two phenomena (i) lower density of LWACs containing waste glass as aggregate when compared to LWACs with quartz/dune sand (Fig. 7), (ii) substantially lower thermal conductivity of waste glass aggregate when compared to quartz aggregates (Du et al., 2021; Sikora et al., 2017). Conforming to other literature findings (Federowicz et al., 2021; Sikora et al., 2020c), it was found that the introduction of nanosilica to the mix reduced the thermal conductivity values of LWAC; however, the effect is minimal. The influence of water type, either tap water or seawater, on TC was also found to be marginal.

4.5 Open Water Porosity

Open (capillary) water porosity is a method that measures the volume of open pores accessible for water. It gives a realistic indication of the possibility of water movement inside concrete similar to normal conditions. Fig. 9 presents the results of capillary water porosity measurement. Most of the pores in expanded glass do not contribute to the open water porosity since they are closed pores that are not accessible to water. The packing of fine materials and the microstructure of the cement matrix are the main parameters affecting the total porosity of concrete. Concrete open porosity is governed by the pore size, pore connectivity, and filling of pores with hydrated products. Clearly, the type of fine materials, quartz sand, dune sand or crushed glass, does not significantly influence concrete porosity. In all cases, porosity values were observed to be between 13 vol% and 16 vol%. Also, Fig. 9 shows that the inclusion of seawater resulted in a slight increase in open water porosity compared to mixes produced with tap water.

To date, very limited data on the effect of seawater on the open porosity of seawater-mixed concrete are available. According to available literature inclusion

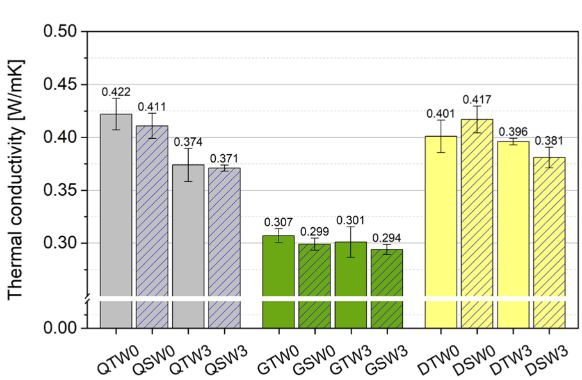

Fig. 8 Thermal conductivity of LWACs

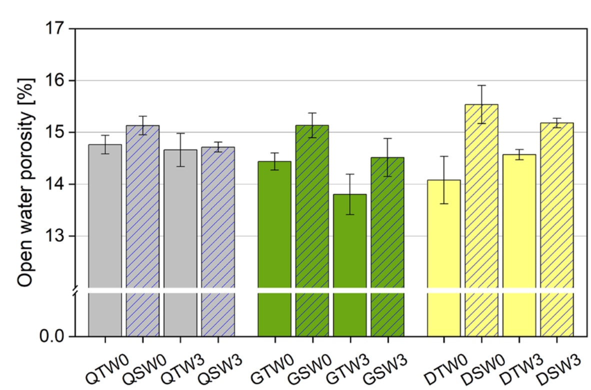

Fig. 9 Capillary water porosity of LWAC mixes

of seawater results in the refinement of pore structure and, thus, decreases the total porosity of the mixes (Ebead et al., 2022). A previous study by Sikora et al. (2020a) reported a negligible effect of seawater on the open porosity of conventional cement mortars. Mercury intrusion porosimetry (MIP) studies performed by Adiwijaya et al. (2017) on seawater-mixed granulated blast-furnace slag concrete showed that most of the seawater-mixed concrete exhibited lower porosity after 28 d and 365 d than their tap water-mixed counterparts. However, seawater-mixed concrete with a high water-to-binder ratio (w/b = 0.6) exhibited higher porosity than tap water-mixed concrete at age of 28 d.

Despite the small differences in open porosity, adding nanosilica can control the measured porosity values. It fills the pores between particles and forms additional C-S-H by consumption of CH in the pozzolanic reaction leading to the refinement of the pores and reducing the size of the coarse pores (Federowicz et al., 2021; Krivenko et al., 2019).

4.6 Sorptivity

Fig. 10 shows the water absorption coefficient of LWAC samples up to 24 h. Contrary to the results of water porosity, water sorptivity evaluations showed clear trends depending on the type of water and aggregate used. Inclusion of glass aggregate and dune aggregate results in a decrement in the water absorption coefficient of LWACs, which could be attributed to the lower absorption of these aggregates. In contrast, seawater incorporation has a significant effect on reducing the water absorption coefficient (sorptivity) compared to tap water. A similar observation was found previously by Sikora et al. (2020b). For example, for mix QTW0 prepared with tap water the absorption coefficient is ~ 0.1 kg/m^{2}h$^{0.5}$ while seawater-mixed LWAC (QSW0) exhibited the water absorption coefficient reduced to about 0.08 kg/m^{2}h$^{0.5}$ (about 20% decrease). For the mix prepared with crushed glass and tap water, the sorptivity was 0.85 kg/m^{2}h$^{0.5}$ and decreased to about 0.55 kg/m^{2}h$^{0.5}$ (about 35% reduction). Similarly, in mix SSW0, the sorptivity value is lower than in mix STW0 by about 30% due to the use of seawater.

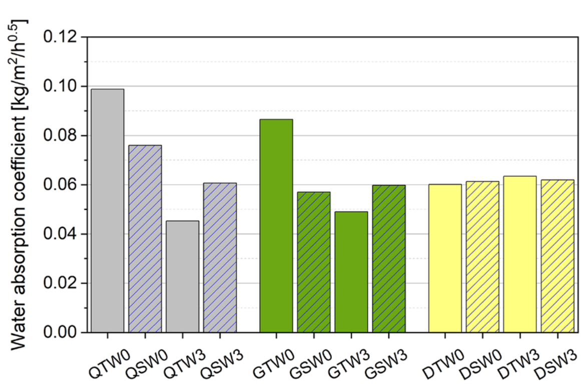

Fig. 10 Water absorption coefficient of different LWAC mixes

Nanomaterials addition is well-known to reduce the total porosity of concrete, as mentioned in the previous section. In this research, the dose of NS has been chosen as 3 wt%, based on previous experimental studies (Sikora et al., 2020a, 2020b, 2020c). The addition of nanomaterials can enhance cement hydration and produce more C-S-H to fill the voids and decrease the open porosity. Production of additional C-S-H with dense microstructure associated with consumption of CH characterized by porous microstructure leads to refinement of the pore structure, reducing the capillary pores volume and increasing the number of fine pores which will not participate in the transport of liquids and harmful substances into concrete. Besides the contribution of enhanced pozzolanic reaction to the refinement of pores, the inclusion of nanomaterials fills and blocks the connectivity of pores inside the concrete due to their sub-micron or nanoparticle sizes. The aforementioned physical and chemical effects of adding nanosilica to cementitious matrix can lead to a significant reduction in the water absorption coefficient, as revealed in Fig. 10.

4.7 Compressive Strength

Lightweight concrete is characterized by its low strength compared to conventional concrete due to its high volume of pores inside the aggregate, cement paste, or both. In this research, the high volume of pores comes from using lightweight aggregate with reduced density compared to normal-weight aggregate. It is clear from Fig. 11 that all mixes have compressive strength > 17 MPa at the age of 28 d. For the group of mixes prepared with quartz sand, seawater increases the early strength gain (2 d) compared to tap water. A ~ 13% compressive strength increment was reported in QSW0 when compared to QTW0. At 28 d, mix QSW0 exhibited around 10% higher compressive strength than the corresponding QTW0. The addition of nanosilica contributes to the improvement of compressive strength, at early ages. The addition of NS resulted in 7% higher compressive strength of QTW3 than QTW0. A combination of seawater and nanosilica exhibited higher performance regarding compressive strength at both early and later ages. The compressive strength of QSW3 was reported to be higher by ~ 15% at 2 d and ~ 19% at 28 d, when compared to the corresponding QSW0.

For other groups prepared with crushed glass and dune sand, the same trend can be noticed. Including nanosilica

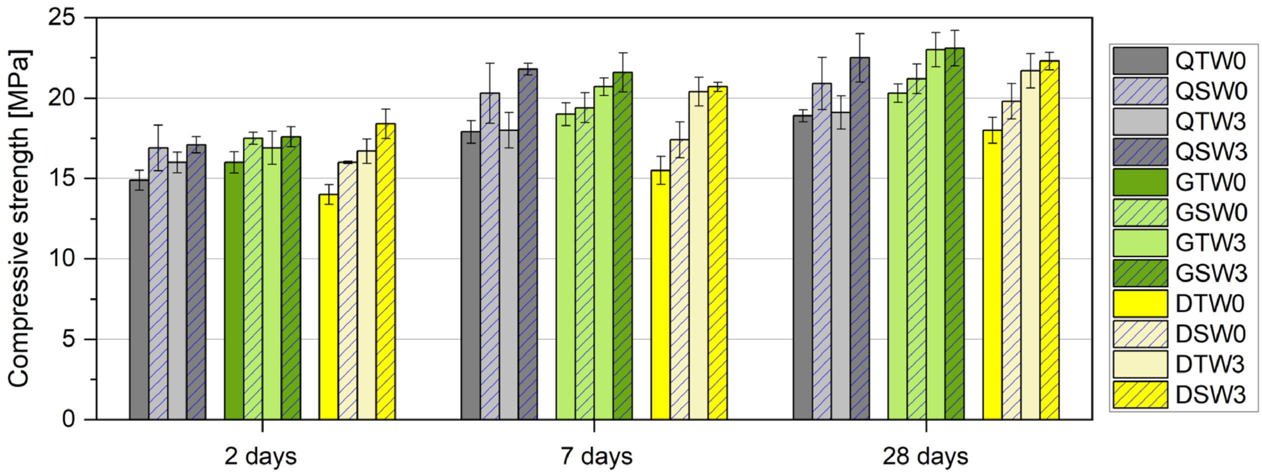

Fig. 11 Compressive strength development of LWACs

and replacing tap water with seawater improve the compressive strength at early and later ages. This finding corroborates well with the results of cement hydration obtained from the calorimetry. Regarding the fine aggregates, it is clear that both quartz sand and dune sand have a similar effect on the strength development of lightweight concrete in this study. Interestingly, the compressive strength results of mixes prepared with crushed glass are similar or even better than quartz sand and dune sand. The early age strength of the four mixes prepared with crushed glass is comparable to that prepared with either quartz sand or dune sand. Additionally, at 28 d, the compressive strength of lightweight aggregate incorporating crushed glass is the highest compared to other mixes. This can be attributed to the edged shape of the crushed glass particles, which increases the interlocking with other particles, increases friction and consequently improves the compressive strength of the lightweight aggregate concrete.

Beyond the improvement of strength at early ages, a good increase in strength was observed even at 28 d of curing. The continuous improvement in compressive strength development shall be attributed to the presence of slag in CEM III. Seawater activates the Al-rich slag phases to produce more hydration products and form a denser matrix due to continuous hydration (Etxeberria et al., 2016; Krivenko et al., 2021; Li et al., 2018a). Such reactions contribute to the increase in compressive strength in seawater concrete mixes even at 28 d of curing.

4.8 Drying Shrinkage

Fig. 12 presents the experimental results of drying shrinkage of LWACs after 2, 7, and 28 d. All concrete specimens were cured in a controlling chamber under the same temperature and humidity conditions. Gradual increment of drying shrinkage is reported along with age. The drying shrinkage strain measured at 7 d represents about 75% of

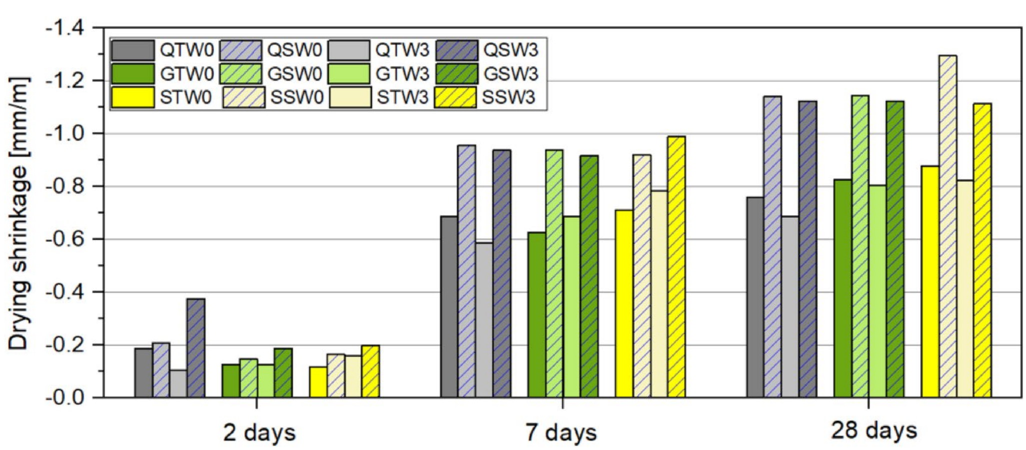

Fig. 12 Measured drying shrinkage of LWAC at different ages

the shrinkage at 28 d. For all mixes, the use of seawater resulted in higher drying shrinkage values than in corresponding mixes containing tap water. In general, the drying shrinkage strain values increased by 20% in seawater-mixed LWACs compared to tap water-mixed LWACs. The reason for that can be the presence of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) in the seawater, which influence the hydration rate of cement with water and consequently affect the volumetric changes of concrete in different ways. Also, the morphology of the pore structure could densify with the acceleration in the rate of hydration at an early age and, thus, increases the number of micropores in the cementitious matrix (Lun Lam et al., 2022). The presence of more micropores raises the capillary tension in the cementitious systems and, thus, results in higher shrinkage (Wang et al., 2018b). However, this increase in drying shrinkage reported at an early age between freshwater and seawater concrete gradually reduces with time and the difference between shrinkage measurements after 56 d of these two concretes is within 5% (Younis et al., 2019). Such inference is similar to the findings of Khatibmasjedi et al. (2019) which highlighted the synergetic effect of adding seawater and choosing a lower w/b ratio towards the limitation of shrinkage in cement-based composites at later ages.

Both waste glass and dune sand aggregates were found to have minor effects on the drying shrinkage of LWACs compared to LWACs containing quartz aggregate. Incorporating nanosilica into LWACs resulted in a noticeable decrement in drying shrinkage of LWACs, especially after 7 d and 28 d. Such reduction can be attributed to the enhancement in the impermeability of the interfacial transition zone and improvement in the bond between the cement matrix with the surrounding aggregate particles as a result of enhanced hydration. This reduces the moisture availability in the capillary pores and decreases the rate of moisture movement and consequently lowers the drying shrinkage values in LWACs with nanosilica (Farzadnia et al., 2015). Adding 3 wt% of nanosilica reduced the shrinkage of LWACs by more than 10%. Indeed, the addition of nanosilica has two contradictory influences regarding the volumetric changes of concrete. The first one is that it increases the hydration heat of cement due to the acceleration of the hydration rate, and thus can increase the drying shrinkage, which could explain the increase of drying shrinkage after 2 d. The second influence is mentioned above by improving the microstructure characteristics and reducing the easiness of water movement in the pore structure of concrete. The experimental drying shrinkage results prove that the secondary influence is more pronounced; therefore, the shrinkage values are decreased with the incorporation of nanosilica. These results agree with results published in the literature (Liu et al., 2020; Saleh et al., 2022; Wang et al., 2018b).

From the results, it is clear that shrinkage strains measured in the LWACs are greater (> 1.0 mm/m) than the typical strains observed in normal-weight concretes (Reichard, 1964). Recent research work also highlighted this significant increase in the shrinkage strains in lightweight and ultra-lightweight aggregate concretes and attributed them to the small elastic modulus of LWA, higher water and total binder content in the mixes (Liu et al., 2020).

4.9 LCA Study Analysis

To compare the environmental impacts of mixes for the same FU, the amounts of each component are calculated and provided in Additional file 1: Table S2. The result shows that the use of waste glass decreased the thermal conductivity of concrete and consequently reduced the thickness of the wall required to achieve a specific transmittance value (U-value = 0.3).

Fig. 13 depicts the breakdown of GHG emissions over the life cycle for various mixtures. GWP has been decreased by 2–30% compared to the QTW0 mixture (reference), not only because of decreasing the cement content but also decreasing the required volume of FU. In this study, the Portland cement has a significant impact on the GWP in all mixtures which is between 83.8% in DTW0 and 73.0% in QSW3, having the highest and lowest contributions, respectively. This finding is consistent with Napolano et al. (2016), which estimates that cement contributes more than 60% of the GWP of lightweight concrete. The use of nanosilica reduces the carbon footprint of mixtures containing quartz sand, QTW3, and QTW3 by 5% and 6%, respectively. However, it had the opposite effect on other mixtures, owing to minor thermal conductivity improvements and intensive manufacturing GHG emissions. In addition, seawater consumption does not change the carbon footprint.

The water use profile calculated using the AWARE Method was 7.2 and 3.1 m^3 world equivalent/FU for QTW0 and GSW3, respectively, as shown in Fig. 14. Water used in the cement industry, nanosilica, and Liaver production account for the majority of indirect water consumption. When seawater is used instead of tap water for mixtures, water consumption is reduced by approximately 30%. GSW3 with seawater, waste glass, and nanosilica resulted in the best results, followed by GSW0 without nanosilica.

5 Summary of Results and Discussion

Seawater-mixed LWACs with waste glass, dune sand, and nanosilica demonstrates the possibility of producing more sustainable building materials with

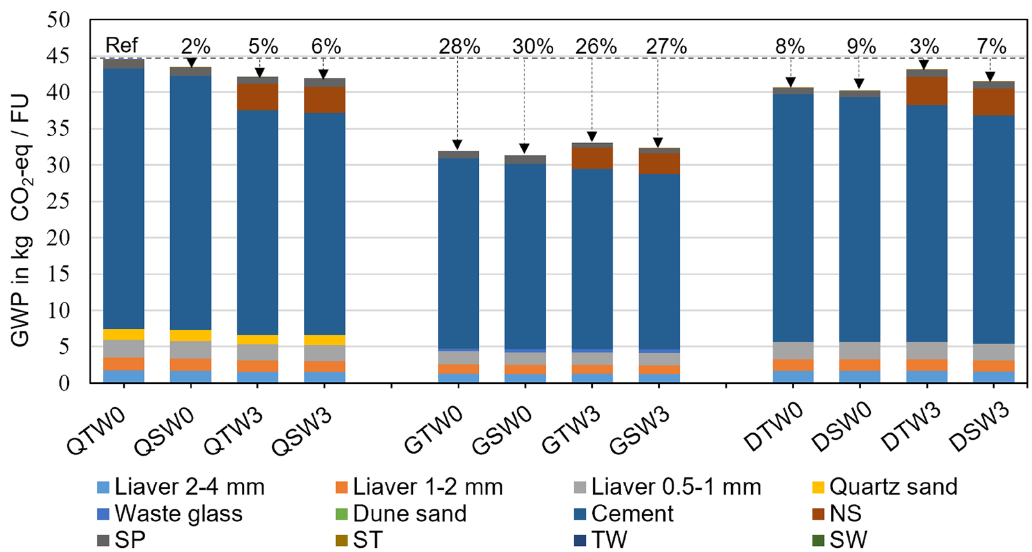

Fig. 13 GWP of LWAC mixes per FU

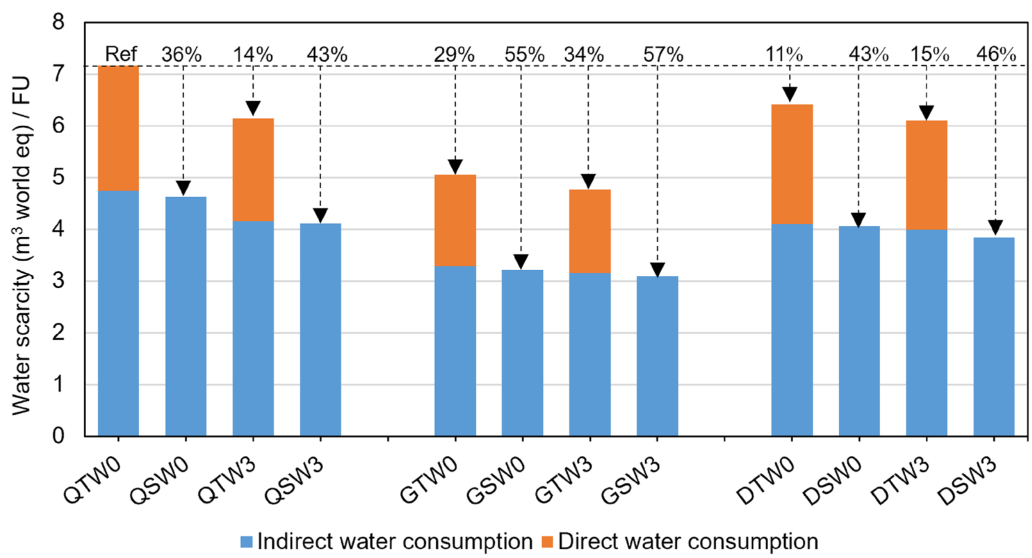

Fig. 14 Water footprint (AWARE) of LWAC mixes per FU

comparable (or even higher) performance than conventional LWAC. The heterogeneity of the LWAC leads to the two-way or three-way interaction effect on measured properties of the concrete and the results are summarized as follows. The dense packing concept adapted to produce LWAC was suitable to produce concretes with density lower than 1000 kg/m^3 and self-compacting ability. Also, the assessment of fresh properties reveals that the workability of the concrete does not significantly reduce with seawater mixing. However, a reduction in flow of LWACs was observed in the mixes substituted with nanosilica and crushed glass. The early-age strength of LWACs made with seawater increases significantly due to the combined effect of seawater and nanosilica contributing to the acceleration of cement hydration process. Furthermore, the acceleration in cement hydration refines the pore structure and hence, reduces the water sorptivity values of LWAC mixes with nanosilica.

The drying shrinkage values of LWACs with nanosilica and seawater observed to be lesser than LWAC with seawater alone. The addition of nanosilica compensated the increase in drying shrinkage of seawater-mixed LWAC and showed a net decrease in the final values. The physical properties of materials such as crushed glass and dune sand influences the oven-dry density and thermal conductivity of the developed LWACs mixed with seawater. LWACs made with crushed glass have lesser oven-dry density and thermal conductivity.

Finally, the environmental impact of LWACs made with dune sand, waste glass, seawater is much lesser than the conventional LWAC made with freshwater. The reduction in GWP of the developed seawater-mixed LWACs can be between 2 and 30% when compared to conventional LWACs. Similarly, the water footprint of these LWACs made with seawater, dune sand and waste glass can be less than 10% to 50% against the conventional LWACs with more water footprint.

6 Limitations and Way Forward

Sections 4 and 5 demonstrate the possibility of producing sustainable seawater-mixed LWACs having strength greater than 20 MPa and density less than 1000 kg/m^3 with waste glass or dune sand. In recent times, the countries with severe water-stress look for alternative sources of water and aggregates for construction. However, the field implementation of these novel LWACs requires necessary changes and amendments to the existing standards for producing building materials due to the limitations on the total solids content in mixing water. Furthermore, more research shall be carried out to understand the long-term strength and durability performance of these LWACs exposed to acidic, alkaline, and corrosive environments.

7 Conclusions

In conclusion, the feasibility of using seawater, dune sand and crushed glass in developing lightweight concrete with a density < 1000 kg/m^3 is demonstrated. The reduction in strength of LWACs with choice of low density aggregates was compensated with the addition of nanosilica and the refinement of pore structure with nanosilica addition was elucidated. Physical, mechanical, durability and environmental properties of the developed lightweight concrete were measured and evaluated to complete the picture of the possibility of replacing fresh water with seawater in developing sustainable lightweight concrete. LWAC with dune sand, waste glass and seawater could be an interesting alternative for producing non-structural building elements in the construction market of MENA countries.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40069-023-00613-4.

Additional file 1: Table S1. Life cycle inventory of components. **Table S2.** The amount of components for defined FU of LWACs mixes.

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Author contributions
PS: conceptualization, methodology, investigation, validation, visualization, formal analysis, data curation, writing—original draft, writing—review and editing, project administration, supervision. LA: conceptualization, investigation, validation, data curation, formal analysis, writing—original draft, writing—review and editing. SR: validation, visualization, writing—original draft, writing—review and editing, project administration. MN: methodology, investigation, validation, visualization, writing—review and editing. SYC: validation, writing—review and editing, DS: methodology, resources, writing—review and editing, funding acquisition, supervision. MAE: conceptualization, methodology, investigation, validation, formal analysis, data curation, writing—original draft, writing—review and editing, supervision. All authors read and approved the final manuscript.

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Availability of data and materials
The data presented in this study are available on request from the corresponding authors (P.S. and M.A.E.).

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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