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Effects of nano-silica on the gas permeability, durability and mechanical properties of high-strength lightweight concrete

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HIGHLIGHTS

- Lightweight coarse aggregate (LWA) has been produced by pelletization technique.
- LWA has been replaced with coarse natural aggregate at different levels.
- The negative properties of LWAs can be remedied by the addition of nS particles.
- nS particles give better performance results in conventional concretes than LWCs.
- The durability of HSLWCs has been improved significantly by using nS particles.

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ABSTRACT

This study presents an experimental investigation on the effect of nano-silica (nS) on the gas permeability, durability and mechanical properties of high strength lightweight concrete (HSLWC). In order to expose the effects of nS on the performance of concrete, the lightweight coarse aggregate (LWA) has been fabricated through cold bonded method by the pelletization process by mixing 10% of cement with 90% of fly ash (FA). Then, the utilization of HSLWCs has been finished off by volumetric substitution of normal coarse aggregate with 5 different levels, namely (0%, 10%, 20%, 30% and 40%) with and without nS at a constant water/binder ratio of 0.35 and a constant ratio of 20% of FA. The concrete has been tested at the age of 28 and 90 days for splitting tensile strength, sorptivity index, gas permeability and compressive strength as well as 3 and 7 days for compressive strength. It has been observed that the increase in the replacement of lightweight coarse aggregate affecting the strength and permeability properties negatively. On the other hand, the results indicate that the addition of 3% nS to HSLWCs reduce the negative properties of lightweight coarse aggregate and leads to remarkable increase in mechanical properties while the sorptivity and gas permeability values have been decreased up to 25% and 40% respectively, when the values compared with the same replacement levels of LWAs. Moreover, it has been found that nS particles have better results on normal concrete compared to the LWCs.

1. Introduction

Waste management is of great importance in the prevention and reduction of environmental pollution. To cope with this problem and reduce contamination, it is important to employ and recycle the waste in the building sector. About 19 M tons of fly ash (FA) production which was 3% of the world total, was realized in Turkey in 2012. It is estimated that the amount of FA would increase by 30% by 2020 [1,2]. Therefore, the production of artificial aggregates solves two problems, decreases the environmental pollution and prevents the depletion of natural resources through the creation of a lack of natural aggregates in building industry [3,4]. Cold bonded and sintering are two practical methods to produce lightweight aggregate FA. Less energy is used during the cold bonded method to make the pellets by agglomeration of fine particles depending on its pozzolanic reactivity of FA resulting in lower strength aggregate [5,6].

The lightweight aggregate utilization in concrete has many advantages [7–9]. These are summarized as;

– Reduce the amount of dead load that's lead to reduce the footing sizes and gets lighter and smaller upper structure.

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- Lighter weight and smaller precast elements, low cost of transportation.
- Reduction in sizes and dimensions of beams, columns, and slabs, larger flat area.
- High thermal efficiency.
- Enhanced resistance against fire [10].

The production and usage of LWA have many benefits;

- Effective recycling of FA.
- Conserve the natural materials (sand and coarse aggregate) which are found rarely in nature
- Protects the river bed, and beaches from scarring activities of aggregate mining.
- It is much lighter than the natural aggregate.
- Reduces the greenhouse gas emissions and specific energy consumption rates by reducing the need for the vast amount of cement which contributes majorly to carbon dioxide emissions [11,12].

High strength and high-performance concrete materials are used due to the aggressive environments that cause the premature deterioration of concrete structures. High-performance concrete (HPC) production is the best choice to produce a composite concrete characterized by its fine pore structure and low porosity that results in improvement in mechanical, transport and durability properties [13,14]. The mechanical properties and durability of HPC are mainly influenced by refining the hardened structure of the cement paste and enhancing paste-aggregate interface progressively by incorporating admixtures and additions [15,16]. There are many studies in the literature about the use of mineral admixtures to overcome and enhance the characteristics of concrete [17–19]. The addition of chemical and mineral admixtures to the conventional concrete leads to the emergence of new developments in the concrete related study to enhance the strength and durability [20].

Quing et al. [17] represented that nS is a quite effective in boosting strength, durability, and microstructure of cement paste when compared to the other traditional pozzolanic materials. There are many advantages of integrating nanotechnology into cement and concrete. It enhances the manufacture of cement, improves the properties of concrete, and revolutionizes the ability to monitor performance and has the ability to reduce permeability [21–23].

Li [24] reported that the FA has low initial activity but after using small amounts of nS, the pozzolanic activity notably increased and the reacts of nano-particles with calcium hydroxide crystals produce C-S-H gel resulting arrayed in the Interfacial transition zone (ITZ) between hardened cement paste and aggregate.

Beside strength appreciation, concrete deterioration is based on the difficulty to migrate the gas or liquid which migrate during the hardness process of concrete. As a result, the measurement of permeability provides an indication of the durability of concrete, for that reason the permeability is also called the key to durability [25,26]. The physical properties of concrete play a great role in a variety of processes of technological and environmental concern. Consequently, the permeability is very important for the structures under serious environmental and chemical effects [27,28]. In recent years, the gas permeability has been investigated by some researchers to estimate the pore structure and durability properties of concrete [29,30].

Du et al. [31] studied the effect of nS on mechanical and transport properties of LWA and they found the ITZ became denser and compact, the compressive strength increased and resistance to chloride ion and water has been improved with added 1% nS. Based on our search in the literature, this paper presents the first detailed experimental investigation about the effects of nS on the gas permeability, durability and mechanical properties of high strength lightweight concrete.

Within the scope of this study, the lightweight aggregate has been fabricated through cold bonded method by the pelletization process by mixing 10% of cement with 90% of FA. Then, the utilization of HSLWCs was finished off by volumetric substitution of normal coarse aggregate with 5 different levels, namely (0%, 10%, 20%, 30% and 40%) with and without nS at a constant water/binder ratio of 0.35 and a constant ratio of FA. The concrete was tested at the age of 28 and 90 days for splitting tensile strength, sorptivity index, gas permeability and compressive strength as well as 3 and 7 days for compressive strength only. This paper can contribute to a better understanding of the production of HSLWCs and parameters affecting its performance.

2. Experimental details and methodology

2.1. Materials

Through this study, a CEM I 42.5 R (TS EN 197-1:2012) ordinary Portland cement has been used to produce LWA with 10 different concrete mixtures. Class F of fly ash used in the production of LWA and concrete mix with respect to the requirements of Ref. [32]. nS with a specific area of 150 m2/g and high range water reducing admixtures (HRWRA) Glenium 51 with a specific gravity of 1.07 have been used in order to give all the mixes desired flowability. Table 1 shows the physical and chemical properties of materials used.

2.2. Aggregate

The LWA preparation consists of mixing, pelletizing and curing. The process begins by adding 90% of fly ash and 10% of cement to the total weight which is less than 10–13 kg as a dry powder. To ensure the homogeneity, the disk which has a pan diameter of 800 mm and depth of 350 mm was revived at a regular velocity and a slope angle. After that, water valve was operated to apply a water quantity at 18–20% of the total weight of powder materials. The total period for the pelletization process approach 20 min. It has been observed that the formation of the pellets occurred in the first 10 min at the moment of water spraying finished while the further time is necessary for sufficient stiffness.

The level of curing of LWAs must start at the end of pellets creation by conserving the fresh pellets for twenty-eight days in sealed bags at room temperature of 20 °C and relative humidity of 70%. The solidified LWA has been obtained at the end of the curing period. After that, the aggregate sieved to 4 to 16 mm to produce lightweight coarse aggregate which is used later to produce concrete. Fig 1 shows the production of LWAs.

Table 1
Chemical composition and physical properties of cementitious materials used.

Item	PC	FA	nS
CaO (%)	62.12	2.24	–
SiO_2 (%)	19.69	57.2	99.8
Al_2O_3 (%)	5.16	24.4	–
Fe_2O_3 (%)	2.88	7.1	–
MgO (%)	1.17	2.4	–
SO_3 (%)	2.63	0.29	–
K_2O (%)	0.88	3.37	–
Na_2O (%)	0.17	0.38	–
Loss on ignition (%)	2.99	1.52	≤1.0
Specific gravity	3.15	2.04	2.2
Blaine Fineness (m^2/kg)	394	379	–
Surface-volume ratio (m^2/g)	–	–	150 ± 15
Average primary particle size (nm)	–	–	14

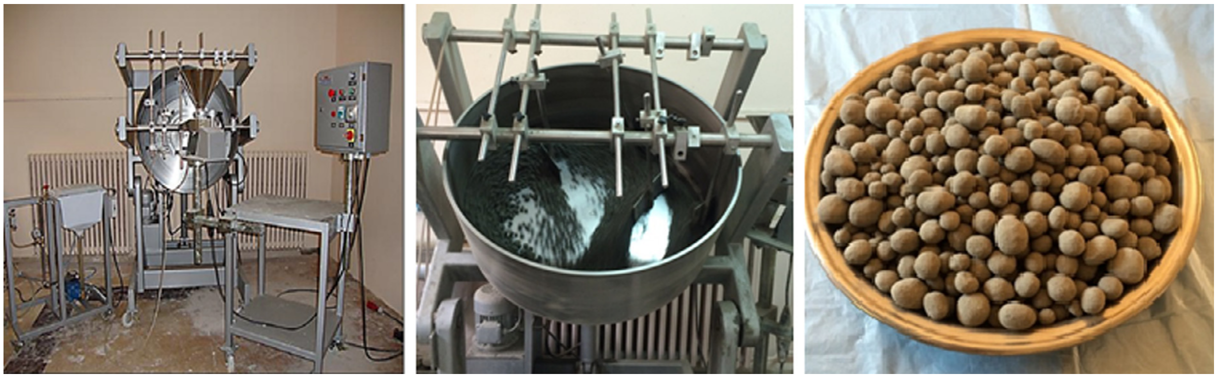

Fig. 1. Production of LWAs.

Physical properties of LWAs used in this study were carried out with respect to ASTM C 127 (TS EN 1097-6) [33]. The water absorption of LWAs for 24 h submerging in water was calculated to be 21.12% and specific gravity was found 1.64 g/cm^3 in saturated surface dry (SSD) conditions. Additionally, the crushing strength test of LWAs was performed as per BS 812, part 110 [34]. Individual pellets in different sizes from (4–14) mm were located between two parallel plates and the failure occurs when they loaded diametrically. Fig. 2 shows the crushing strength results of LWAs.

River gravel and river sand have been used as coarse and fine aggregate material which have specific gravity values of 2.67 and 2.7 for gravel and sand, respectively. Fig. 3 shows the aggregates gradation curve with respect to TS 802 [35].

2.3. Mixture proportion details and casting

A total of 10 HSC mixtures has been prepared with a w/b ratio of 0.35 and total binder of 420 kg/m^3 to check out the effects of nS incorporating the mixtures. The LWA are weakened than natural aggregate so that the results of aggregate replacement can be considered more indicative in low w/b concretes with high cement to minimize the possible strength loss. The chosen volume fractions of LWAs practically used in HSCs were 0, 10, 20, 30, and 40% of the total natural coarse aggregate by volume. The control mixes are prepared by using natural aggregate, the first group has been prepared without nS while the second group has been prepared with 3% of nS. Each group consisted of 5 mixes and one of them is called as the reference mix.

All the concrete mixtures were prepared in a power-driven revolving pan mixer of 30-liter capacity. A special procedure has been followed for batching, mixing and casting of concrete to avoid the quick slump loss of LWA because of its high water absorption capacity.

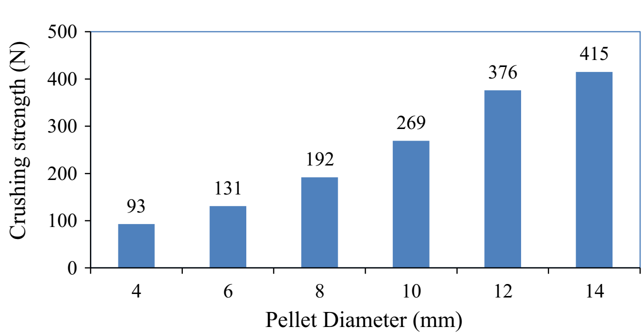

Fig. 2. Lightweight aggregate crushing strength.

Firstly, LWA has been mixed with cement, then coarse and fine aggregate have been added to the mixer to obtain a homogeneous mix after 30 s mixing, then one-third of mixing water has been added to the mix for one minute. Finally, remaining mixing water with SP has been added for 3 min. The total period of mixing process was about 5 min.

All the HSLWCs were designed for a slump test 15 ± 2 cm for easy mixing, molding and high strength concrete requires which is found by using superplasticizer. Two identical batches were carried out by performing the same procedure. Each casting specimens were vibrated for a couple of seconds. The fresh poured concrete specimens wrapped with plastic sheet and kept in the casting room for 24 h at about 20 ± 2 °C. After that, the specimens have been demounted and transferred to the water tank for curing up to 28 and 90 days. Mix proportions for 1 m^3 concrete are given in Table 2. Additionally; the rate of SP has been used to provide the needed workability for the designed slump.

2.4. Test procedures

The compressive strength test has been conducted on three cubical samples of 150 × 150 × 150 mm for each mix in 3, 7, 28 and 90 days respectively by 3000 KN capacity testing machine according to the Ref. [36]. The average results of the three samples of the mix at each testing age have been measured.

Splitting tensile strength have been performed on three specimens of Ø150 × 300 mm [37]. The concrete cylinder samples have been put between the horizontal plates of the testing machine.

Water sorptivity of three specimens with dimensions Ø100 × 50 mm cut from Ø100 × 200 mm with according to [38]. The specimens must be completely dried before the test in an oven of 105 ± 5 °C to reach their constant mass and then trapped in a sealed container to cool down at the ambient temperature. In this experimental study, the sorptivity index was elected for 28 and 90 days. Only one specimen surface is exposed to water. The specimens' sides have been coated with paraffin which is a water resistant material with a mass of 0.01 gr. And the test has been carried out by placing the specimens on glass rods in a tray containing water. The bottom surface of the tray was 5 mm deep in water. The bottom surface allowed free movement of water according to the capillary. The specimens were removed from the tray and weighed at different time intervals up to 64 min to evaluate the mass gain. The test setup was shown in Fig 4. To find the sorptivity index, the amount of water drenched up has been graphed with respect to the square root of time. The sorptivity index represented the slope of the drawn line.

The gas permeability of HSLWCs samples has been employed at 28 and 90 days due to the CEMBUREAU method recommended by RILEM [39]. The test samples were prepared in concrete disk

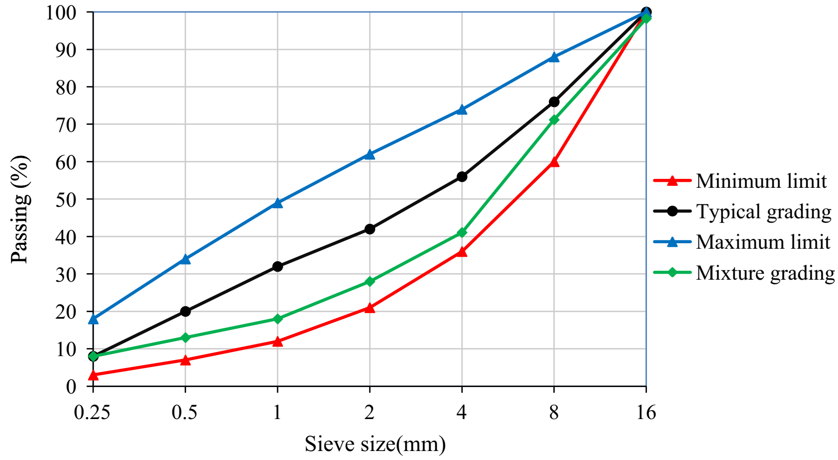

Fig. 3. The gradation curve of aggregate, according to TS 802 standard limits [35].

Table 2
Details of mix proportions in kg/m^3.

Mix ID	w/b	Binder	Cement	Water	FA	nS	SP	Fine Agg	Coarse Agg	LWA
LWA0%,nS0%	0.35	420	336.0	147.0	84	0.0	6.3	942.5	932.0	0.0
LWA10%,nS0%	0.35	420	336.0	147.0	84	0.0	6.3	942.5	838.8	57.2
LWA20%,nS0%	0.35	420	336.0	147.0	84	0.0	6.3	942.5	745.6	114.5
LWA30%,nS0%	0.35	420	336.0	147.0	84	0.0	6.3	942.5	652.4	171.7
LWA40%,nS0%	0.35	420	336.0	147.0	84	0.0	6.3	942.5	559.2	229.0
LWA0%,nS3%	0.35	420	323.4	147.0	84	12.6	9.2	936.4	926.0	0.0
LWA10%,nS3%	0.35	420	323.4	147.0	84	12.6	9.2	936.4	833.4	56.9
LWA20%,nS3%	0.35	420	323.4	147.0	84	12.6	9.2	936.4	740.8	113.8
LWA30%,nS3%	0.35	420	323.4	147.0	84	12.6	9.2	936.4	648.2	170.6
LWA40%,nS3%	0.35	420	323.4	147.0	84	12.6	9.2	936.4	555.6	227.5

*LWA: Lightweight aggregate, nS: Nano-silica, SP: Superplasticizer.

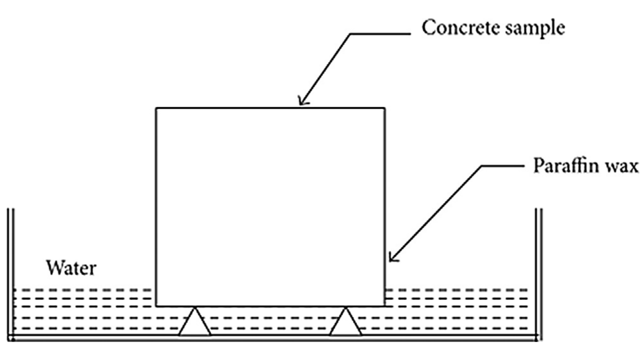

Fig. 4. Water sorptivity test set up.

shapes of 50 mm thick and 150 mm diameter when the curing period has been finished. The samples have been dried in an oven. The change in sample weight would not over 1% of the total sample weight. After that, the samples are left in a sealed container to cool at ambient temperature. The implementation has been done through specimens by Oxygen gas as a medium permeate. 150, 200, 250 and 300 kPa of inlet gas pressure values have been applied to get the apparent gas permeability coefficients for each level. The details of gas permeability presented in Fig 5. To determine the gas permeability coefficients, the Hagen-Poiseuille relationship has been used for laminar flow for compressible fluids through a porous mass with fine capillaries under steady state conditions. Modified Darcy's Equation which is applied to calculate the apparent gas permeability coefficient is shown below:

$$K = \frac{2P_2QL\eta}{A\left(P_1^2 - P_2^2\right)}$$

where: K: coefficient of gas permeability, P_1: inlet gas pressure (N/m^2), P_2: outlet gas pressure (N/m^2), A: cross-section area of the sample (m^2), L: height of sample (m), η: oxygen viscosity (2.02×10^{-5} N sn/m^2), Q: rate flow of air bubble (m^3/sn).

Three specimens of HSLWCs have been tested and the average K value has been determined.

3. Test results and discussions

3.1. Compressive strength

The compressive strength results for 3, 7, 28 and 90 days are graphically presented in Fig 6 considering the replacement level of LWA and incorporating 3% of nS to the HSLWCs mixes. It has been observed that there was a notable reduction in all HSLWCs compressive strengths in all ages due to the loss of products evoked through the hydration process. For instance, the 28 days compressive strength of the first group mixes without nS varied from 64.08 to 54.08 MPa as the LWA replacement level increased from 0% to 40%. While the second group mixes with 3% nS, the compressive strength changed between 72.36 to 55.87 MPa as the replacement level increase with the same percentage of the first group.

It is investigated that, there is about 2.94–16% decrease in the 28-day compressive strength of the mixtures without nS particles. It is calculated that there is about 3.90–23% decrease in the

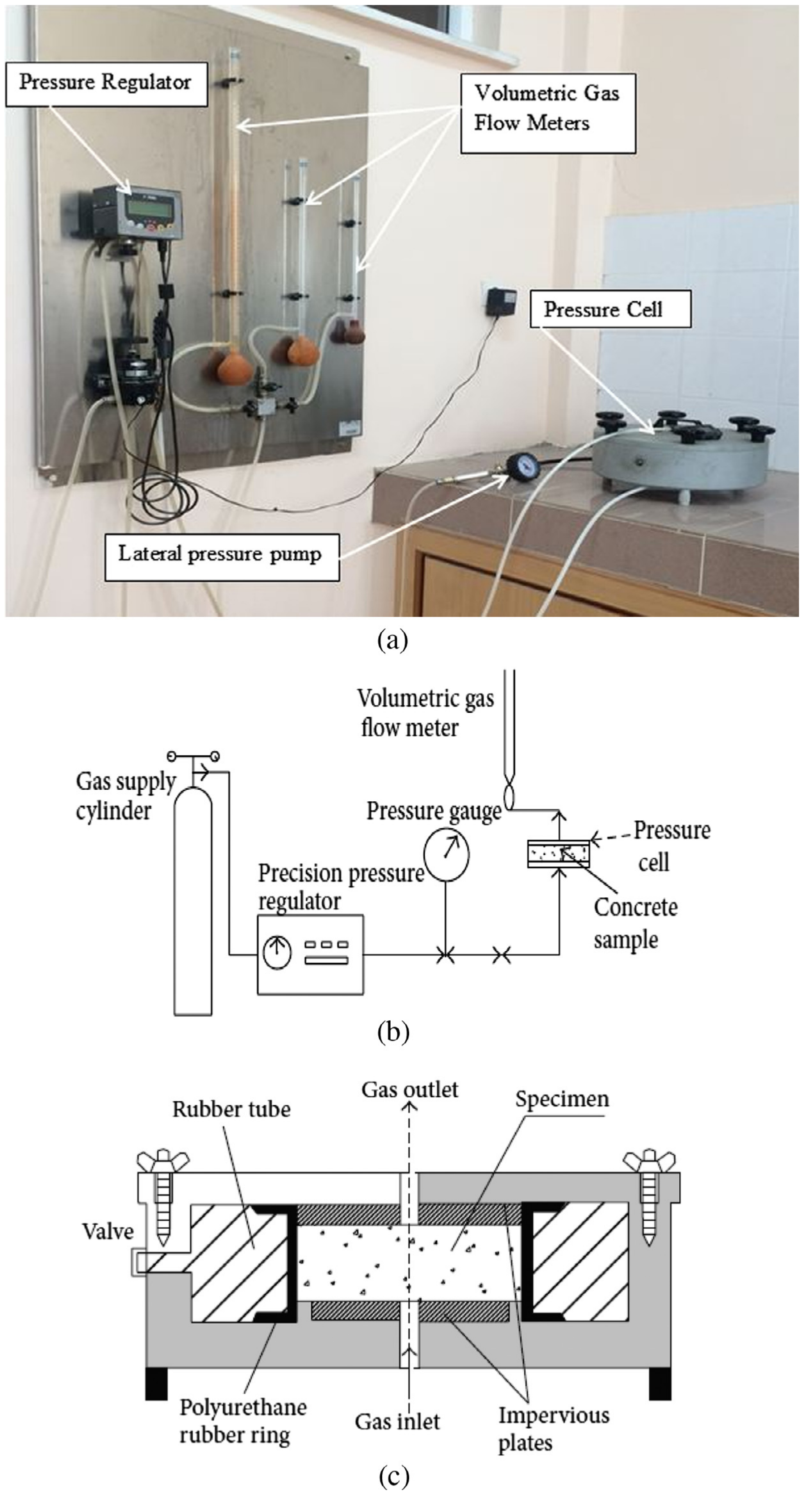

Fig. 5. Gas permeability test set up details; (a) photographic view, (b) schematic view and (c) the details of the pressure cell and test specimen.

compressive strength for the second group which contains nS particles with the same replacement values of the first group.

A gradual decrease in compressive strength has been observed when the LWA has been replaced with the NWA. This is because of the physical properties of LWA which have a specific gravity lower than NWA. Additionally, the LWA has higher water absorption ratio compared to the NWA.

There are similar studies reported the same behavior that the lower density and higher porosity of fine LWA compared to natural aggregate reduce the concrete performance especially in terms of mechanical properties. The physical process has a significant influence at an early age and limits densification of ITZ that results from absorption of the LWAs. The chemical process becomes effective only at a later age that's related to the pozzolanic activity of LWAs [40,41].

Moreover, there are unfilled microvoids in mixes increased with increasing LWA, and they act as weak zones which cause lower compressive strength values. In other words, NWA has a larger sur-

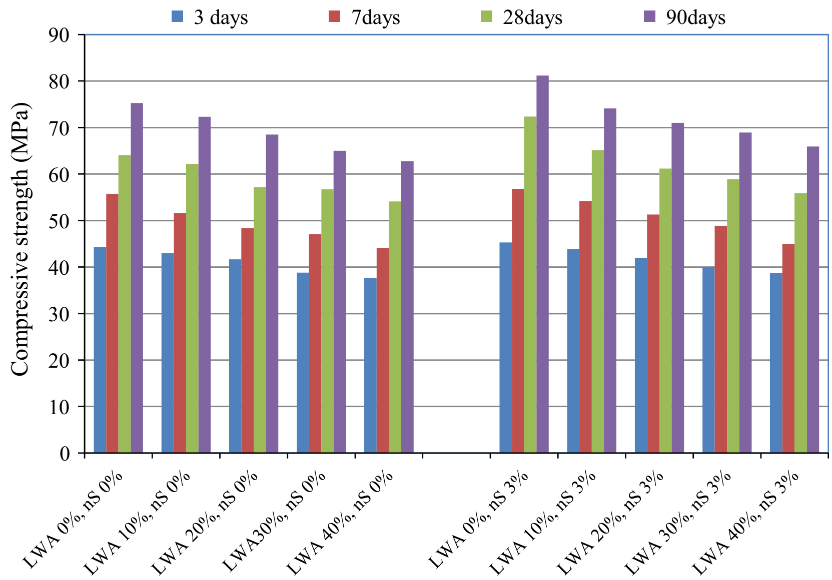

Fig. 6. The 3, 7, 28 and 90-day compressive strength values of HSLWCs.

face area compared to the LWA that leads to lower bonding strength in the ITZ around aggregate particles [42].

When compared the two groups with the same replacement level of LWA, the effect of nS particles can be noticed easily. The 28 and 90-day results showed that the overall mixes contain 3% nS by weight of cementitious material replacement have a higher compressive strength when compared to the mixtures don't have the same level of replacement of LWA. It has been found that the increase percentage for group two of control mix was 12.91% while it is found 4.77%, 6.90%, 3.81% and 3.31% for 0%, 10%, 20%, 30% and 40% replacement levels respectively, for 28 days with 3% nS.

The increase in mechanical properties in all ages related to nS particles in cement paste is related to the nucleus that tightly bond with cement hydrate boosting the cement hydration process [43,44]. It also prevents the growth of crystals that improves the strength of cement paste. On the other hand, the nS particles have the ability to fill the cement pores and increase strength by reacting with $Ca(OH)_2$ to generate C-S-H in hydration process [45].

It has been found that the effects of nS on the control mix that represent the conventional concrete 100% natural aggregate had better performance than LWA. The compressive strength for 28-day with respect to LWA replacement level 0% was found 64.08 MPa, while it has been found 72.36 MPa with 3% nS. The negative effects of LWA can be remedied by addition of 3% nS by increasing the strength values.

Moreover, the increases in compressive strength in all concrete mixtures containing FA when incorporation of nS back to an accelerated pozzolanic activity of fly ash earlier than expected and results in additional production of C-S-H compounds [46–48]. There is another reason to improve compressive strength when incorporated nS that its particles are smaller in size than cement and fly ash and be able to reduce the size pores in the cement paste. Replacing a portion of cementitious by nS particles has created a more accurate particle size distribution of concrete leads to enhance the concrete pore structure and filled most of the various size voids. Similar trends can be noticed in other HSLWCs mixes compressive strength with 90 days.

Figs. 7 and 8 show the shape of failure in compressive strength specimens. It's obvious that the perimeter of the specimen is failed in 28 days while the core of the specimen is still constant, either in 90 days the perimeter and the core are failed in compressive strength by lateral shearing stresses, therefore, they are different from each other because of more hydration process took place through a water curing condition at very long period and curing plays a great role in strength development and durability of concrete. The effects of chemical admixtures such as fly ash, superplasticizer, and nS particles are significantly obvious at longer time intervals. In general, the specimens produced a loud noise at the instant of failure.

3.2. Splitting tensile strength

Concrete is not usually designed to resist tension. But it's necessary to know the tensile behavior to estimate the load which causes cracks. In general, the splitting tensile strength is depended on the aggregate and curing type, w/b ratio, degree of compaction, strength, and age of the concrete.

The splitting tensile strength at 28 and 90 days for HSLWCs mixes produced with and without LWA and nS are graphically presented in Fig 9. It has been observed that splitting tensile strength of all mixes increased with age regarding the replacement level of LWA.

In general, the splitting tensile strength decreases with an increase in the LWA level in the mixes. The splitting tensile strength values for 28-day for the first group (without nS) have been calculated to be 4.471, 3.925, 3.745, 3.531, and 3.454 MPa respectively for 0%-40% of LWA while these values have been calculated to be 4.951, 4.648, 4.447, 4.393, and 4.017 MPa respectively for the second group (with 3% of nS) (See Fig. 9).

A significant reduction in tensile strength is due to the formation of great moisture gradient in drying attribute to increase the overall water content as a high water absorbent artificial aggregate used in concrete production. The influence of LWA on splitting strength of concrete mixes is the same of compressive strength when considering the total variation. Reducing the tensile strength of concrete mixes was due to the fracture path propagating throughout grains of LWA leading to shorter fracture path. The initiation and propagation of tensile cracks have been detected by the weakness of LWA due to the unfilled micro-voids offering a lower ultimate tensile strength of concretes.

In addition, splitting tensile strength has been increased by adding nS to the concrete and it became visible comparing the first and second group mixes in 28 and 90 days neglecting the replacement level of LWA. In general, compressive strength and splitting tensile

Fig. 7. Compressive strength type failures at 28-day.

Fig. 8. Compressive strength type failures at 90-day.

strength have the same behavior and influenced by the same factors. The average increase in splitting tensile strength is approximately 10.74% for control mixes of two groups for 90 days.

3.3. Water sorptivity

There are many factors affecting the sorptivity index of a concrete such as concrete mix proportions, chemical or cementitious materials existence in the mix, age, the volume of air voids, pore structure types and aggregate, etc. Fig 10 presents the sorptivity index values of various HSLWCs mixtures at 28 and 90 days. As expected, the lightweight aggregate replacement level, the age of samples and nS content affect the results of sorptivity coefficients of HSLWCs. These factors also affect the pore structure intensification.

The sorptivity coefficient of 0.077 mm/min$^{0.5}$ and 0.045 mm/min$^{0.5}$ of LWA 0%, nS 0% mix of the first group without nS particles were increased to 0.1171 mm/min$^{0.5}$ and 0.0783 mm/min$^{0.5}$ at 28 and 90 days respectively when replaced 40% of natural aggregate with LWA. While the second group that contains nS particles under the same condition, it's apparent increase in LWA0%, nS3% mix from 0.0592 and 0.037 mm/min$^{0.5}$ to 0.0998 mm/min$^{0.5}$ and 0.0711 mm/min$^{0.5}$ when replacement 40% of natural aggregate by LWA with FA at 28 and 90 days respectively. The increase in sorptivity index of HSLWCs results from the increase in pore structure and total porosity [45].

The biggest difference between the first group and second group is because of the nS content of the mixtures. NS particles are famous to reduce the size of capillary pores and increase the probability by converting the continuous pores to discontinuous pores. The reduced sorptivity values according to finer pore structure that prevents the penetration of aggressive solution to the pore structure as well as the increase in hydration process due to the addition of nS to cement paste results in a pozzolanic reaction activity lead to a lower number of continuous capillary pores resulting in a decrease in water absorption [28]. Moreover, the pozzolanic reaction of nS and FA contributes a further reduction in water sorptivity of cement paste and reduce the capillary porosity and make them disconnected. Similar findings have been reported in the literature [49,50].

3.4. Gas permeability

This test can be considered as one of the most important methods to investigate the porous material and characterize pore structure of concrete [40]. The gas permeability coefficient of specimens at 28 and 90 days are presented in Fig. 11.

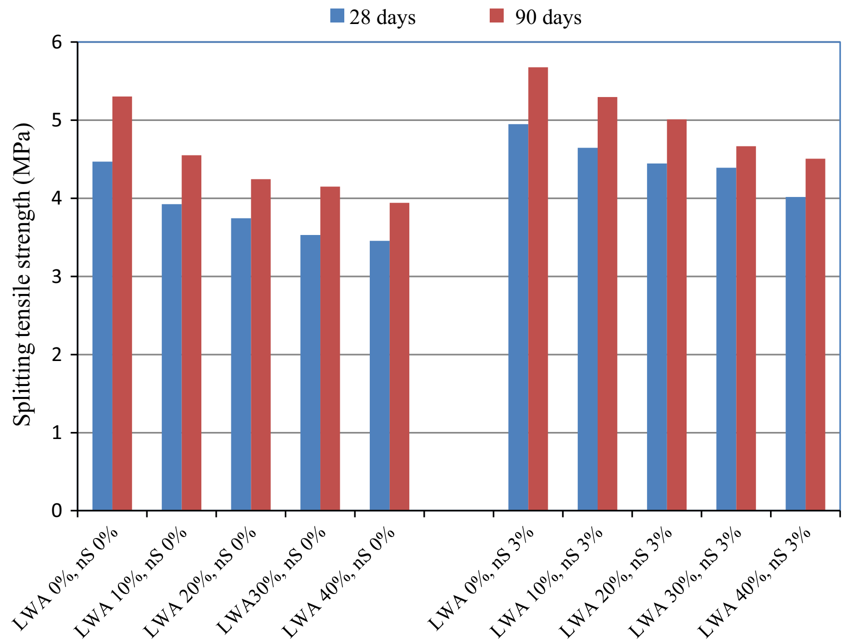

Fig. 9. The 28 and 90 days splitting tensile strengths value of HSLWCs.

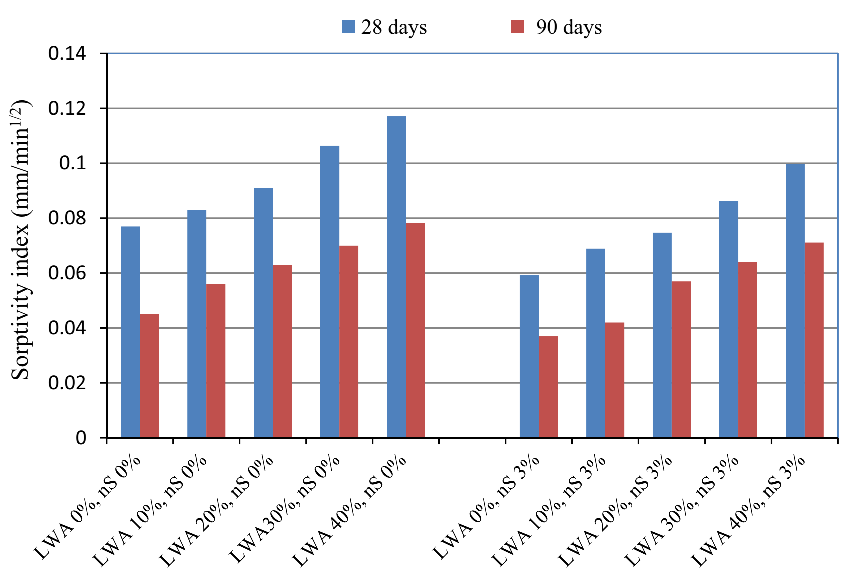

Fig. 10. The 28 and 90 days sorptivity index value of HSLWCs.

It's obvious from the Fig. 11 that gas permeability coefficients clearly increase when substation of natural aggregate with LWA depending on the replacement level of LWA in both ages. The upper limit of gas permeability coefficients has been calculated to be $4.896 \times 10^{-16}\,m^2$ and $4.141 \times 10^{-16}\,m^2$ at 28 and 90 days respectively. Because of the transport properties of concrete are firmly depending on its pore structure, the raising of gas permeability in concrete can be attributed increasing the pore structure in concrete due to LWA addition. Nevertheless, LWA seemed to be more prone to cause an increase in gas permeability coefficient. For instance, the variations of apparent gas permeability coefficients for the 1st and 2nd group mixes have been changed between $2.862 \times 10^{-16}\,m^2$ to $4.896 \times 10^{-16}\,m^2$ and $1.790 \times 10^{-16}\,m^2$ to $4.289 \times 10^{-16}\,m^2$ at 28 days respectively. However, the values of 90 days of the first and second groups change between $1.343 \times 10^{-16}\,m^2$ to $4.141 \times 10^{-16}\,m^2$ and $0.731 \times 10^{-16}\,m^2$ to $3.101 \times 10^{-16}\,m^2$ respectively as seen in Fig. 11. This was due to the concrete with low porosity is not fully accessible to gasses and the higher porosity gasses can penetrate concrete more easily. Moreover, the porous structure of LWA has contributed to the permeability of the matrix which leads to high permeability [46]. Mixture proportion of concrete, age advancement, the existence of chemical additives like silica fume or nS, aggregate types and properties and type of pore structure are main factors affecting the gas permeability [47].

In comparison to the mixtures without nS, addition of 3% nS to the HSLWCs mixes causes a reduction in gas permeability by 30.95%, 26.60%, 15.44% and 12.40% at 28-day and 32.40%, 40.65%, 35.33% and 25.11% at 90-day respectively with the same replacement level of LWA (Fig. 12). The addition of nS particles to concrete leads to improve pore structure, enhance the density of concrete by acting as a filler due to the enormous specific surface area. It also

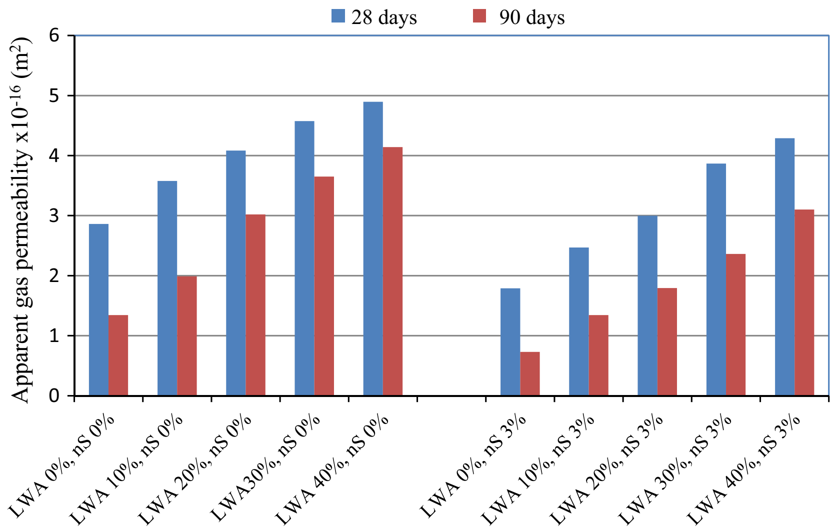

Fig. 11. The 28 and 90 days apparent gas permeability values of HSLWCs.

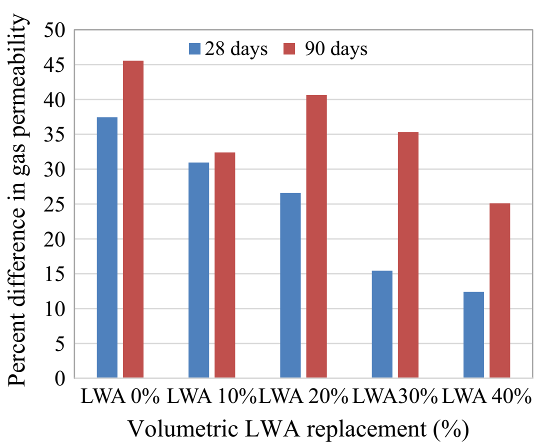

Fig. 12. Percent difference in gas permeability of HSLWCs containing different LWAs with respect to the addition of 3% nS.

reduces the porosity of concrete and accelerates cement hydration because of the higher activity of particles reacting with calcium hydroxide crystals quickly. The improvement in the pore structure of concrete due to incorporate of nS interpreted the mechanism that nS particles are uniformly dispersed in concrete in a cube behavior that's lead to identified in distance between nS particles. As the hydration starts, the hydrated process products a percolate and wrapped nS particles as a kernel. The limitation of growth of $Ca(OH)_2$ crystals has been done by appropriate of content and distance of nS particles. Similar findings are also reported in the literature of [49–52].

The results indicated that the use of nS particles in HSLWCs are increasing the efficiency of LWA concrete mixes because of the refinement of the pore structure of concrete and it is the key issue to improve the characteristics of concrete. Actually, the term of durability is directly related to concrete porous structure, since the capillary pores are in charge of fluids or gasses migration in the concrete matrix. The amount of continuous capillary pores decreases because of the pozzolanic reaction owing to a reduction in $Ca(OH)_2$ content in the hydrated matrix. When the number of capillary pore decreases, the resistance of the material against the corrosive environment enhances.

4. Conclusions

The following conclusions may be drawn from the experimental study presented above:

1. Due to this study, it can be said that the effect of nS in conventional concrete gives better results and performance than the lightweight concrete.
2. HSLWCs mechanical and transport properties are directly proportional to the percentage of nS and inversely proportional to the percentage of LWA until a certain level of LWA and nS percentages.
3. There is a considerable decrease in compressive strength depending on the replacement level of LWA because the LWA is weaker than the NWA. The increase in strength value leads to be said that the negative effect of LWAs can be remedied by addition nS particles. Because of the smaller and finer particle size of nS, it fills the spaces between the paste grains resulting in strength development.
4. It has been observed that, as a result of strength limitations of LWA, HSC including LWA has a lower splitting strength than the control mixes. In this study, the splitting tensile strength values have been calculated to be 4.951 MPa and 3.454 Mpa for 28 days, and the tensile strength showed an identical pattern with the compressive strength.
5. HSCs incorporating LWA revealed a systematic increase in sorptivity index values by increasing the replace amount of LWA at both ages. The sorptivity coefficients have been measured to be 0.0592 $mm/mm^{0.5}$ to 0.1171 $mm/mm^{0.5}$ for 28 days. The sorptivity indexes of HSLWCs which contain nS are better than other mixes including the same replacement of LWA due to the micro-filling effects and pozzolanic reactivity of nS particles.
6. As expected, according to higher water absorption and lower specific gravity of LWA the gas permeability increased by increasing the replacement level of LWA. The LWA has poor transport properties especially in terms of permeability. In addition, the reduction of gas permeability reaches up to 40% in 90 days by adding nS which provides age advancement and refinement of pore structures. The gas permeability has been calculated to be $4.896–1.79 \times 10^{-16}\ m^2$ and $4.141–0.731 \times 10^{-16}\ m^2$ at 28 and 90 days respectively.

7. According to this study, it can be said that nS particles are very useful for concretes in two ways. The first is the chemical effect that the pozzolanic reaction of free $Ca(OH)_2$ formed more C-S-H dividing the larger pores to smaller pores. The second contribution is due to the physical characteristics of nS. The smaller nS particles should be able to fill the micro-voids and improve the density of ITZ. It leads to enhance the permeability properties and develops strength properties and durability of the concrete for aggressive environments.
8. This paper should be considered as a research treating part of environmental issues by utilizing disposal material like FA powder through a simple procedure which consumes low energy as well as saving resources, decrease hazardous effects of wastes and increase the performance of construction materials in structural engineering.

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