Effects of Perlite, Leca, and Scoria as Lightweight Aggregates on Properties of Fresh and Hard Self-Compacting Concretes

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Abstract
In this study, the effects of Perlite, Leca, and Scoria as lightweight aggregates have been investigated on the properties of self-compacting concrete at the fresh and hardened phases. For this purpose, the ratio of water to cement and super lubricant were kept constant in the mixing rules. Performance tests, such as Slump flow, J ring, U box, L box, and V-funnel tests, were used to investigate the flow ability, passing ability, and the resistance of concrete against detachment. The results showed that the performance of the witness concrete decreased due to the high water absorption of lightweight aggregate. The mechanical properties of hard self-compacting concrete have also been investigated in this study. A set of experiments, such as compressive strength, tensile strength, flexural strength, water diffusion, water absorption, and also corrosion tests in the sulfate and acid environments, were performed for this purpose. The results indicated that the addition of lightweight aggregate decreased the strength and increased the value of water absorption in all cases. It was also observed that the self-compacting lightweight concrete (SCLC) had less resistance during the compression in comparison with the ordinary self-compacting concrete in sulfate and acid environments.

1. Introduction
Concrete is the most important construction material in the building industry due to its impermeability, availability, and reasonable cost. Nevertheless, the high weight of this material, in comparison with other construction materials, makes it inapplicable in some cases. Besides, new high-performance construction materials and tools have been developed today with low requirements for skilled workers (Kamgar et al. 2019, 2020; Maghsoudi and Rahgozar 2009; Askari Dolatabad et al. 2019). Today, the addition of different materials to improve the behavior of concrete members has widely attracted the attention of researchers of the field (Chaboki et al. 2019). Developing the various types of self-compacting concrete (SCC), with high performance, and low-weight concrete (LWC) is necessary for fast buildings (Aïtcin 2011; Aydin et al. 2015; Bentur et al. 2001; Kılıç et al. 2003). LWC can decrease the total weight and the total cost of construction for a building. It also can increase the resistance of the building against earthquakes by reducing the dead load of the structure. The addition of lightweight aggregate due to their low specific weight to the ordinary concrete might also decrease some of the concrete problems such as aggregate separation. Adding these particles to the SCC, which has higher powder materials and lower aggregates, in comparison with the ordinary concrete, increases its viscosity and solves such problems as aggregate separation (Hwang and Hung 2005; Wang 2009). The SCC has excellent advantages such as high efficiency and production rate and requiring low time for construction. It also is applicable as the in-situ concrete with a suitable performance without the need for vibration. Also, the Low-weight SCC (LWSCC) has a similar advantage (Uysal and Sumer 2011). Ahmad et al. (2019) presented the formulation for using the lightweight aggregates as thermal insulation. Azari Jafari et al. (2018) used pozzolanic materials in the SCC and showed that the result of the V-funnel test reduces by adding these materials. Gonen and Yazicioglu (2018) examined the effect of basaltic pumice aggregate on the curing conditions of SCLWCs. They concluded that some properties of permeation, such as carbonation and capillary water absorption, got worse. Wan et al. (2018) investigated the effect of Perlite, Scoria, and polystyrene aggregates on the properties of SCC at the fresh and hard phases. In the paper mentioned above, the stress-strain curve for the SCCs was also investigated. The coarse lightweight expanded clay aggregates were used as a replacement for the SCCs by Nepomuceno et al. (2018). They depicted that a satisfactory performance could be shown with a uniform distribution of lightweight aggregates when the dynamic and static segregation analysis were performed.

In this study, the effects of Perlite, Leca, and Scoria on the properties of fresh and hard self-compacting concrete have been investigated. Many studies have been conducted on the use of different lightweight aggregates

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in the self-compacting concrete. These studies have presented the effect of adding these aggregates at the fresh and hardened phase (Aslani et al. 2018; Kim et al. 2010; Toutanji et al. 2015). It should be noted that there is some research on obtaining the optimum mix design for SCC (Habibi and Ghomashi 2018) and studying the mechanical properties of SCC (Habibi et al. 2012; Rezaee and Rahgozar 2015; Sharifi et al. 2010). In this study, however, three types of lightweight aggregates (Perlite, Leca, and Scoria) with different percentages have been added to the SCC to study the durability, strength, and self-compacting of LSCC.

2. Experimental program

2.1 The used materials

2.1.1 Cement

In this study, the Portland cement of type 2 from the Kerman Cement Company, Iran, has been used. It was produced according to ASTM C150 standard, with the presented chemical analysis in Table 1.

2.1.2 Natural aggregates

In this paper, the river sand with 4.75 mm maximum diameter has been used, whose apparent specific weight of saturation state with a dry surface was equal to 2.63 gr.cm\(^{-3}\), its 24-hour water adsorption was 2.45\%, and the value of soft module was 2.78. The crushed gravel stone with 12.5 mm maximum size was also used, whose specific weight of saturation state with a dry surface was equal to 2.56 gr.cm\(^{-3}\), and its 24-hour water adsorption was equivalent to 2.2\%. The aggregate grading test was performed according to ASTM C33/C33M-18 (2018) standard. The grading characteristics of the used fine and coarse aggregates are given in Tables 2 and 3, respectively.

2.1.3 The lightweight aggregates

The lightweight aggregates used in this study are Perlite, Leca, and Scoria (Fig. 1). The strength of LWAs has a significant influence on the compressive strength of LWSCCs. For this aim, the strength of LWAs was measured according to BS 812-110 Part III (1990). This experiment describes a method for the determination of ten percent fines value (TFV) of the aggregates, which gives a relative measure of the resistance of an aggregate to crushing under a progressively applied compressive load. The TFV values of lightweight aggregates have been presented in Table 4.

Perlite is a volcanic rock with a non-crystalline structure. This lightweight aggregate has a rhyolitic and acidic composition and is formed in either aqueous or humid environments. This type of lightweight aggregate is available in a variety of colors such as green, brown, light gray, and for the expanded type of this aggregate, the color is white.

The production stages of Perlite aggregate include milling, agglomeration, and heating up to the initial melting temperature. Therefore, after agglomeration, the Perlite is first directed to the preheated section. Then, it is sent to the furnace at a temperature between 700 and 1100\(^\circ\)C. This temperature evaporates the water in the Perlite, creating an air bubble and a porous structure. Therefore, the expanded Perlite inside the furnace produces a lightweight aggregate.

| Physical Characteristics of cement |
|-----------------------------------|
| Compressive strength (MPa) | Time of setting (min) | Blaine fineness (cm\(^2\)/g) | Specific gravity | Autoclave expansion (%) |
| Three days | Seven days | 28 days | Initial | final | 2950 | 3.12 | 0.19 |
| 26.3 | 34.3 | 44.9 | 140 | 190 | |

Table 1 A The chemical properties of the used cement, Perlite, Leca, and Scoria.

| Chemical composition | L.O.I | SiO\(_2\) | Al\(_2\)O\(_3\) | Fe\(_2\)O\(_3\) | CaO | MgO | SO\(_3\) | K\(_2\)O | Na\(_2\)O | MnO | TiO\(_2\) | P\(_2\)O\(_5\) | MnO | SiO\(_2\) | Cl | I.R. |
|----------------------|-------|----------|----------------|----------------|-----|-----|---------|---------|---------|------|----------|----------|------|--------|-----|------|
| Cement (%)           | 1.33  | 21.7     | 4.62           | 3.95           | 65.04| 1.25| 2.78    | 0.61    | 0.62    | -    | 2.31     | 3.9      | -    | 0.49   | 0.47| 0.04 |
| Scoria (%)           | 5.62  | 60.8     | 17             | 3.4            | 3.5  | 2.5 | -       | 2.31    | 3.9     | -    | 0.49     | 0.47     | 0.78 | 0.21   | 0.09| 0.03 |
| Leca (%)             | -     | 66.05    | 16.57          | 7.10           | 2.46 | 1.99| -       | 2.69    | 0.69    | -    | 0.78     | 0.21     | 0.09 | 0.03   | -   | -    |
| Perlite (%)          | -     | 72.31    | 14.32          | 0.76           | 1.35 | 0.34| 0.005   | 5.46    | 4.62    | 0.086| 0.0230.012| -        | -    | -      | -   | -    |

Table 1-B The physical characteristic of the used cement.

Fig. 1 The lightweight aggregates; (a) Perlite; (b) Leca; (c) Scoria.
would be pushed upwards, and its color would change to snow white (Fig. 1). In this study, the Perlite produced in Abtin Factory in Isfahan, Iran, was used. The used Perlite had a maximum size of 8.5 mm, its 24-hour water absorption was equal to 40%, and its specific gravity was 540 kg/m³. The Perlite agglomerations used in this study are listed in Table 5, according to ASTM C33/C33-18 (2018), and their chemical analysis can be seen in Table 1.

The Leca lightweight aggregates were obtained by clay expansion in the furnace at temperatures between 1000 and 1200°C. The large porosity in the Leca grains was about 73% to 88% of the total space. This porosity created some features for Leca, such as low thermal conductivity, low weight, and low noise loss. In this study, the Leca produced in Shahr-e-Babak mines has been used. The used Leca had a maximum size of 12.5 mm, its 24-hour water absorption was equal to 6.26%, and the specific gravity was equal to 870 kg/m³. The Leca aggregates used in this study were done by the ASTM C33/C33-18 (2018) standard, which are shown in Table 6, and their chemical analyses have been illustrated in Table 1.

Scoria is one of the oldest lightweight aggregates used in concretes. This lightweight aggregate is caused by volcanic meltwater entering water reservoirs such as rivers and lakes and cooling the lava, and its color is dark grayish brown. In this study, the Scoria produced in Shahr-e-Babak mines has been utilized. This Scoria has a maximum size of 12.5 mm, with a 24-hour water absorption equal to 15.5%, and the specific gravity of 1320 kg/m³. The Scoria aggregates used in this study have been done by the ASTM C33/C33-18 (2018) standard, which are depicted in Table 7, and their chemical analyses have been shown in Table 1.

### 2.1.4 Water and chemical admixture

The drinkable water was used for concrete production, following the ASTM D1129 (2013) standard. A high range water reducer (HRWR) was also used to enhance the flowability of the mixtures based on the polycarboxylate with 1.10 gr.cm⁻³.

### 2.2 Mixing rule

In this paper, the mixing proportion has been obtained according to ACI 237R-07 (2007) and procedure suggested by Su et al. (2001). Since the SCC needs to satisfy the flowability, filing, passing, and segregation resistance ability, many trial mixes have been conducted in the laboratory to determine the limits of material content to achieve SCC. The main aim of this research was to produce lightweight concrete; therefore, 15, 30, 45, and 60% of the gravel stone were replaced with leca, perlite, and scoria lightweight aggregates. The amounts of water, cement, sand, and superplasticizer are assumed to be the same for all the states. Weight of added superplasticizer was found to be 1.5% of cement weight. Furthermore, the water to cement ratio was also considered to be equivalent to 0.45.

It should be noted that the used lightweight aggregates had enough time for water-absorbing, and then their surfaces were dry before being added to the mixture. First, 1/3 of the used water was applied to the mechanical mixture which contained gravel stone, sand, cement, and lightweight aggregate, and the materials, as mentioned above, were mixed well. Then, another 1/3 of the used water with the used lubricant was applied to this mixture. Finally, the remaining 1/3 of the used water was added. The total mixing time was about 6 to 7 minutes (see Table 8).

### Tables

| Table | Description | Data
|-------|-------------|------|
| Table 1 | Particle size distribution of coarse aggregates. | Sieve size (mm) | Passing (%) |
|  | | 12.5 | 95.2 |
|  | | 9.5 | 49.3 |
|  | | 4.75 | 4.1 |
|  | | 2.36 | 0 |
| Table 2 | Particle size distribution of fine aggregates. | Sieve size (mm) | Passing (%) |
|  | | 4.75 | 97 |
|  | | 2.36 | 88.9 |
|  | | 1.19 | 76.8 |
|  | | 0.595 | 38.6 |
|  | | 0.297 | 8.2 |
| Table 3 | Particle size distribution of Perlite. | Sieve size (mm) | Passing (%) |
|  | | 12.5 | 100 |
|  | | 9.5 | 100 |
|  | | 4.75 | 25.5 |
|  | | 2.36 | 5.1 |
|  | | 1.19 | 2.1 |
| Table 4 | Particle size distribution of Leca. | Sieve size (mm) | Passing (%) |
|  | | 12.5 | 98.5 |
|  | | 9.5 | 44.5 |
|  | | 4.75 | 14.5 |
|  | | 2.36 | 2.5 |
| Table 5 | Particle size distribution of Scoria. | Sieve size (mm) | Passing (%) |
|  | | 12.5 | 95.8 |
|  | | 9.5 | 62.4 |
|  | | 4.75 | 10.3 |
|  | | 2.36 | 1.2 |
Table 8 The mix proportion’s for LWSCCs.

| Mix No. | Cement (kg/m³) | Water (kg/m³) | Superplasticizer (kg/m³) | Sand (kg/m³) | Coarse Aggregate (kg/m³) | Scoria (kg/m³) | Leca (kg/m³) | Perlite (kg/m³) |
|---------|----------------|--------------|--------------------------|--------------|--------------------------|----------------|-------------|----------------|
| Control | 437.5          | 197.22       | 6.55                     | 970          | 850                      | -              | -           | -              |
| S15     | 437.5          | 197.22       | 6.55                     | 970          | 722.5                    | 127.5          | -           | -              |
| S30     | 437.5          | 197.22       | 6.55                     | 970          | 595                      | 255            | -           | -              |
| S45     | 437.5          | 197.22       | 6.55                     | 970          | 467.5                    | 382.5          | -           | -              |
| S60     | 437.5          | 197.22       | 6.55                     | 970          | 340                      | 510            | -           | -              |
| L15     | 437.5          | 197.22       | 6.55                     | 970          | 722.5                    | -              | 127.5       | -              |
| L30     | 469.42         | 206          | 6.55                     | 708          | 595                      | 255            | -           | -              |
| L45     | 437.5          | 197.22       | 6.55                     | 970          | 467.5                    | -              | 382.5       | -              |
| L60     | 437.5          | 197.22       | 6.55                     | 970          | 340                      | -              | 510         | -              |
| P15     | 437.5          | 197.22       | 6.55                     | 970          | 722.5                    | -              | -           | 127.5         |
| P30     | 437.5          | 197.22       | 6.55                     | 970          | 595                      | -              | -           | 255            |
| P45     | 437.5          | 197.22       | 6.55                     | 970          | 467.5                    | -              | -           | 382.5          |
| P60     | 469.42         | 206          | 6.55                     | 708          | 340                      | -              | -           | 510            |

2.3 Fresh and hard concrete experiments procedures

2.3.1 Fresh concrete tests

A set of experiments, such as Slump flow, V-funnel, L box, U box, and L ring tests, were used according to the EFNARC standards (EFNARC 2002). The aim was to examine the performance of fresh SCC and LWSCC with three types of Perlite, Leca, and Scoria lightweight aggregate. All the tests were carried out at 20°C.

Also, a slump flow test was used to determine the deformation ability of concrete under its weight without any restrictions.

For this purpose, an incomplete cone with a large diameter of 20 cm and a small diameter of 10 cm was placed on a base plate with a completely flat (90 × 90 cm). Then, after lubricating the cone, about 6 liters of concrete was poured into the funnel. Next, the surface of the concrete was smoothed by a spade. Subsequently, the cone was pulled upward, and the diameter of the deformed concrete was measured in two perpendicular directions.

The offloading time of the concrete was measured using the V-funnel test to find the filling ability and also the flow performance of the concrete. For this purpose, about 12 liter concrete was poured into this funnel, and then it was offloaded after 10 seconds, by its weight.

The J ring test was also used for obtaining the passing ability of SCC through the reinforcement. For this purpose, an incomplete cone with a large diameter of 20 cm and a small diameter of 10 cm was employed at the center of a J ring with a 30 cm diameter. About six liter concrete was poured into this cone, and then, the cone was pulled downward. Finally, the height difference of concrete inside and outside of the ring was measured at four points. Finally, the average of these values was reported.

The L-box test was used to determine the flowability and concrete blockage due to the presence of bars. For this purpose, about 14 liter concrete was poured into the vertical part of this device, and then, its valve was opened after 1 minute. Finally, the blockage factor was obtained by dividing the height of concrete in the horizontal part to its height in the vertical component.

2.3.2 Hard concrete tests

This section presents a set of experiments that were designed for the evaluation of the performance of hard concrete. These experiments are the compressive strength, the tensile strength, the flexural strength, the water diffusion, the water adsorption, and the corrosion in the sulfate and acid environments. It is difficult to test concrete in direct tension due to problems of gripping the specimen; hence direct tensile strength is not widely used. The tensile strength of concrete is commonly measured by splitting tensile strength and flexural strength. In addition to the splitting tensile test, the flexural strength test is also performed to estimate the maximum load that will cause the development of cracking in the member under flexural loading.

Since the aim of this study was to investigate the effects of different percentages of different lightweight aggregates on the compressive strength of self-compacting concrete and had a comparative aspect, the 100 × 100 × 100 mm cube was used. The use of 100 × 100 × 100 mm cubes for compliance testing would alleviate such problems. The 100 × 100 × 100 mm cubes are easier to handle and will result in the saving of materials and labor. It will save storage and curing space as well as the testing time. Finally, it should be noted that the 10 × 10 × 10 cm³ cubic specimens have been considered for the compressive strength test, according to the BS 1881-116 (1983) standard. These specimens had 3, 7, and 28 days curing time after the 24 hours of drying time at the standard environment condition. Then, these samples were broken by a compressive jack (see...
Fig. 2) with an increased loading rate (0.3 MPa/sec-1), with three repetitions for each sample.

At first, 10 × 10 × 10 cm³ cubic specimens have been presented for the compressive strength test, according to the BS 1881-116 (1983) standard. These specimens had 3, 7, and 28 days curing time after the 24 hours drying time at the standard environment condition. Then, these samples were broken by a compressive jack (see Fig. 2) with an increased loading rate (0.3 MPa/sec³), with three repetitions for each sample.

Besides, the Brazilian (or indirect) method was used for the tensile strength test. Cylindrical specimens with 10 cm diameter and 20 cm height were used for this purpose, according to the ASTM C496-11 (2011) standard. To this end, the loading device and conditions have remained similar to the compressive strength test (see Fig. 3).

The two-point load method was used for the flexural strength test (see Fig. 4). For this purpose, 10 × 10 × 50 cm³ samples were provided, according to the BS 1881-118 (1983): 108-109-110 standard, similar to both of the previous strength tests. An increased loading rate was considered to be equal to 100 kg/sec⁻¹.

The 15 × 15 × 15 cm³ cubic specimens were also used for the water diffusion test, according to the DIN 1048 (1991) standard at the age of 56, and 90 days. After 48 hours of drying time in an oven, these samples were subjected to the 5 atm pressure of water for three days, with two repetitions for each sample (see Fig. 5). Then, water penetration depth was measured for these samples.

The 10 × 10 × 10 cm³ cubic specimens were used for the water absorption test, according to the ASTM C642-13 (2013) standard, at the age of 28 days. These samples were weighed after complete drying in an oven. Then, these samples were immersed in water for three days, and the weight of the samples was measured at different time steps. This procedure continued until it reached a low weight variance (about 1 day), with two repetitions for each sample. The water absorption of the samples was calculated using the following equation:

\[ A = \frac{m - m_o}{m_o} \times 100 \]  

where \( m_o \) shows the initial weight and \( m \) also depicts the final weight of the specimen. Two different environments (i.e., sulfate and acid environments) were used for the corrosion test. Aqueous solutions of MnSO₄ (5%) and H₂SO₄ (5%) were used for simulating the sulfate and acid environments, respectively. The 10 × 10 × 10 cm³ cubic specimens were used for this test. After 28 days of curing and 48 hours of drying time in the standard condition, two specimens were immersed under the water, two specimens were put in the sulfate environment, and two specimens were placed in an acid environment. Their weight changes were recorded after 7, 14, 28, 42, 56, and 70 days (see Fig. 6). Finally, these specimens were examined with the compressive strength test on the age of the seventh day.
3. Results and discussion

3.1 Fresh concrete experiments results

In this section, the obtained results from the experiments of fresh concrete have been presented. Since there is no particular standard for SCC, therefore, the EFNARC standard (EFNARC 2002) has been used, which is given for LWSCC.

The filling and stability properties of self-compacting concrete in the case of fresh concrete are determined by four characteristics of flowability, viscosity, permeability, and increased segregation resistance. One or more experiments can determine each attribute. For example, flowability and viscosity can be measured by the slump test $T_{500}$ and V-funnel test, respectively. In this research, some experiments such as slump test, slump $T_{500}$ test, V-funnel, L-box, U-box, and J-ring have been performed based on EFNARC standards (EFNARC 2002) to investigate the flowability, viscosity, and detachment of concrete samples. The results are given in Figs. 7 - 13.

It should be noted that EFNARC (EFNARC 2002) has set the allowable value for the slump test to be located at the range of 550-850 mm. However, it recommends three categories as SF1 (550-650) for particular purposes, SF2 (660-750) for typical applications such as beams, columns, etc., and SF3 (760-850) for places with a high density of rebars and unique shapes. As shown in Fig. 7, all mixture schemes are within the permissible range of the SF2 class. The results of the slump flow show that, in most cases, by adding the lightweight aggregate, the efficiency has decreased in comparison with the control sample because of high water absorption by the lightweight aggregates. Specific weight, appearance, and percentage of water absorption of the lightweight aggregates are important factors. For example, Perlite, Leca, and Scoria have 40%, 6.26%, and 15.5% water absorption, respectively. Also, the specific gravity for Scoria, Leca, and Perlite are 1320 kg/m$^3$, 870 kg/m$^3$, and 540 kg/m$^3$, respectively. Therefore, due to its rounded appearance, as well as its specific gravity and medium water absorption, Leca has the highest slump between the two other lightweight aggregates, making it have more slump than the witness sample in some cases. Regarding the self-compacting concrete flows under its own weight, the use of lightweight aggregate with higher specific gravity provides more self-weight for SCC to flow under gravity and will be able to increase the slump flow spread slightly. Similarly, due to the porous structure of LWAs, it is noteworthy that it has a high water absorption capacity, which tends to absorb...
the water during batching, resulting in poor workability. As shown in Table 1, scoria has the highest specific gravity, but its 24-hour water absorption is higher than that of Leca. For this reason, the slump flow diameter of scoria is close to the leca slump flow diameter and there are inflection points in Fig. 7.

According to the EFNARC (EFNARC 2002), the $T_{500}$ slump limit is 2 to 5 seconds. EFNARC (EFNARC 2002) also divides the $T_{500}$ slump flow into two classes VS1 ($T_{500} < 2$ sec) and VS2 ($T_{500} > 2$ sec). As shown in Fig. 8, all the mixture schemes are within the permissible range of the VS2 class.

One way to measure the viscosity of the concrete is the V-funnel test. The results of all mixtures are shown in Fig. 9. EFNARC (EFNARC 2002) divides the viscosity value based on the V-funnel test into two classes VF1 (V-FUN < 8 sec) and VF2 (9 < V-FUN < 25 sec). As shown in Fig. 9, all mixture schemes are placed in the VF2 class. It is also illustrated in Fig. 10 that all the mixing designs are in the VS2/VF2 class, so it can be concluded that all of them can be used in ramps, walls, and columns. It is found that it also depends on the specific gravity of the lightweight aggregate, and the flow-ability properties of the concrete. Therefore, the control
sample has the least exit time due to its higher specific gravity. Also, among the lightweight aggregate, Scoria, with the highest specific gravity and Perlite, with the lowest specific gravity, has the lowest and the highest exit times, respectively.

The L-box test with three rebars was used to investigate the passability of self-compacting concrete. The results of this experiment are shown in Fig. 11. EFNARC (EFNARC 2002) sets the permissible range for this experiment to be higher than 0.8. As can be seen, all mixing designs are in the PA2 class and within the allowable range. In the case of the L-box results, Leca and Scoria have relatively better results than Perlite because of their higher flowability. It should be noted that there are no obstructions between the bars in any of the cases in the L-box test.

Two tests of J-ring and U-box were also carried out to investigate more precisely the permeability and fill ability of the manufactured concrete. EFNARC (EFNARC 2002) reported a maximum height difference of 10 mm for the J-ring test, and 30 mm for the U-box experiment.

As shown in Figs. 12 and 13, all the results are within the EFNARC standard range except for sample P60, which has little error in the U-box test. Perlite is the least efficient because of high water absorption. Also, because of this decrease in the ability, the results obtained in high percentages of Perlite in the U-box experiment have a negligible error. It should be noted that in the experiment of the J-ring, Perlite has the highest crossing ability due to its fineness compared to the other two lightweight aggregates. As shown in Figs. 7 - 13, increasing the volume of Perlite reduces the slump flow diameter and increases the T500 time, the V-Funnel time, U box values, and h2/h1 values in L-box test. Therefore, increasing the volume of Perlite decreases filling ability, passing ability, and viscosity of LWSCCs. This is due to more water absorption and also lower specific gravity. This behavior was not observed by increasing the volume of Leica and Scoria due to lower water absorption and higher specific gravity.

3.2 Hard concrete experiments results

3.2.1 Compressive strength test

The obtained results from the compressive strength test have been represented in Fig. 14. The results demonstrated that the compressive strength of all the specimens increased with increasing the curing age, and the rate of increase for compressive strength decreased with increasing the curing age. The maximum strength was for the witness specimen. Adding the lightweight aggregate led to a decrease in the compressive strength of concrete. Their specific weight, filling ability, and porosity should be considered to analyze the results. Scoria, which has the maximum specific weight, has the maximum compressive strength among the other lightweight aggregates used in the construction of LWSCC. Also, Leca has less compressive strength than Scoria due to more porosity and less specific weight, subsequently. Perlite has a better filling ability, because of its apparent shape and small size than the other two lightweight aggregates. The optimum percent for the lightweight aggregates was calculated based on the ratio of 28-day compressive strength to the average dry weight of samples at the age of 28-day. This optimum value
was calculated by 15% for all the investigated lightweight aggregate. ACI 213R-87 (1999) recommended that the low weight structural concrete should have more than 17 MPa 28-day cylindrical compressive strength. The obtained results showed that adding each percent of Scoria satisfied this condition. Nevertheless, only 15% and 30% of Perlite and 15% of Leca had proper compressive strengths. The average ratios of 28-day compressive strength to specimen weight of dry sample at the age of 28-day were 15.45, 15.17, and 13.54 for Perlite, Scoria, and Leca, respectively.

As it is evident in Fig. 14, the reduction values for the ratios of compressive strength of LWSCC, in comparison with its value for the witness specimen at age 28-days, are 18.27%, 26.01%, 31.27%, and 36.53% for the P15, P30, P45, and P60 specimens. It should be noted that P15 shows an LWSCC with a 15% replacement of gravel with Perlite. Also, these values are 8.98%, 12.38%, 13.93%, and 15.48% for S15, S30, S45, and S60 specimens, respectively. Also, S15 shows an LWSCC with a 15% replacement of gravel with Scoria. Finally, these values are 22.91%, 31.58%, 34.98%, and 43.03% for L15, L30, L45, and L60 specimens, respectively. Finally, L15 shows an LWSCC with a 15% replacement of gravel with Leca. It shows that the maximum and minimum ratios of reduction for compressive strength occur for the Leca and Scoria, respectively.

3.2.2 Tensile strength test

The tensile strength test indicates the starting point of cracking for the concrete elements subjected to the external loads. Cement paste strength and also the adhesion between the cement paste and the aggregate are two important factors that can affect the tensile strength of samples. The results of this test have been shown in Fig. 15. It is clear from this figure that the addition of lightweight aggregate has decreased this kind of strength. It is also observed that the specimens with Scoria have the maximum tensile strength among the two other studied lightweight aggregates. The specimens with Leca have more tensile strength than the specimens with Perlite except for the L30 sample. Therefore, the LWSCC made of Leca has less compressive strength and more tensile strength in comparison with the LWSCC made of Perlite. The reduction ratios for the tensile strength of LWSCC in comparison with its value for the witness specimen at age 28-day are 13.82%, 23.17%, 37.8%, and 42.68% for P15, P30, P45, and P60 specimens, respectively. Also, these reduction values are 3.25%, 8.13%, 13.01%, and 14.23% for S15, S30, S45, and S60 specimens, respectively. Finally, these values are equal to 9.35%, 27.64%, 30.49%, and 39.84% for...
L15, L30, L45, and L60 specimens, respectively. Therefore, the maximum and minimum reduction ratios for the tensile strength exist for Perlite and Scoria, respectively. It is also observed that for all of the investigated cases, the reduction ratio for the compressive strength is faster than the reduction ratio for the tensile strength, except for P45 and P60 samples.

3.2.3 Flexural strength test

Figure 16 shows the obtained results of concrete samples for the flexural strength test. It is obvious that the maximum flexural strength, as well as the compressive and tensile strengths, is for the LWSCC with the Scoria after the witness concrete. It is observed that 15%, and 30% of Perlite, and also 45%, and 60% of Leca have high enough flexural strengths. The reduction ratios for the flexural strength of LWSCC in comparison with its value for the witness specimen at the age of 28-day, are 9.02%, 17.29%, 30.83%, and 35.34% for the P15, P30, P45, and P60 specimens, respectively. In addition, these values are 4.51%, 11.28%, 21.05%, and 27.07% for the S15, S30, S45, and S60 specimens, respectively. These values are equal to 10.53%, 24.81%, 27.82%, and 33.83% for the L15, L30, L45, and L60 specimens, respectively. It can be observed that the minimum reduction ratio for the flexural strength exists for the specimens with Scoria. It is also evident that, for all the replaced percentages of Scoria, the reduction ratio for the flexural strength is faster than this value for the tensile strength.

3.2.4 Water diffusion test

One of the most critical weaknesses of concrete is its permeability, which can have significant effects on the life and durability of concrete structures. Water penetration into the concrete members causes the penetration of the sulfate and chloride ions to real members, leading to a decrease in the resistance capability of the structure during the freezing and thawing cycle. Therefore, it is vital to reduce its permeability. Several methods that have been suggested for this purpose are reducing water to cement ratio, adding additives (such as micro or nanoparticles of Silica), and using special concretes (such as SCC). Figure 17 shows the obtained results from the water diffusion test. It is observed that the replacement of lightweight aggregates with gravel can increase the permeability of the concrete since an increase occurs in the porosity of the concrete. The highest amount of water penetration was seen in Leca, Scoria, and Perlite, respectively. Also, with increasing the age of the samples, the permeability of samples decreased due to increasing their compaction. The results show that by replacing the Perlite, Scoria, and Leca lightweight aggregates, the average depth of penetration at age 56-day increased by 26.38%, 49.99%, and 59.71% in comparison with the witness concrete, respectively. Also, this value has increased by 26%, 50%, and 64.06% at the age of 90-day in comparison with the witness concrete, respectively.

3.2.5 Water absorption test

Water absorption test is one of the simplest criteria used to determine the durability of the concrete, and two of its significant benefits are its ease of use and the need for no special equipment. The water absorption test is one of the criteria of concrete durability, whose benefits are its simplicity, and also, no need for special devices. The material properties used in concrete, as well as the size of cavities in the concrete, can affect the water absorption of concrete samples. It should be noted that in
the concrete samples made of lightweight aggregate, the volume of pores is larger than the concrete without lightweight aggregate. Figure 18 shows the obtained results for the water absorption test. It can be seen that the addition of lightweight aggregate has increased the water absorption of concrete. The maximum value of absorption is for Perlite (3.99%), and the second and third values are 3.54% and 2.99% for Leca and Scoria, respectively.

3.2.6 Corrosion test in sulfate environment
Exposure of concrete to the sulfate environment causes the occurrence of chemical reactions within the concrete. Some of these reactions are 1- the conversion of Ca(OH)₂ to CaSO₄ (which causes expansion and demolition), and 2- converting of Al₂CaO₄ to (Ca₆Al₂(SO₄)₃)₁₂, and also 3- the chemical decomposition of Ca₂H₂O₅Si (which causes softness and reducing the concrete strength). Therefore, it is vital to protect it from the sulfate attack. One of the suggested methods for this purpose is adding additives such as micro or nanoparticles of Silica. The results of the corrosion test in the sulfate environment in the form of mass losses at ages 7-, 14-, 28-, 42-, 56-, and 70-day, have been shown in Fig. 19. Also, the compressive strength for the samples at age 70-day has been depicted in Fig. 20. The average values of the mass losses at age 70-days for LWSCC and the witness sample are 3.05%, 4.40%, 4.48%, and 3.54% for the witness, Perlite, Leca and Scoria specimens, respectively. These values show that the minimum mass reduction is for Perlite (3.99%), and the second and third values are 3.54% and 2.99% for Leca and Scoria, respectively.

3.2.7 Corrosion test in an acidic environment
Portland cement has a high alkali content that is attacked by acidic environments. Inorganic acids, such as H₂SO₄, HCl, and HNO₃, have more corrosive properties than organic types of acids. The reaction of acids with...
the Portland cement creates soluble salts in water and destroys the concrete. Figures 21 and 22 show the obtained results for the corrosion test of samples immersed in the acid environment. The mass losses of the samples at age 7-, 14-, 28-, 42-, 56-, and 70-day in the acid environment have been shown in Fig. 21. Also, the compressive strength of the samples immersed in the acid and water environments has been depicted in Fig. 22. This figure is for the samples at the age of 70-day. The average values for the mass reduction of the samples at the age of 70-day in comparison with the mass reduction of the samples at age 7-days are 11.14%, 17.97%, 17.28%, and 15% for the witness, Perlite, Leca, and Scoria, respectively. Figure 22 depicts that the immersion of LWSCC into the acid environment decreases the compressive strength of concrete in comparison with the witness concrete (SCC). The ratio of compressive strength reduction of samples at age 70-days in the acid environment to similar values for the samples immersed into the water are 44.62%, 62.87%, 59.93%, and 54.33% for the witness, Perlite, Leca and Scoria concretes, respectively.

Investigating into the effects of acid and sulfate environments on the mechanical properties of concrete revealed that the reduction of strength and mass for LWSCCs was more than the witness concrete (SCC) for both of these environments. Therefore, LWSCC had lower resistance in the sulfate and acid environments in comparison with the SCC. It was also observed that the LWSCC made of Perlite had more resistance than the LWSCC made of Leca in the sulfate environment, whereas, for an acidic environment, the samples with Leca were more resistant. The high penetrability and absorption indicate bad compaction and low durability of LWSCCs in different environmental conditions. The reason for these may be due to the sulfuric acid and other harmful materials being able to penetrate deep into the LWSCC microstructure. Hence, damage takes place in the interfacial transition zone between the aggregates and hydration products. As shown in Figs. 17 and 18, replacement of crushed limestone aggregate in SCC with LWAs such as Leca, Scoria, and Perlite causes an increase in penetrability and water absorption because of pore structure and high water absorption ability of lightweight aggregates compared with crushed limestone. Therefore, it can be concluded that LWSCC has less resistance in the sulfate environment.

4. The proposed formula

In this section, some equations are proposed to evaluate the flexural and splitting tensile strengths concerning the compressive strength at the age of 28-day. Figures 23 and 24 depict the proposed formula for the LWSCCs with different lightweight aggregates. The results show that the proposed formulas have enough accuracy (having acceptable R-squared values) to predict the flexural and splitting tensile strengths for the LWSCCs as a function of compressive strength at the age of 28-day.

5. Conclusions

In the present study examined the performances of fresh and hard LWSCC, containing different percentages of
Perlite, Leca, and Scoria. The obtained results have been listed below:

1. The addition of lightweight aggregates to the concrete decreased the performance of fresh concrete due to the increasing water absorption of these aggregates. The results of the V-funnel test were depended on the specific weight of concrete. Therefore, after the witness concrete, the LWSCC made of Scoria was shown to have the minimum offloading time. Also, the results of the L- and U-box tests were depended on the flowing ability of samples. Besides, the particle size and the flowing capacity of the concrete can affect the results of the J-ring test. Therefore, the LWSCC made of Perlite, which was shown to have the smallest particles, reported the best performance in this test.

2. The results of the compressive strength, tensile strength, and flexural strength tests revealed that the addition of lightweight aggregates decreased these strength due to a decrease in the specific weight of concrete. Scoria, Perlite, and Leca concrete had different values of these strengths as below:

   - For compressive strength: Scoria > Perlite > Leca
   - For tensile strength: Scoria > Leca > Perlite

3. Results of the water diffusion test demonstrated negative effects for the addition of lightweight aggregates on the permeability of concrete. In fact, due to an increase in its porosities, the LWSCCs had different permeability as below:

   - For water permeability: Leca > Scoria > Perlite

4. Results of the water absorption test made it obvious that the addition of lightweight aggregates increased the value of this parameter due to the special properties of these additives, leading to an increase in the porosities of LWSCCs. The LWSCCs had different values for water adsorption as below:

   - For water absorption: Perlite > Leca > Scoria

5. Results of the corrosion test in the sulfate and acid
environments demonstrated that the reduction percentage of mass and compressive strength for the LWSCCs was more than SCC. Among the lightweight aggregates, Scoria, Perlite, and Leca had different resistances in these environments as below:

Resistance in the sulfate environment:
Scoria > Perlite > Leca

Resistance in the acid environment:
Scoria > Leca > Perlite

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