Mechanical Characterization of Lightweight Concrete Produced with Steel Slag and Light-Expanded Clay Aggregate

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Abstract

Light-expanded clay aggregates (LECA) is an alternative material which widely used in building materials and many other applications. This paper investigates the permeability, compressive, and splitting tensile strength of concrete specimens produced with ordinary coarse aggregate or LECA. Eight concrete mixes with the partial replacement of cement by steel slag powder were prepared to get an appropriate mix design for ordinary coarse aggregate or LECA concrete. The variables in the current study include steel slag content (0% to 60%) and curing time (7, 28, or 90 days). This study finds out that 40% of cement can be replaced by steel slag powder, which causes the compressive and splitting tensile strength to increase. The steel slag content has no important effect on the permeability coefficient of specimens. Furthermore, the compressive and splitting tensile strength of coarse aggregate concrete specimens is more than that of LECA concrete specimens for a given steel slag content and curing time. In general, increasing curing time results in an increase in both the compressive and splitting tensile strength of specimens.

Keywords: LECA, Steel Slag,Concrete, Permeability, Compressive Strength, Tensile Strength.

1. Introduction

The durability characteristics of concrete include various aspects such as permeability, compressive and tensile strength, abrasion, and frost resistance[1]. The advantages of structural concrete such as strength, workability, and high durability make it a most common material in the construction industry. However, the high density of concrete increases the weight of construction which is the main disadvantage of concrete structures. A possible solution for this problem may be the use of lightweight aggregate such as light expanded clay aggregate (LECA) to produce lightweight concrete [2]. LECA has expanded clay aggregates which are subjected to desiccation, heating, and firing in a rotary kiln at high temperatures. LECA is a subtype of lightweight aggregates used for various civil engineering applications such as self-curing concrete [3], geopolymer lightweight aggregate and porous concretes [4–11] and filler material [12]. [13][13] reviewed the prior studies related to conventional cementitious materials and geopolymers comprising LECA and indicated that the incorporation of LECA in the matrix increases the workability, water absorption, thermal insulation, fire resistance, and a decrease in the density, mechanical stress, chloride penetration or freeze/thaw resistances. Priyanka et al. [14] indicated that an increase in LECA content in lightweight geopolymer concrete decreased the compressive strength and increased the workability. Nevertheless, the strength is higher than the conventional concrete due to geopolymerization. Movahedi and Linul[12] used LECA foam elements as the filler material inside the empty thin-walled circular aluminum tube. The results showed that the presence of LECA enhanced energy absorption. Nahhab and Ketab[15] studied the effects of LECA content and volume fraction of micro steel fibers on the mechanical characteristics of self-compacting lightweight concrete. The results showed that an increase in fiber or LECA content had an adverse effect on water sorptivity.The utilization of industrial waste materials in the construction industry has received a lot of attention in the press recently due to rising construction costs, declining natural resources, and environmental protection[16–18]. Steel slag is an industrial byproduct as the solid waste generated in the crude steel refining process and often features high hardness which caused serious pollution to the environment [19–22]. Steel slag containing active compounds contains MgO and CaO similar to cement, so it has the cementing properties of cement. Rosales et al. [23] studied the cementation reaction properties and mechanical behavior of steel slag. The authors recommended that the application of steel slag reduces the use of raw materials for manufacturing cement and up to 20% of cement can be replaced by stainless steel slag. Previous studies indicated that steel slags can be utilized in concrete products or as aggregate material in construction applications that reduce carbon emissions from concrete production [24–30].

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Studied the utilization of steel slag in concrete, focusing on the effects of steel slag on the mechanical behavior of concrete.

The results of the tests showed that the compressive strength of concrete is not monotonous with an increase in steel slag content. However, the presence of steel slag in the concrete has a positive effect on the energy absorption characteristics.

Mohmood et al. [31] used steel slag in high-density geopolymer concrete. Based on the results, it can be conducted that the addition of steel slag offers higher bulk density to concrete and increase workability. Li and Jiang [24] investigated the utilization of limestone powder as an activator for slag concrete. The results showed that limestone addition significantly increases the early-age strength of slag concrete and improves the workability of slag concrete.

Permeability is most important characteristics affecting concrete durability against ions and pollutants penetration [32–34]. Decreasing permeability coefficient results in a decrease of fluid penetration in concrete which is beneficial. Hosseini Balam et al. [35] indicated that using urea-CaCl2 solution for curing control results in an increase of water absorption and permeability of lightweight aggregate concrete. Zhang et al. [36] showed that increasing steel slag as aggregates and sulphoaluminate cement as binder improves the mechanical characteristics, and decreases the water permeability.

In this research, steel slag was substituted for 20%, 40%, and 60% of cement in ordinary and porous concrete cubes and its effects on the permeability, compressive and splitting tensile strength at particular curing times7, 28, and 90 days were investigated.

1. Materials and Methods

2.1. Materials

In this work, Portland cement was used for all concrete mixes. The physical and chemical properties of the cement are reported in Table 1. Two types of coarse aggregate were used in this study, namely natural coarse aggregate and LECA. The natural coarse aggregate with an apparent density of 2693 kg/m3 and gradation specifications in Table 2 was used in this study.

The LECA with three different maximum sizes, namely 5, 15, and 20 mm with a specific gravity of about 1.25 was used. The steel slag with an apparent density of 2950 kg/m3 was used in the current study provided by the Isfahan steel factory, in Isfahan, Iran. The X-ray diffraction (XRD) results of the steel slag are presented in Fig. 1. Table. 3. gives the mineral content of the steel slag obtained from XRD analysis.

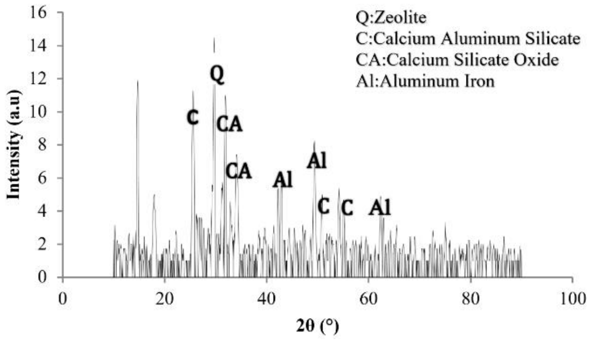

Fig. 1. X-ray diffraction (XRD) results of steel slag.

Table. 1. Physical and chemical properties of the cement.

Property/Composition	Value
SiO_2(%)	22
Al_2O_3(%)	5
Fe_2O_3(%)	3.82
CaO(%)	64
MgO (%)	1.90
SO_3(%)	1.50
L.O.I (%)	1
Na_2O (%)	0.25
K_2O (%)	0.49
Specific gravity	3.14
Specific surface area (m^2/kg)	325
Compressive strength of 2 days (N/mm^2)	33

Table. 2. Coarse aggregate gradation specification.

Sieve size (mm)	% Passing
37.5	100
25	70-100
19	30-75
12.5	20-35
9.5	10-25
4.75	0-5
2.36	0

Table. 3. Mineralogical compositions of the steel slag.

Composition	Value (%)
Sio_2	32.09
AL_2O_3	15.4
Fe_2O_3	1.53
Cao	39.32
Mgo	8.75
SO_3	2.28
Na_2O	0.42
K_2O	0.47
TiO_2	1.23
MnO	0.99
L.O.I	0.02

2.2. Mixture Design and Preparation of Specimens

The concrete mix proportions were shown in Table. 4. As shown from Table. 4., In the CgSs-specimens, pulverized steel slag was used as a portion of cement. The replacement fractions of cement with pulverized steel slag were 20%, 40% and 60%. The specimen containing no steel slag and LECA was selected as the reference specimen (CgCs). In the LeSs-specimens, LECA was used instead of coarse aggregate with the steel slag content equal to 0%, 20%, 40% and 60%.To prepare specimens, aggregates including pulverized steel slag, coarse aggregate or LECA were premixed to obtain well-mixed aggregates and then were premixed with 30% of total water consumption. Afterward, the remaining water mixed with the required cement and then was added to the materials.

Table. 4. Mixing proportions of concrete specimens.

Specimen codes	W/C	Cement (kg)	Steel slag (kg)	Coarse aggregate (kg)	LECA (kg)
CgCs	0.35	0.422	-	1670	–
CgSs20	0.35	0.338	0.084	1670	–
CgSs40	0.35	0.253	0.169	1670	–
CgSs60	0.35	0.169	0.253	1670	–
LeCs	0.35	0.422	–	–	186
LeSs20	0.35	0.338	0.084	–	186
LeSs40	0.35	0.253	0.169	–	186
LeSs60	0.35	0.169	0.253	–	186

For specimen preparation, the mixture was poured into the molds in three layers. Each layer was pre-compacted by hand rodding 25 times and then these molds were subjected to vibration for the 30s on the vibration table for further compaction. For water permeability, tensile, and compressive strength tests, the cylindrical specimens with dimensions of 100 mm diameter and 200 mm height were prepared. The specimens were cured and kept in a standard curing condition (i.e. 20 ± 2℃ and 95 ± 2% relative humidity) for 24 h, and then kept in 20 ± 2℃ water until the testing time. The water permeability, tensile and compressive strength tests were performed in triplicates on cylindrical specimens after curing periods of 7, 28, and 90 days and the test results were reported as averages.

Compressive strength is an effective characteristic and an indicator of concrete quality contributing to concrete durability. The specimens were tested for compressive strength as per the standard specified in ASTM C 39 with a displacement rate equal to 0.02 mm/s. The specimens were also tested for the splitting tensile strength based on the ASTM C496 with a constant stress rate of 0.6 MPa/min. Fig. 2. shows the testing setup for the compressive and splitting tensile strength. The permeability of concrete is a basic indicator to evaluate the durability characteristics of concrete. In this study, the permeability of concrete mixtures was evaluated by DIN 1048 (part 5). After 28 days of underwater curing, the specimens were oven dried for 2 days at 60 °C to remove any moisture content. A constant hydrostatic pressure of 10 bar was applied from the top on each specimen for 24 hours.

Fig. 2. Testing setup for (a) compressive and (b) splitting tensile strength.

After the testing was completed, the specimen was split into two halves and the maximum depth of penetration in each specimen was measured. The mean of the maximum depth of three specimens was noted as the depth of penetration. The maximum depth of penetration can be converted to the equivalent permeability coefficient using Valenta’s equation [37]:

$$k = \frac{e^2 \nu}{2ht} \qquad \text{Eq. (1).}$$

where k is equivalent permeability coefficient in m/s, e is maximum depth of penetration (m), v is the fraction of the volume of concrete occupied by pores which represents discrete pores that do not become filed with fluid except under pressure and can be calculated from the increase in the mass of concrete during the test, h is hydraulic head (m), t is time under pressure (s).

3. Results and Discussion

Fig. 3. shows the compressive strength results of coarse aggregate or LECA specimens under different curing times of 7, 28, and 90 days. As shown in Fig. 4(a), the compressive strength value of coarse aggregate specimens is more than the corresponding compressive strength value of LECA specimens which is in good agreement with the previous research [3, 14]. The difference between the compressive strength values of coarse aggregate or LECA specimens is more pronounced in the specimens without steel slag than in other specimens and it is almost independent of the curing time. The results indicate that the compressive strength value of coarse aggregate or LECA specimens enhances gradually due to the increasing steel slag content from 0% to 40% and then decreases with more addition of steel slag content up to 60%. The compressive strength value of CgSs40 after 90 days was 23.03 MPa and 64% more than that of the reference specimen (CgSs) at this period of curing. However, the compressive strength value of LeSs40 was 17.4 MPa and 145% more than that of reference specimen (LeCs) after 90 days. This indicates that steel slag content has a more significant effect on the LECA specimens than the coarse aggregate specimens. The compressive strength value of both coarse aggregate and LECA specimens enhances gradually due to the increasing curing time. The curing time has a more important effect on the compressive strength of the coarse aggregate specimens than that of the LECA specimens.

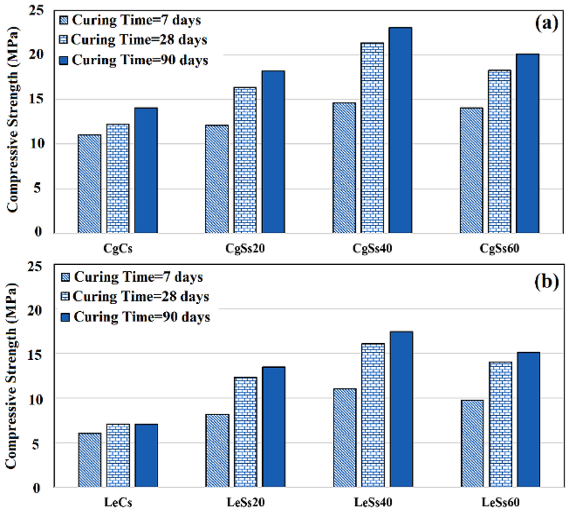

Fig. 3. Variation of compressive strength of (a) coarse aggregate specimens (b) LECA specimens.

Fig. 5. shows the splitting tensile strength results of coarse aggregate or LECA specimens under different curing times of 7, 28, and 90 days. Fig. 4.(b) shows the splitting tensile strength of coarse aggregate specimens versus the splitting tensile strength of LECA specimens.

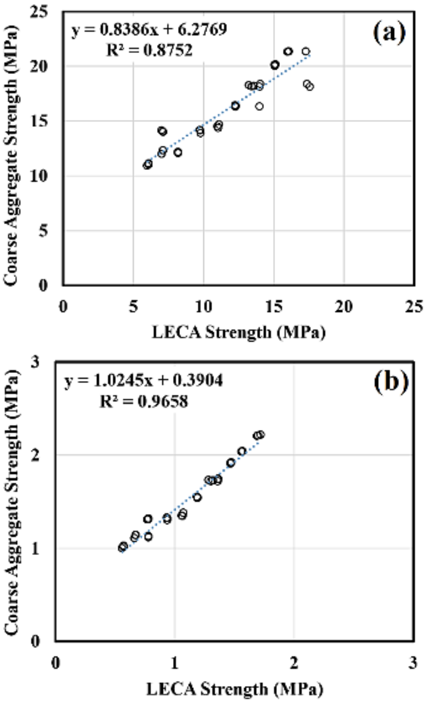

Fig. 4. Tests results of coarse aggregate specimens versus LECA specimens (a) Compressive strength (b) Splitting tensile strength.

As shown, the splitting tensile strength value of coarse aggregate specimens is also more than the corresponding splitting tensile strength value of LECA specimens which is the same as the previous works [38, 39].The results indicate that the splitting tensile strength as well as the compressive strength of the coarse aggregate or LECA specimens increases as the steel slag content increases from 0% to 40% and then decreases with more addition of steel slag content to 60%.

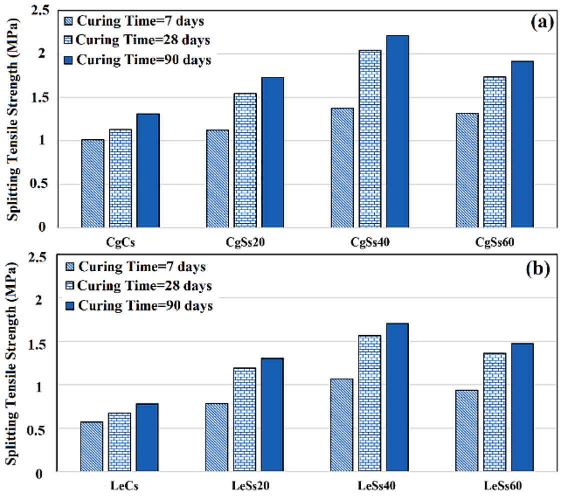

Fig. 5. Variation of compressive strength of (a) coarse aggregate specimens (b) LECA specimens.

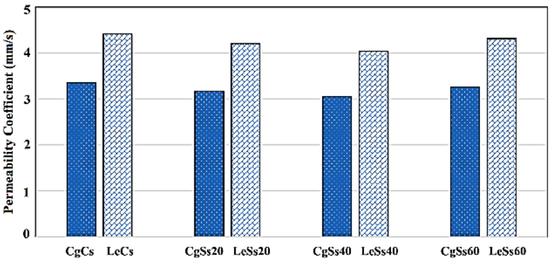

Fig. 6. Variation of permeability coefficient of specimens.

For example, the splitting tensile strength value of CgSs40 after 90 days was 2.2 MPa which is 69% more than that of the reference specimen (CgCs) at this period of curing. However, the splitting tensile strength of LeSs40 was 1.7 MPa and 118% more than that of the reference specimen (LeCs) after 90 days. Here, too, steel slag content has a greater effect on the splitting tensile strength of LECA specimens than that of coarse aggregate specimens. The results indicate that the splitting tensile strength of coarse aggregate is also more than that of LECA specimens for a given condition. In addition, increasing curing time results in an increase in splitting tensile strength, as shown by the results. A review of the results indicates that the effect of steel slag content on the compressive and splitting tensile strength is more effective at a curing time of 90 days than at other curing times.

Fig. 6. shows the permeability coefficient of specimens which is the average value obtained from three specimens. As shown, the permeability coefficient of LECA specimens is approximately 1.3 times that of coarse aggregate specimens. However, the steel slag content has very little effect on the permeability coefficient. The specimens containing 40% steel slag have the lowest permeability coefficient.

4. Conclusion

The utilization of industrial waste such as steel slag particularly in civil projects as an alternative material has gained popularity, which can be useful in waste management. In this study, a series of compressive strength, splitting tensile strength and permeability tests were performed on coarse aggregate and LECA specimens to investigate the effects of steel slag content and curing time on the mechanical properties of specimens. Based on the obtained results the following conclusions can be drawn:

1. The compressive and splitting tensile strength of coarse aggregate concrete specimens is more than that of LECA concrete specimens for a given steel slag content and curing time. However, the permeability coefficient of LECA concrete specimens is more than that of coarse aggregate specimens.
2. The steel slag content has no important effect on the permeability coefficient of both coarse aggregate and LECA concretes. Based on the compressive and splitting tensile test results, it can be conducted that the possible optimum replacement content of cement by slag material in both coarse aggregate and LECA concretes was found to be 40%.
3. The steel slag content has a more significant effect on the compressive and splitting tensile strength of LECA concrete specimens than the coarse aggregate concrete specimens. In general, the compressive and splitting tensile strength value of coarse aggregate concrete specimens is more than that of LECA concrete specimens. In addition, increasing curing time results in an increase in both the compressive and splitting tensile strength of specimens.

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Declaration

Conflict of interestThe authors declare no conflict of interest.

Author Contributions

S. Shiran: Conceptualization, Resources, Investigation, Writing - original draft.

M. Bayat: Supervision, Methodology, Formal analysis.M. Nourmohammadi: Formal analysis, Writing-original draft, E. Behzadpour: review & editing.

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