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Structural Behavior of Lightweight Concrete Made With Scoria Aggregates and Mineral Admixtures

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***Abstract*—**Structural lightweight concrete is used primarily to reduce the dead-load weight in concrete members such as floors in high-rise buildings and bridge decks. With given materials, it is generally desired to have the highest possible strength/unit weight ratio with the lowest cost of concrete. The work presented herein is part of an ongoing research project that investigates the properties of concrete mixes containing locally available Scoria lightweight aggregates and mineral admixtures. Properties considered included: workability, unit weight, compressive strength, and splitting tensile strength. Test results indicated that developing structural lightweight concretes (SLWC) using locally available Scoria lightweight aggregates and specific blends of silica fume and fly ash seems to be feasible. The stress-strain diagrams plotted for the structural LWC mixes developed in this investigation were comparable to a typical stress-strain diagram for normal weight concrete with relatively larger strain capacity at failure in case of LWC.

***Keywords*—**Lightweight Concrete, Scoria, Stress, Strain, Silica fume, Fly Ash.

I. Introduction

LIGHTWEIGHT concrete is not just one item; it is spectrum of different concretes with variety of characteristics, and it fills a number of needs; it can be gaseous or foam concrete using specially prepared chemicals; a no-fines concrete using ordinary gravel or crushed stone on a gap-graded bases; a normal weight concrete with an excessive amount of entrained air; or a concrete that is made using lightweight aggregate. Lightweight aggregates are aggregates prepared by expanding, calcining or sintering products such as blast furnace slag, clay, diatomite, fly ash, shale or slate. Also, aggregates can be prepared by processing natural materials such as pumice, scoria or tuff [1]-[3].

The primary use of structural lightweight concrete is to reduce the dead load of concrete structures, which then allows the structural designer to reduce the size of the beams, columns, and other load bearing elements. Use of LWAC instead of normal weight concrete (NWC), for example, as a floor slab in a multi-story building, depends on the relative costs and the potential savings that can occur by the use of a lighter material. LWAC is about 25% lighter than normal concrete and, in a design where the dead load is equal to the live load, a saving of 15% in energy intensive steel reinforcement can result. Equal or greater savings are achieved in columns and footings. For long-span bridges, the live load is a minor part of the total load and a reduction in density is translated into reductions in not only mass, but also in section size [4]-[6].

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The potential of using lightweight concrete (LWC) as a construction material has received considerable attention from the construction industry in recent years. The lightweight concrete is similar to normal weight concrete except that it has a lower density. LWC offers the consumer an outstanding combination of properties such as reduced mass, improved thermal and sound insulation, reduced energy demand during construction, less need for structural steel reinforcement, and better fire resistance [7]-[10]. It is expected that the outcome of this investigation will firmly establish the feasibility and the merits of locally available natural lightweight aggregates, for producing structural lightweight concrete (SLWC). The main objectives of this investigation include: developing lightweight concrete (LWC) mixes suitable for structural applications using locally available materials.

II. Experimental Program

The experimental program focused on investigating the properties of fresh and hardened concretes containing two types of locally available natural lightweight aggregates, and mineral admixtures such as silica fume and fly ash.

A. Materials

The materials used in this investigation include lightweight aggregates (LWA), cement, silica sand, and mineral admixtures. Two types of natural LWA's were procured from different locations in Saudi Arabia, Harrat Khyber and Harrat Kishab, designated as Type KH and Type KI respectively, in this investigation. The physical properties of the aggregates were determined following ASTM standards [11]-[13], as shown in Table I.

TABLE I
Physical Properties of Lightweight Aggregates and Silica Sand

		(LWCA) Type KH	(LWCA) Type KI	(LWFA) Type KH	Silica Red Sand
Unit Weight Kg/m^3	Loose	965	757	996	1580
	Rodded	1071	820	1040	1620
Bulk Specific Gravity	Dry	2.04	1.78	2.14	2.63
	SSD	2.1	1.85	2.1	2.60
Absorption %		5.75	13.8	5.6	0.5

B. Mix Proportions

The absolute volume method, ACI 211 [1], was used for designing the basic concrete mix. The final mix was optimized for workability, density and strength, using the following ingredients: cement, silica sand, natural lightweight coarse and fine aggregates, silica fume, fly ash, high range water-reducers, and water. After casting many trial mixes, and making necessary adjustments, the concrete mix that achieved relatively a good degree of workability, minimum density and an acceptable level of strength was considered as a basis for further investigation of the effect of mineral admixtures on the behavior of SLWC. The concrete mixes designed in this investigation were of similar workability and water to cementitious materials ratio. The details of these mixes are listed in Tables II and III.

TABLE II
CONCRETE MIX PROPORTIONS IN KG/M³ USING TYPE KH -LWA

Mix No.	Cem ent	Fly Ash	Silica Fume	Red sand	LWC A	LWFA	Wate r	**SP** (L)
1KH	400	0	0	200	550	350	250	1
2KH	380	0	20	200	550	350	250	3
3KH	360	0	40	200	550	350	250	3
4KH	340	0	60	200	550	350	250	4
5KH	380	20	0	200	550	350	250	2
6KH	360	40	0	200	550	350	250	1.5
7KH	360	20	20	200	550	350	250	3
8KH	340	40	20	200	550	350	250	2
9KH	340	20	40	200	550	350	250	4
10KH	320	40	40	200	550	350	250	4
11KH	320	20	60	200	550	350	250	3

SP: Superplasticizer

TABLE III
CONCRETE MIX PROPORTIONS IN KG/M³ USING TYPE KI-LWA

Mix No.	Cement	Fly Ash	Silica Fume	Red sand	LWC A	LWFA	Wate r	**SP** (L)
1KI	400	0	0	200	450	350	260	3.5
2KI	360	0	40	200	450	350	260	3.5
3KI	360	20	20	200	450	350	260	3.5
4KI	340	40	20	200	450	350	260	2.5
5KI	340	20	40	200	450	350	260	3.5
6KI	320	40	40	200	450	350	260	3
7KI	320	20	60	200	450	350	260	4.5
8KI	300	40	60	200	450	350	260	4.5

III. RESULTS AND DISCUSSION

The results of the experiments conducted on structural lightweight concretes produced with local aggregates will be discussed. Experiments conducted include, workability, unit weights, compressive strength, splitting tensile strength, and stress-strain diagram in compression.

A. Workability

The workability of the concrete mixes cast in this investigation was measured using the slump test. The slump test results varied from 150mm to 180mm immediately after mixing. The larger slump for LWC is desirable in order to account for the gradual loss in workability, caused by the high absorption of the aggregates, which may occur 1 to 2 hours after mixing, i.e. at the beginning of pouring the concrete in the formwork. To be within the scope of this investigation, the workability of all the LWC mixes cast, was kept almost the same by changing the dosage of superplasticizer whenever needed, in particular for the mixes containing relatively high percentages of silica fume and fly ash.

B. Unit Weight

The fresh unit weights of most of the LWC mixes made with type KH aggregates showed a unit weight varying from 2030kg/m^3 to 2050kg/m^3, whereas most of the mixes made with type KI- LWC showed a unit weight varying from 1816kg/m^3 to 1875kg/m^3. Being lighter in weight, 757kg/m^3 for LWC type KI, compared to 965kg/m^3 for LWC type KH, it is expected that the concretes made with type KI aggregates will have lower unit weight as shown in this investigation. Therefore, mixes made with type KI aggregates will be more suitable for significant reductions in dead loads needed in structural design. Most of the specification standards classify structural lightweight concrete based on air dry unit weight not exceeding 2000kg/m^3. The air-dry unit weight for type KH-LWC mixes varied from 1935 to 1995kg/m^3 with a corresponding range for type KI-LWC mixes varying from 1649 to 1875kg/m^3. It can be noticed that the range of air dry unit weight for type KH-aggregate does not meet ACI requirements of air dry density not exceeding 1850kg/m^3; whereas the range of air dry unit weight for type KI aggregate complies with the ACI specifications for structural LWC. This is expected since type KI aggregates were lighter in weight compared to type KH as mentioned previously. It should be noted that the air-dry unit weights of type KH aggregates LWC, can be reduced to meet ACI requirements by making some adjustments on the composition of the mixes without sacrificing the structural strength required at 28 days.

C. Compressive Strength

Most general use concrete has a compressive strength between 21 MPa and 35 MPa. With given materials, it is generally desired to have the highest possible strength/unit weight ratio with the lowest cost of concrete. The test results listed indicate that producing structural lightweight concrete, SLWC, using locally available natural lightweight aggregates, LWA, and mineral admixtures seems to be feasible. The concrete produced possesses 28 days compressive strength of about 43 MPa and a corresponding air dry unit weight of about 1995kg/m^3 for type KH aggregates; whereas the concrete produced with type KI aggregates possesses 28 days compressive strength of about 39 MPa and a corresponding air dry unit weight of about 1786kg/m^3 which falls far below the ACI requirements of 1850kg/m^3 for producing SLWC. Furthermore, all LWC mixes made with type KI aggregates can be used for producing SLWC without violating the ACI requirements. It can also be observed from Figs. 1 and 2 that the early strength at 7 days of the LWC mixes developed are structurally acceptable and comparable with those produced for normal weight concrete. Figs. 1 and 2 show that the range of 7 days strength for LWC produced with type KH aggregates varied from 16 to 23 MPa; whereas the corresponding range for LWC made with type KI aggregates varied from 20 to 24 MPa. The same figures show that the range of 28 days strength for LWC produced with type KH aggregates varied from 22.5 to 43 MPa; whereas the corresponding range for LWC made with type KI aggregates varied from 29 to 38.7 MPa.

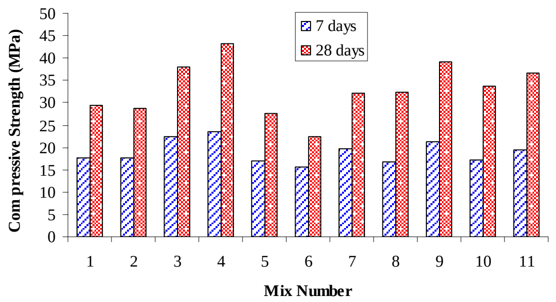

Fig. 1 Compressive strength of type KH- LWC at 7 and 28 days

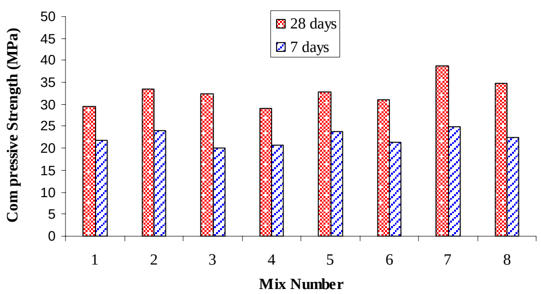

Fig. 2 Compressive strength of type KI- LWC at 7 and 28 days

D.Splitting Tensile Strength

Majority of the splitting tensile strength test results for air dried LWC were about 8-9% of the corresponding compressive strength. This is slightly below the standard range reported in the literature of 10% for normal weight structural concrete [2], [3]. This could be due to the cellular structure of light weight concrete that enhanced the initiation and growth of microcracks under tensile loading, and thus resulted in larger decrease in tensile strength compared to normal weight concrete.

E. Stress-Strain Diagrams in Compression

The compressive behavior of the LWC mixes designed in this investigation can best be understood by plotting the complete stress-strain response. All specimens were tested under uniaxial compression by applying a vertical load gradually until they reached complete failure. During the test, the displacement readings of the vertical LVDTs were recorded with the corresponding load. The readings of the vertical LVDTs attached to the specimen sides with a gage length of 120mm were used to record the axial deformation and axial strains at the surface of the specimen. The axial strains determined were also double checked by pasting two electrical strain gages of 60mm gage length on the sides of each specimen. The results of all tested specimens were recorded and analyzed in terms of their axial stress-strain curves as shown Figs. 3 through 8.

The shape of the stress-strain curves of LWC tested, can be characterized with a linear elastic response up to about 40 to 50% of its ultimate load carrying capacity; a curvilinear response up to the peak followed by a post peak curvilinear segment of decreasing slope. Close to the peak load, vertical hairline cracks starts appearing on the surface of the specimen. The number and width of these cracks keep on increasing with further increase in axial load until they form a major shear crack at an angle of 45^{o} with the longitudinal axis of the cylinder, when the specimen reached its failure load. Because of the porous nature of LWA, the vertical cracks passed through the aggregates, and thus forced longitudinal pieces of the cylinder to split apart.

It can be observed from Figs. 3 and 4 that by adding up to 15% of silica fume, as a partial cement replacement by weight, to the mixes containing Type KH lightweight aggregates caused a significant increase in compressive strength and modulus of elasticity after 28 days, about 37% and 14%, respectively compared to mixes without silica fume; whereas, adding up to 10% fly ash, as partial cement replacement by weight, to the same mixes, caused about 16% decrease in compressive strength, and similar modulus of elasticity after 28 days, compared to mixes without fly ash. For the mixes containing several blends of silica fume and fly ash as shown in Figs. 5 and 6, it can be seen that the mixes containing 10% or more of silica fume, and 5% or more fly ash showed better or similar performance, in terms of compressive strength or modulus of elasticity after 28 days compared to mixes containing equal contents of silica fume or fly ash separately. It should be noticed that the addition of the silica fume decreases the porosity, increases the packing density, and thus enhances the strength of the system. The addition of fly ash improves the workability, reduces early heat of hydration and thus enhances the durability. Therefore, it is preferable to use silica fume, fly ash blends in producing structural LWC without sacrificing strength and workability by incorporating the required dosage of superplasticizer.

Producing structural lightweight concrete using type KI aggregate is also feasible. The test results shown in Figs. 7 and 8 indicate that the stress-strain response of the mixes containing a blend of 5% silica fume and 5% fly ash by weight of cement was almost similar to the response of the reference mix. Whereas, the mixes containing 10% or more silica fume, and 5% fly ash showed a significant increase in compressive strength, about 30%, almost equal modulus of elasticity, and a marked reduction in ductility compared to reference mix. Furthermore, it should be noted that the test results indicate that the mixes containing type KI-LWA, exhibited relatively lower compressive strength, modulus of elasticity and ductility compared to mixes containing type KH-LWA. This is due to lower unit weight, high absorption capacity, and porous structure of type KI compared to type KH aggregates.

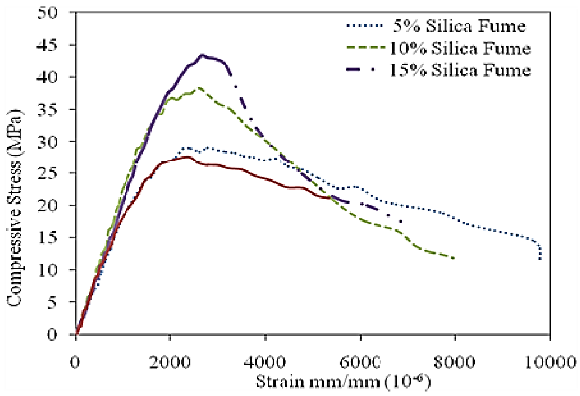

Fig. 3 Effect of silica fume on the compressive behavior of LWC-aggregate KH

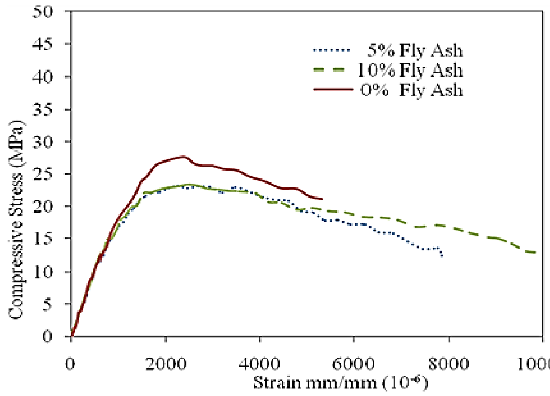

Fig. 4 Effect of fly ash on the compressive behavior of LWC-aggregate KH

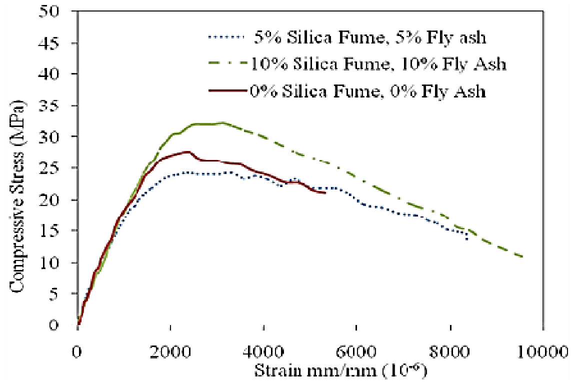

Fig. 5 Effect of silica fume, and fly ash on the compressive behavior of LWC-aggregate KH

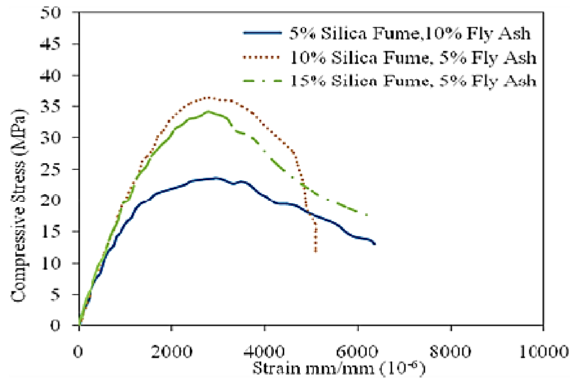

Fig. 6 Effect of silica fume, and fly ash on the compressive behavior of LWC-aggregate KH

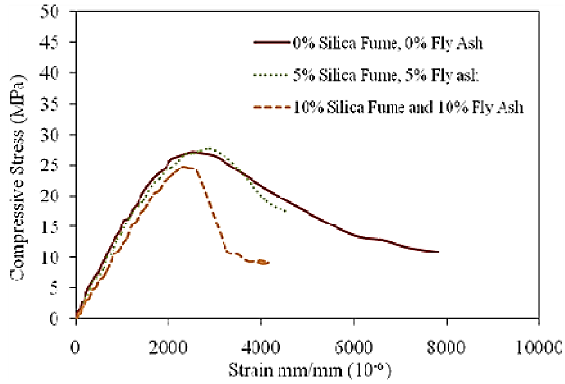

Fig. 7 Effect of silica fume, and fly ash on the compressive behavior of LWC-aggregate KI

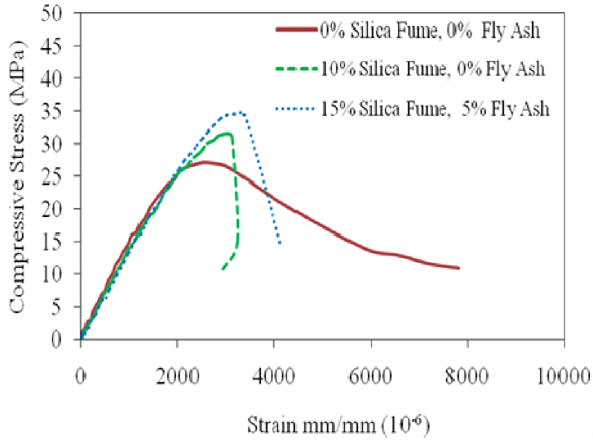

Fig. 8 Effect of silica fume, and fly ash on the compressive behavior of LWC-aggregate KI

IV. Conclusions

Based on the test results of this investigation the following conclusions can be drawn:

1. Lightweight concrete (LWC) mixes suitable for structural applications were developed using two different types of locally available natural lightweight coarse aggregates designated as type KH and type KI and natural lightweight

fine aggregate, Type KH. The properties of the mixes developed are listed in Table IV:

TABLE IV
PROPERTIES OF THE MIXES DEVELOPED

Property	LWC Mixes containing Type KH Coarse Aggregates	LWC Mixes containing Type KI Coarse Aggregates
Fresh unit weight	2025-2066 kg/m^3	1649-1875 kg/m^3
Air dry unit weight	1935-1995 kg/m^3	1720-1820 kg/m^3
Oven dry unit weight	1817-1898 kg/m^3	1558-1674 kg/m^3
Slump	50-180 mm	170-180 mm
Compressive strength (28 days)	22.5-43 MPa	29-39 MPa
Splitting tensile strength (28 days)	2.4-3.5 MPa	2.3-3.4 MPa

2. Replacing cement with 5 to 15% silica fume on weight basis, for type KH-LWC caused up to 37% and 14% increase in compressive strength and modulus of elasticity after 28 days respectively compared to mixes without silica fume; whereas, adding up to 10% fly ash, as partial cement replacement by weight, to the same mixes, caused about 16% decrease in compressive strength, and similar modulus of elasticity after 28 days, compared to mixes without fly ash. The mixes containing several blends of silica fume and fly ash, 10% or more of silica fume, and 5% or more fly ash showed better or similar performance, in terms of compressive strength and modulus of elasticity after 28 days compared to mixes containing equal contents of silica fume or fly ash separately. Furthermore, the test results indicated that the mixes containing type KI-LWA, exhibited relatively lower compressive strength, modulus of elasticity and ductility compared to mixes containing type KH-LWA. This is due to lower unit weight, high absorption capacity, and porous structure of type KI compared to type KH lightweight aggregates.

3. The stress-strain diagrams plotted for the structural LWC mixes developed in this investigation were comparable to a typical stress-strain diagram for normal weight concrete with relatively larger strain capacity at failure in case of LWC.

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