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PROPERTIES OF STRUCTURAL LIGHTWEIGHT HIGH STRENGTH SELF-COMPACTING CONCRETE

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ABSTRACT: Combining structural lightweight concrete and self-compacting concrete advantages is a significant challenge in modern concrete technology research. The density of concrete can be reduced by using lightweight aggregate. Consequently, structural self-weight is also reduced. Porous lightweight aggregates have low compressive strength, which presents a challenge in developing high-strength structural lightweight self-compacting concrete. The strength and weight of self-compacting concrete can be enhanced to obtain a special concrete with multiple benefits. Pumice from North Sinai in Egypt was used as a locally available natural lightweight aggregate. The properties of the concrete produced were studied at fresh and hardened states in different proportions of partial replacement of dolomite with pumice to find the optimum replacement percentage. The optimum mix has a high strength of 60 MPa and 1.98 g/cm³ unit weight, which is considered structural lightweight concrete and high strength. Moreover, it has self-compacting concrete characteristics. Results showed that the workability of self-compacting concrete increased with the decrease of concrete unit weight.

Keywords: Structural lightweight concrete; Self-compacting concrete; High strength concrete; Pumice.

1. INTRODUCTION

Structural lightweight concrete (SLWC) is a special type of concrete. Which gives an additional benefit of reducing the structure's dead weight and thermal conductivity. While self-compacting concrete (SCC) eliminates construction difficulties and errors during the pouring. Numerous studies have investigated the properties of SLWC or SCC separately. However, only a few studies have been investigated combining the benefits of both concrete. SLWSCC is a novel topic in recent research.

There are two types of lightweight aggregate (LWA) artificial and natural. They can be used to replace normal weight aggregate to produce SLWC. These lightweight aggregates are highly porous and very permeable. They have many characteristics that should be taken into consideration during the mixing, such as low crushing strength and a tendency of floating [1]. The unit weight of SLWC is about two-thirds or less than that of conventional concrete. Many recent researchers have tried to study the possibility of using light expanded clay aggregate (LECA), expanded shale, and other different types of LWA to achieve SLWSCC [2, 3].

LECA was used as a type of LWA to develop SLWSCC with normal strength [4]. The physical and mechanical properties of the SLWSCC produced were studied in this research [4]. The mechanical properties of SCC with recycled LWA were studied using some variable ratios of coarse to fine aggregate (C/F) [5]. Both the fresh and mechanical properties of SCC with recycled LWA mixtures were reduced in the case of a C/F aggregate ratio exceeding 1.5. 500 kg/m^3 of total binder content was needed to develop normal-strength SLWSCC. At least 600 kg/m^3 of total binder content was needed to develop a high-strength SLWSCC. It was required to add supplementary cementitious materials to enhance the flowability of these high-strength mixtures [5].

Pumice aggregate (PA) is an alternative kind of aggregate for structural lightweight concrete construction. The effect of pumice as LWA was investigated on the SCC in terms of thermal expansion for the first time [6]. The pumice lightweight aggregate (PLA) was used to study the properties of SLWSCC in terms of various conditions of curing [7]. A sufficient dosage of superplasticizers and viscosity modifying admixture was needed to correct the floating of pumice on the mixture's surface due to its lightweight [7]. Immersion of pumice in water for 24 hours before concrete mixing increases the compressive strength of SLWSCC [7]. Pumice is natural. It has more pores. Thus, it has high water absorption, and less density than the normal-weight aggregate (NWA). Therefore, the compressive strength and unit weight of LWC produced with pumice aggregate is expected to be less than the concrete produced with normal aggregate. The effect of pumice as coarse aggregate replacement was studied on the concrete properties. The use of PLA of 50% to 100% can be categorized as SLWC [8]. To face any negative impact on the concrete strength, it should be important to enhance the strength of the paste binder of the concrete due to the lower strength of the porous lightweight aggregate. The mortar phase of concrete made with pumice was improved through the incorporation of Nano-silica [9]. The compressive strength of pumice concrete with the addition of Nano-silica is greater than the compressive strength of pumice concrete without Nano-silica [9].

The workability and mechanical properties of the SLWSCC were studied in terms of the effect of fine particles amount [10]. Silica fume (SF) has the best impact on the SCC fresh properties and achieves a high strength in the hardened state. Therefore, mixtures that contained SF can be recommended in the production of lightweight concrete with the advantages of SCC properties [10].

Because of the above considerations, the main aim of this experimental study is to produce a novel SLWHSSCC that has a lower density than normal-weight HSSCC using locally available pumice from North Sinai, Egypt.

2. RESEARCH SIGNIFICANCE

The specific objectives of the present study are to assess the mechanical and rheological properties of this innovative concrete SLWHSSCC. Establish a preliminary comparative study on the SLWSCC properties to those of normal SCC in the fresh and hardened state. The development of this special type of high-performance concrete responds to some urgent needs of the construction sector due to all its combined benefits of low weight, high strength, and self-compact ability properties**.**

3. EXPERIMENTAL WORKS

The experimental study consists of two stages: First, by absolute volume method, several trials of mixes at fixed coarse to fine (C/F) aggregate ratio 1:1 and variable water/binder ratios were cast and tested to find out the self-compacting properties with high compressive strength at 28 days. According to the results obtained, the mix, which achieves the self-consolidating properties with high strength and has the minimum density, was selected for further investigation as a control mix or a standard mix.

Second, from the control mix chosen, four self-compacting concrete mixes with high compressive strength were prepared. By using pumice as a lightweight aggregate to reduce the density. The used percentage ratios of pumice to dolomite are (100%: 0%), (75%: 25%), (65%: 35%), (50%: 50%) and (35%: 65%) respectively, by volume. The same water-to-binder ratio w/b, which equals 0.3, was used for all self-compacting concrete mixes. Moreover, a fixed 1.5 % of Super-plasticizer dosage was added to all mixes to obtain an acceptable flowability without segregation. The water, fine aggregate, and cement contents were kept constant for all self-compacting concrete mixes.

3.1 Used Materials

3.1.1 Cement and silica fume

In this experimental investigation, all materials used were locally available in Egypt. Ordinary Portland cement (CEM I 52.5 N) and silica fume (Micro silica) were used as the binder materials in all SCC mixtures. Cement was supplied from Sinai Cement Company with properties listed in table no.1, which meet Egyptian Standard Specification (E.S.S. 4756-1/2013) [11]. Silica fume was supplied from the Ferro-silicon alloys company (Aswan, Egypt). The product is a very fine particle, which has a good impact on cohesion and resistance to segregation. It was used in this study also, for its effectiveness in reducing or eliminating bleeding.

Table 1 Physical and mechanical properties of Sinai cement

Test	Results
Specific gravity	3.10
Fineness (Blaine) [m^2/kg]	420
Soundness [mm]	1.1
Compressive strength 2 Days [MPa]	30.9 (Min 20)
Compressive strength 28 Days [MPa]	68.0 (Min 52.5)
Initial setting time [min.]	138 (Min 45 min)

3.1.2 Coarse aggregate

As shown in Fig. 1, there are two types of coarse aggregate were used; crushed dolomite as a normal weight aggregate and pumice as a lightweight aggregate. The sieve analysis test was conducted for both types.

Fig.1 a) Pumice

Fig.1 b) Dolomite

The crushed dolomite was supplied from Attakai with 15 mm of maximum nominal size. It has an angular and irregular particle shape. It was satisfied the (E.S.S 1109/2008). Results of its sieve analysis test were tabulated in table 2.

Table 2 Sieve analysis results of dolomite

Sieve size [mm]	40	20	16	10	5	2.36
% Passing by weight	100	100	97	75	30	6

Pumice was collected from the northern coast of the Mediterranean Sea at El-Arish, North Sinai, Egypt, with 12 mm of maximum nominal size. Table no. 3 summarizes the properties of pumice. While table no. 4 shows the sieve analysis test results of pumice.

Table 3: Properties of pumice.

Description	Water absorption	Specific gravity
pumice	20 %	1.0

Table 4: Sieve analysis of pumice.

Sieve size [mm]	40	20	10	5	2.36
% Passing by weight	100	100	80	25	7

3.1.3 *Fine aggregates*

As for the fine aggregates, natural siliceous clean sand was used from El-Khatatba, as shown in figure (1-c). It satisfies the Egyptian Code (E.S.S. 1109/2008) and ASTM C-33 [12] specifications with a specific gravity of 2.6. Results of its sieve analysis test were tabulated in table 5

Table 5: Sieve analysis of fine aggregate – sand.

Sieve size [mm]	5	2.36	1.18	0.6	0.3	0.15
% Passing by weight	100	94.7	79.5	43	10	5

3.1.4 *Superplasticizer*

Sika Viscocrete3425 is a superplasticizer supplied by Sika Egypt Company. This product is used as a double effect viscosity-enhancing agent (VEA) and high-range water reducer. The manufacturer provides the physical and chemical properties of this product as tabulated in Table (6). It satisfies the three superplasticizer standards specification SIA 162 (2989), EN 934-2, and ASTM- C494 type G and F.

Table 6: Viscocrete3425 properties by the manufacturer

Properties	Value
Appearance	liquid
Density	1.08 kg/Lit
PH Value	4.0
Solid content	40 % by weight
Chloride content	Zero

3.2 Mix proportions:

The proportions of the SCC mixtures at different percentages of pumice replacement by volume was represented in Table 7.

4. METHODOLOGY

Tests such as slump flow test, time at 500 mm slump flow diameter T_{50}, J-ring, V-funnel, and L-box were used to assess the rheological properties of the SLWHSSCC produced. Compression, indirect tensile (splitting mode), and pullout tests were conducted to evaluate the mechanical properties. The durability properties were assessed through water absorption and sorptivity (capillary water absorption).

4.1 Fresh state

According to EFNARC [13]: The flowability and filling ability of the SCC were indicated by the slump test and T_{50} test. Visual stability index (VSI) was determined through the observation of water bleeding at the edge of the spread, or concentrating aggregates at the center. The viscosity of SCC was assessed by measuring the V-funnel and T_{50} times. The passing ability of SCC can be determined by both tests J-Ring and the three-bars L-box when flowing under its weight through more congested reinforcements without segregation or blocking. Fig. 2 presents the tests of SCC at a fresh state: slump flow, L-box, J-Ring, and V-funnel tests respectively .

Table 7: Mix proportions for SCC with PLA at different proportions.

Mix no.	Pumice percentages	Cement [kg/m^3]	Silica fume [kg/m^3]	Water [kg/m^3]	S.P. [kg/m^3]	Fine Aggregate [kg/m^3]	Coarse Aggregate [kg/m^3]	
							Dolomite [kg/m^3]	Pumice [kg/m^3]
1	SCC- 0%	550	55	183	9.075	799	799.0	0
2	35%	550	55	183	9.075	799	519.4	91.88
3	50%	550	55	183	9.075	799	399.5	131.264
4	65%	550	55	183	9.075	799	279.7	170.64
5	75%	550	55	183	9.075	799	199.8	196.89
6	100%	550	55	183	9.075	799	0	799

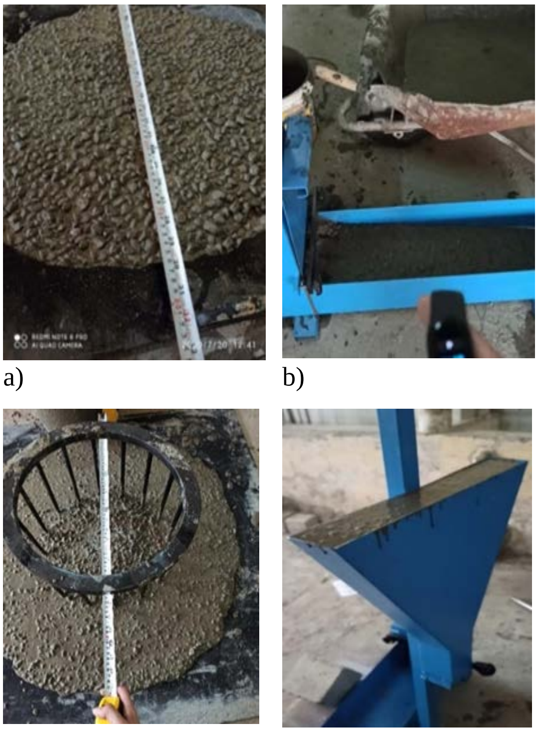

a) b)
c) d)

Fig.2: SCC Tests at fresh state a) Slump test b) L-Box test c) J-Ring test d) V-Funnel test

4.2 Hardened state

Immediately after measuring the rheological properties of the fresh SCC, cube specimens of size 150x150x150mm were cast without any compaction as shown in Fig. 3-a, 3-b, 3-c, and 3-d.

Fig. 3-a): Cube specimens for SCC – Mix 1-(control mix).

Fig. 3-b): Cube specimens for SCC – Mixes 3 & 4.

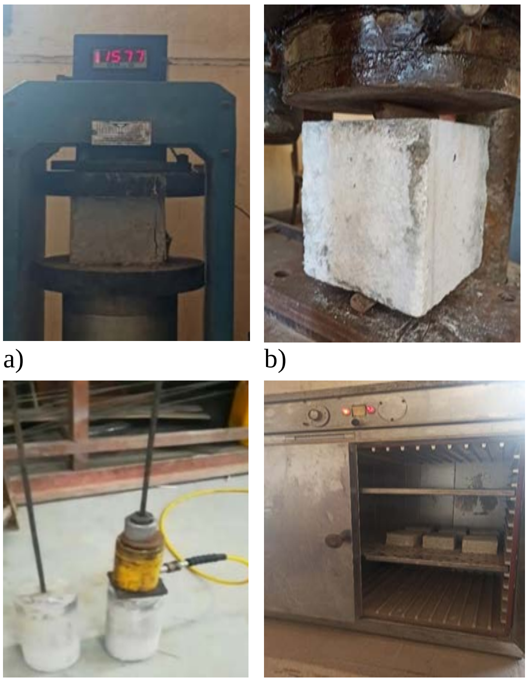
Fig. 3-c): Cube specimens for SCC – Mix 2

Fig. 3-d): Cube specimens for SCC – Mix 5

All specimens of hardened tests were cast without any compaction, as shown in Fig.4. After 24 hours, all specimens were de-molded with care so that no edges were broken. The curing was carried out by placing them in the curing tank containing water at ambient temperature for 7-days and 28-days before testing strength.

Fig. 4: Casting specimens for hardened tests without compaction.

Fig 5 presents all performed tests in the hardened state. All cubes specimens were tested in a digital compression testing machine of 2000 KN capacity to investigate the compression strength of the concrete, as shown in Fig. 5a.


a) b)

c) d)

Fig. 5: Tests at hardened state a) compressive strength test b) splitting tensile strength test c) Pullout test d) dry specimens in the oven.

The failure mode of SCC cubes specimens observed during testing was similar to the normal concrete, as shown in fig.6.

Fig. 6: failure mode of cubes

In addition, splitting tensile strength was performed at 28-days using 150x150x150 mm cube specimens. This test measures the tensile strength of SCC developed indirectly by applying compression force on the cube through a line load applied along its length. Supplementary steel loading bars are used to present the line load, as shown in Fig. 5b.

As per ASTM C 900-19 [14], the bond strength was determined by measuring the force required to pull an inserted steel rebar of 12 mm diameter from a cylinder specimen. Fig.7 represents the failure modes of specimens during the splitting tensile strength test and pullout test.

Fig. 7 a): Failure modes of cubes under splitting tensile test.

Fig. 7 b): Failure in the steel bar during pullout test.

Cubic specimens sized 100 x 100 x 50 mm specimens were also used for sorptivity test and water absorption test at 28 days. Firstly, specimens were dried in an oven at 105ºC – 110ºC, as shown in Fig.8. Then they were cooled to room temperature until they reached a constant weight. Thereafter, they were covered with a sealant to be submerged in a tank of water for 5 hours. The weight change was determined every 30 min.

Fig. 8: Specimen’s weight during sorptivity test.

5. RESULTS AND DISCUSSION

5.1 Fresh properties

5.1.1 Slump flow test, T50, and VSI

Table 8: Fresh properties of different mixes.

Mix no	Pumice percentages	Slump flow d $_{av.}$ [mm]	T at 500 mm [s]	VSI.
1	SCC – 0 %	670	7.5	0
2	SCC – 35 %	700	6.0	
3	SCC – 50 %	750	4.0	
4	SCC – 65 %	760	2.5	
5	SCC – 75 %	825	1.5	
6	SCC – 100 %	Exceed the slump table with high segregation		

From the results tabulated in Table 8 and shown in Fig. 9, the results of SCC mixtures indicate that the consistency of all innovative concrete mixes meets the standard specification SCC criteria, and they have good flowability. Except, mix no. 6 doesn’t satisfy the standard characteristics of self-compacting concrete. Mix no.6 has a total replacement of coarse aggregate with pumice. This refers that the increase in pumice percentage eliminating the self-compacting characteristics. The obtained slump flow values increased with the increase of the pumice percentage from 0 % to 75 %. In considering the water binder ratio *w*/*b* fixation at 0.3. This may be due to its weight and round shape. This indicates that the workability increases with the decrease of concrete unit weight, as shown in Fig. 9c. According to EFNARC guidelines [13], the slump flow of SCC (Mix 1) without any lightweight aggregate belongs to SF2. All the developed lightweight self-compacting concretes are divided into two classes in terms of slump results which varied from 660 mm to 850 mm: PLA percentage ≤ 50 % and PLA percentage > 50 %. They belong to SF2 and SF3 respectively. It was observed that no concentrated aggregates at the center of the spread and no sign of bleeding at the outer edge of the spread. Thus, the visual stability index (VSI) was determined by zero, indicating the high stability of the SCC mixtures with free segregation and bleeding. They are homogeneous and have no segregation. T_{50} time was measured during the test to describe the flow rate of the SCC mixtures, which refers to the SCC viscosity. The obtained results showed that the viscosity of the concrete decreases with the increase of pumice replacement percentages.

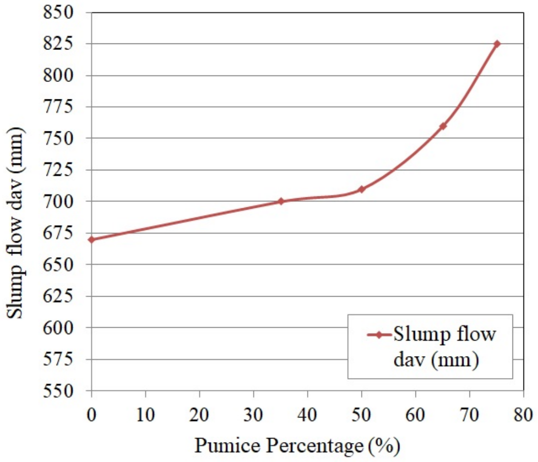


Fig. 9: a) Slump flow results for SCC mixes

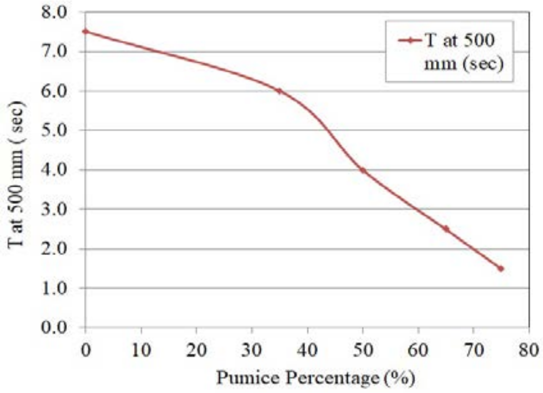


Fig. 9: b) T at 500 mm (sec) for SCC mixes.

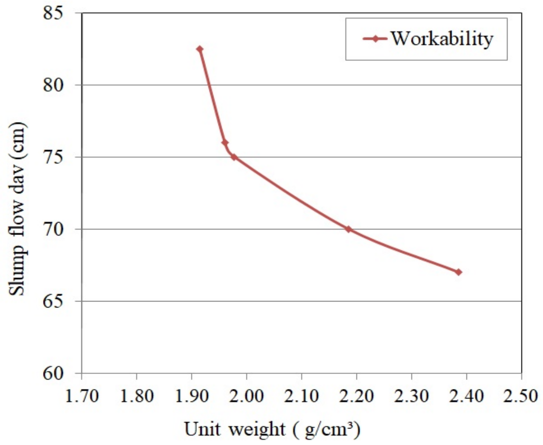


Fig. 9: c) Workability for SCC mixes versus the unit weight of concrete

5.1.2 J-ring, V-funnel flow, and L-box tests

According to ASTM C 1621/ C 1621M [15], the J-ring test proceeded. The passing ability of SCC mixes was indicated by calculating the difference between slump flow and J-Ring flow. The results indicate a good passing ability for each mix. Table 9 provides information about the fresh properties of all SCC mixes developed. All test results at fresh state were within the EFNARC limit [13]. From the results tabulated in the table (9), the V-funnel flow time of SCC (Mix 1) without any lightweight aggregate and the developed lightweight self-compacting concrete results are above 8.0 sec, which belongs to VS2 / VF2 according to EFNARC guidelines [13]. The passing ratio calculated from the L-box test indicates that all SCC mixes belong to PA2 classes.

Table 9: Comparative results between SCC (mix) and SCC selected.

Tests	Property	SCC (0% pumice)	SCC (50% pumice)
Slump flow [mm]	Filling ability	670	710
T50 [s]	Viscosity	7.5	4.0
J-Ring [mm]	Passing ability	670	700
L-box [h_2/h_1]	Passing ability	1	0.8
V-funnel [s]	Viscosity	11.8	9.0
VSI - index	Stability	0	0

5.2 Hardened properties

5.2.1 Unit weight (density)

Measurement of the concrete density is the most important factor when it comes to structural lightweight concrete. The unit weight variation of SCC specimens versus pumice replacement ratios is summarized and shown in Fig.10. It indicates that the increase in the pumice amount is the reason for the reductionism of the unit weight for all mixture compositions. The SCC mix with no replacement of coarse aggregate with pumice has a density of 2.39 g/cm^3. While the density of mixes that contain pumice as a coarse aggregate is up to 1.91 g/cm^3. These results indicate that pumice can produce SCC lighter than normal, with 25%.

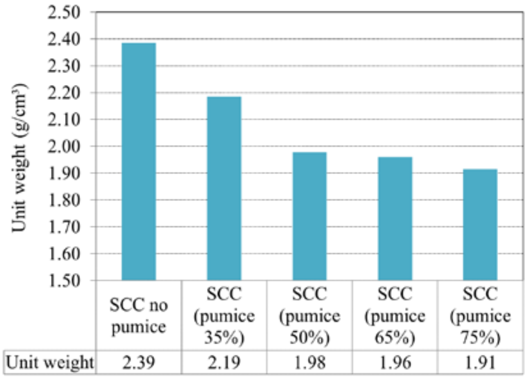


Fig. 10: Variation of unit weight values for SCC mixes vs the percentages of pumice.

The unit weight variation of SCC specimens versus pumice replacement ratios is graphically represented in Fig. 11. These indicate that the replacement of dolomite with pumice has a reduced effect on the unit weight of SCC, as discussed above.

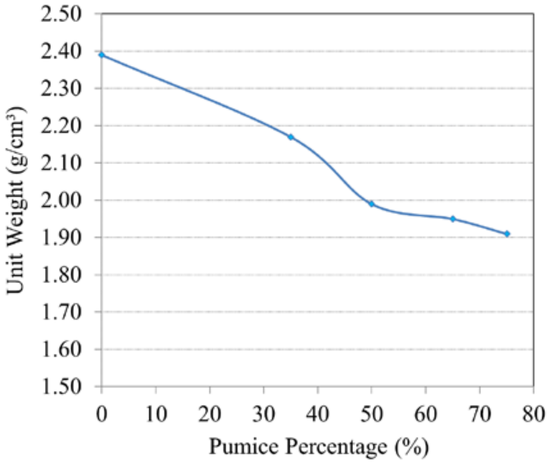


Fig. 11: Unit weight of SCC specimens versus pumice replacement ratios.

5.2.2 Compressive strength test

Compressive strength results of mixes (SCC without pumice) as a control mix and SCC with pumice replacement at various percentages at different curing ages are tabulated in Table 10 and shown in Fig. 12. It can be observed that pumice addition had an unfavorable effect, with compressive strength declining as the pumice replacement was increased. The control mix with no pumice replacement has a high compressive strength of 75 MPa at 28-day curing days. The smallest value is 36 MPa for mix with 75% replacement of pumice from the coarse aggregate.

Table 10: Hardened properties of different mixes at 7 days & 28 days.

Mix no	Pumice percentages	Unit Weight [g/cm^3]	Cube Compressive Strength [MPa]	
			7 Days	28 Days
1	SCC – 0%	2.39	55	75
2	SCC – 35%	2.19	51	67
3	SCC – 50%	1.98	41	60
4	SCC – 65%	1.96	31	41
5	SCC – 75%	1.91	27	36

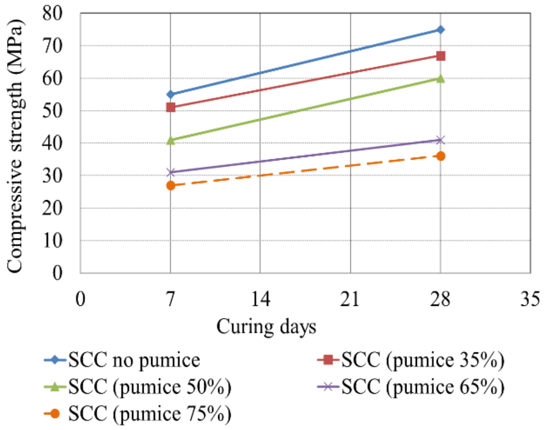


Fig. 12: Variation of compressive strength for SCC mixes at different ages.

As shown in Fig.13, the pumice content significantly affects the compressive strength of the SLWSCC. The optimum mixture which achieves the criteria of SLWSCC is mix 3 with 50 % pumice with high strength of 600 kg/cm^2 at 28-days and a unit weight of 1980 kg/m^3.

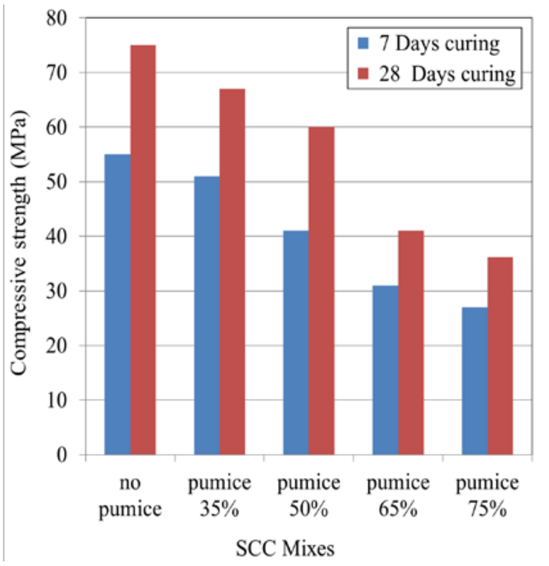


Fig. 13: Histogram of variation of compressive strength for mixes at different ages

The compressive strength test results of the SCC specimens against pumice replacement ratios are graphically presented in Fig.14. These results indicate that the replacement of NWA affects negatively the strength of SCC, as discussed above.

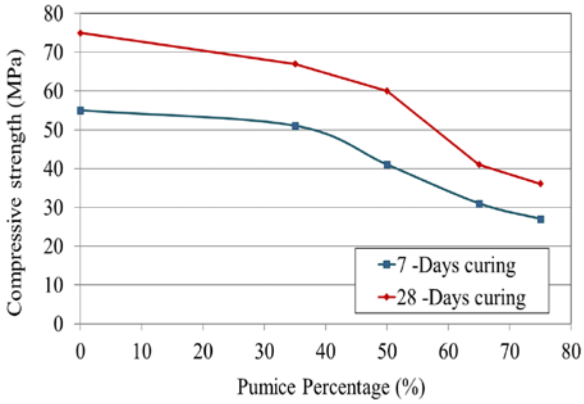


Fig.14: Compressive strength of SCC specimens versus pumice replacement ratios

5.2.3 Splitting tensile strength test and the relative bond strength (pullout) test

The mechanical strength test results of SCC (control mix) versus the selected mix with pumice replacement 50 % ratio are tabulated in Table 11. With a preliminary comparison between splitting tensile strength and bonding strength results of both types of concrete at 28 days. It can be observed that the strength of the selected mix is lower than the normal SCC mix by 20 %. While the tensile strength of the selected mix is, lower by 18 % than the control mix. As seen in table 11, the bond strength results of both mixes are equal.

Table 11: Hardened properties of the SCC standard mix versus selected mix at 28 days.

Mix no	Pumice percentages	Unit weight [g/cm^3]	Hardened strengths at 28 curing days [MPa]		
			Compressive strength	Splitting tensile strength	Bond strength
1	SCC – 0%	2.39	75	13	17
2	SCC – 50%	1.98	60	11	17

5.2.4 Water absorption and sorptivity tests

According to ASTM C 1585 – 04 [16], the sorptivity and water absorption rate of the control mix and the selected mix were calculated. The results are graphically represented in Fig. 15 and Fig. 16.

As shown in Fig. 15, the water absorption values calculated indicate that in the mix of SCC with no pumice the rate of absorption maximizes with the time in the opposite SCC mix with 50 % pumice percentage the rate of absorption is more stable with the time.

The sorptivity S calculated is given by Eq. (1). [16]. The sorptivity values in mm/min$^{1/2}$ are presented in Fig. 18.

$$S = I / t^{0.5} \quad (1)$$

where t is the elapsed time in minutes. The cumulative water absorption I calculated is given in the Eq. (2) [12]:

$$I = (W2 - W1) / (A*d) \quad (2)$$

where $W1$ is the weight of the specimen in g; $W2$ is the weight of the specimen after water absorption in g. A is the surface area of the specimen through which water can penetrate in mm^2, and d is the density of water in g/mm^3.

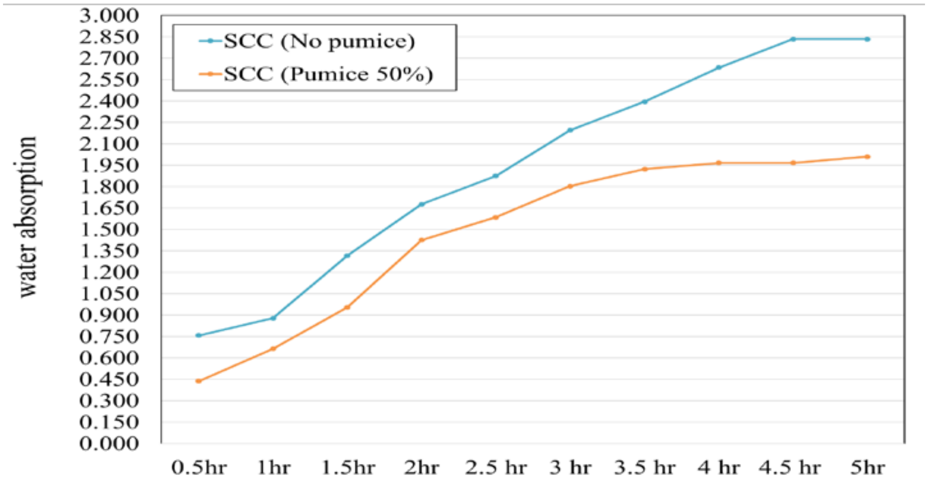


Fig. 15: Water absorption values of the standard SCC & SCC chosen

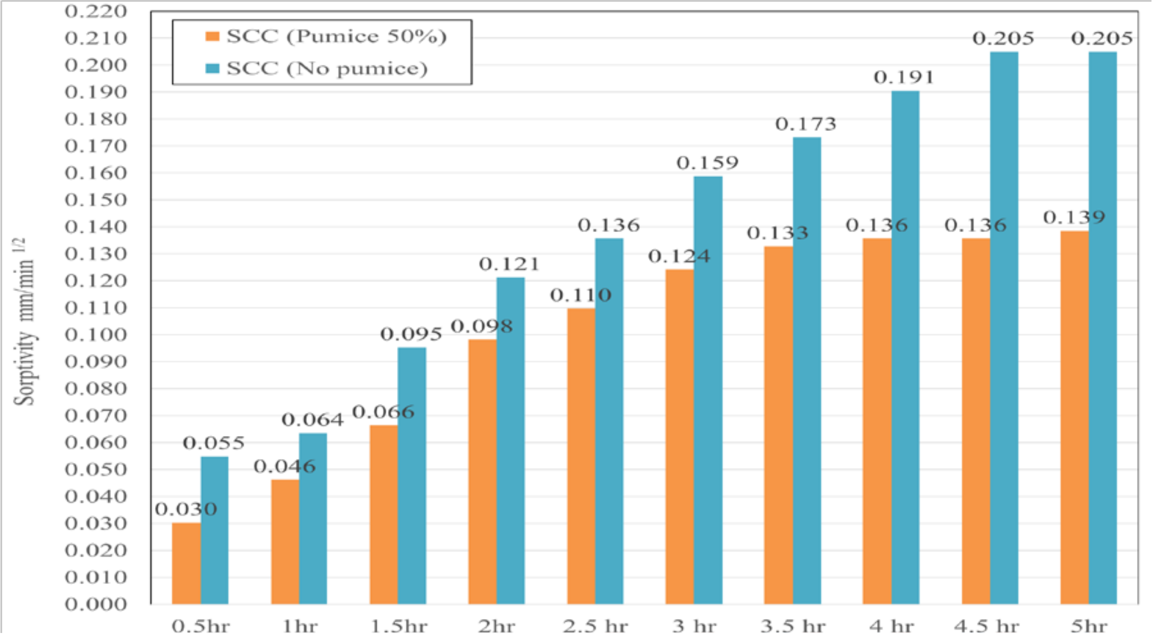


Fig. 16: Sorptivity values of the standard SCC & SCC chosen.

6. CONCLUSIONS

According to the discussion of the experimental results, it can be concluded that it is possible to use pumice aggregate as LWA for the manufacture of SLWHSSCC with low density and high strength as well as self-consolidating characteristics (flowability, deformability, self-compatibility, and stability). The SLWHSSCC produced has a density ≈ 20-25 % lower than HSSCC, which has no pumice for all mixes. The results show that the optimum percentage of PA amount was determined to be 50 % of the total coarse aggregate. When compared to SCC with no pumice, which has a density of 2390 kg/m^3, PLA can lower the density of concrete at 28-days to become 1980 kg/m^3. Therefore, the optimum SLWHSSCC mix obtained has a high strength of 60 MPa and 1.98 g/cm^3 of unit weight, considered lightweight concrete and high strength. All fresh properties of the developed concrete mixes with pumice were satisfying the SCC standards. None of the developed SCC mixes with PLA showed any segregation or bleeding at the slump time test. Except for mix, no. 6. It does not satisfy the standard characteristics of SCC. Which has a pumice percentage replacement of 100 % from coarse aggregates by volume.

The Slump flow values increased as the replacement percentage of pumice increased. T500 time decreased as the replacement percentage of pumice increased. The workability increased with the decrease of concrete unit weight. The density of the mixtures reduced as the percentage of LWA increased. The use of PLA compared with a normal weight coarse aggregate increases the water requirement of the mixture. Therefore, affects the strength negatively. The compressive strength of self-compacted concrete decreased as the replacement percentage of pumice increased. The failure mode of all SCC cubes specimens observed during testing was similar to the normal concrete.

7. RECOMMENDATIONS

It is recommended to investigate another lightweight aggregate. Also, It is recommended to study other engineering properties of SLWHSSCC and HSSCC of developed mixes, such as creep, shrinkage, and others.

8. ABBREVIATIONS

SLWHSSCC: Structural lightweight high strength self-compacting concrete

SLWSCC: Structural lightweight self-compacting concrete

HSSCC: High strength self-compacting concrete

SLWC: Structural lightweight concrete

SCC: Self-compacting concrete

NWA: Normal weight aggregate

LWA: Lightweight aggregate

PLA: Pumice lightweight aggregate

LECA: Light expanded clay aggregate

SF: Silica fume

EFNARC: European Federation of National Associations Representing for Concrete (European Guidelines for Self-Compacting Concrete.)

VSI: visual stability index

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