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Chapter 8

Influence of aggregate type on workability of self-consolidating lightweight concrete

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In this study, the effects of aggregate type on the workability of self-consolidating concrete produced with lightweight aggregate (self-consolidating lightweight concrete – SCLC) were investigated. In experiments, three coarse lightweight aggregate (LWA) types, namely pumice, volcanic tuff and diatomite, were used. Different combinations of water/powder ratio and superplasticiser dosage levels were prepared for the self-consolidating lightweight concrete mixtures. The total powder content (cement and mineral additives) was constant in the experiments. Workability tests such as slump flow, restricted slump flow, filling-box, V-funnel, GTM screen stability, L-box and U-box were performed to characterise accurately the flow ability, passing ability and segregation resistance of self-consolidating lightweight concrete in fresh condition. The results, in general, showed that self-consolidating lightweight concrete with lightweight aggregate in low unit weight has higher flow ability and passing ability. The segregation of self-consolidating lightweight concrete was prevented by use of air-entraining admixture in high water/powder ratios. As a result, it was observed that the aggregate type and water/powder ratio has significant influence on the workability properties of self-consolidating lightweight concrete.

Introduction

Self-consolidating concrete (SCC) is used for specific applications requiring high deformability, high flow ability and high passing ability (Okamura, 1997; Topçu *et al.*, 2009). Numerous studies have been performed for new testing methods on SCC in the past decade. One of them was the use of lightweight aggregates in the production of SCC (Choi *et al.*, 2006; Hwang and Hung, 2005; Lo *et al.*, 2007; Topçu *et al.*, 2007). Lightweight aggregates such as natural or artificial are available in many parts of the world and can be used in producing concrete in a wide range of unit weights and suitable strength values for different fields of application such as internal and external walls, inner leaves of external cavity walls, fill panels and isolation of roof decks and floors (Topçu, 1997; Ünal *et al.*, 2007).

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In practice, lightweight aggregates often have lower particle densities than the density of the mortar matrix and natural aggregates in concrete. The coarse aggregates move upwards with vibration of plain concrete, and thus segregation may take place during the transporting and placing of the fresh concrete (Chia *et al.*, 2005). This is in contrast with the normal-weight aggregate concrete where coarse aggregates may sink to the bottom if the workability is not appropriate. Self-compactability of concrete is a unique property for prevention of upwards movement of lightweight aggregates (LWA) owing to vibration (Topçu and Uygunoğlu, 2008; Uygunoğlu, 2008; Wu *et al.*, 2009). However, when LWAs are used in SCC, aggregate particles are required to have uniform distribution and the minimum segregation risk in self-consolidating lightweight concrete (SCLC) owing to the low density of LWAs (Topçu and Uygunoğlu, 2010; Türkmen and Kantarcı, 2007; Wu *et al.*, 2009).

Aggregates generally constitute about 60% by volume of SCLC. Owing to the large volume fraction they occupy in SCLC, aggregates exert a major influence on the workability of fresh SCLC, and can be expected to have an important influence on other properties as well (Su *et al.*, 2001). There are few studies on workability of SCLC in the literature. This paper presents the extensive test results from the workability of SCLC produced with the different types of LWA. In the study, three types of aggregate – pumice, volcanic tuff and diatomite – were used as LWAs as they are found in large deposits in Afyonkarahisar (Turkey) and the surrounding area.

Experimental programme

Materials used

The cement used was ordinary Portland cement (CEM I 42.5R), which complies with the requirement of European Standard EN 197-1 (Turkish Standard Institute, 2008). Limestone powder and fly ash were used as fine material (or filler) to balance the viscosity. The fly ash (F class) was supplied from Seyitömer/Turkey Thermal Power. Table 1 gives the chemical, physical and mechanical properties of the fine materials that composed the cement, limestone powder and fly ash with a maximum size of 0·125 mm. The admixture was polycarboxylate-based superplasticiser (SP). Its specific gravity and solid content were 1·1 and 20% respectively. Natural river sand was used in all the mixtures. The specific gravity, fineness modulus and water absorption by weight of sand are 2·59, 2·07 and 3·73% respectively. Coarse aggregates were pumice, volcanic tuff and diatomite with a maximum size of 16 mm. The chemical and characteristic properties of these aggregates are presented in Table 1 and Table 2, respectively.

Concrete mixes and tests

The constituents of the SCLC mix were proportioned to achieve maximum packing of the particles and, thus, minimum voids. SCLC mixtures were designed with different water/powder (w/p) ratios, 0·28, 0·31, 0·34 and 0·36, to obtain different fresh-state properties. The powder ratio in the natural sand was also considered in determining the w/p ratio. When the water content increased, the superplasticiser dosage was decreased by ratios of 2·6, 2·3, 2·0 and 1·7% by weight of fine material at the same time. The fine material content, which includes cement, fly ash and limestone powder, and aggregate grading, were kept constant in all mixtures. The aggregate grade was designed as between Turkish Standard curves A-16 and B-16 (Table 3). During the production of SCLCs,

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Table 1 Properties of cement fly ash, limestone powder, pumice, tuff and diatomite

	Cement: %	Fly ash: %	Limestone: %	Pumice: %	Tuff: %	Diatomite: %
Chemical properties						
Calcium oxide (CaO)	63·6	0·67	55·0	5·4	0·5	1·4
Silicon dioxide (SiO_2)	19·3	46·5	0·01	56·9	73·0	67·2
Aluminium oxide (Al_2O_3)	5·6	25·5	0·2	16·7	14·1	10·1
Iron (III) oxide (Fe_2O_3)	3·5	4·9	1·0	4·7	1·0	2·7
$SiO_2 + Al_2O_3 + Fe_2O_3$ (≥ 70)	28·3	76·9	0·2	78·2	88·2	80·0
Magnesium oxide (MgO)	0·9	5·9	0·6	1·8	1·0	0·6
Sulfur trioxide (SO_3)	3·0	1·7	–	–	–	–
Potassium oxide (K_2O)	0·8	1·4	–	5·2	3·7	0·7
Sodium oxide (Na_2O)	0·1	0·4	–	4·6	1·2	0·4
Loss of ignition	2·0	2·8	43·7	2·8	6·3	8·0
Insoluble residue	0·7	–	–	–	–	–
Physical properties						
Fineness by Blaine: cm^2/g	3294	6445	856	–	–	–
Specific gravity	3·07	2·13	2·72	1·84	2·04	2·23
Mechanical properties						
Compressive strength: 7 days	37·5	–	–	–	–	–
MPa: 28 days	46·0	–	–	–	–	–

Table 2 Characteristic properties of pumice, tuff and diatomite

Properties	4/16 mm coarse lightweight aggregates			Standard
	Pumice	Tuff	Diatomite	
Loose bulk density: kg/m^3	739	762	435	TS EN 1097-3
Water absorption: %	28·75	23·82	94·24	TS EN 1097-6
Partical shape (flakiness ındex)	FI_{15}	FI_{35}	FI_{15}	TS 9582 EN 933-3

Table 3 Sieve analyses of lightweight aggregates

Sieve: mm	16	8	4	2	1	0·5	0·25
Passing: %	100	59	46	39	27	17	9

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Table 4 Constituent of concretes for per cubic meter

Series	Materials: kg/m^3										w/p ratio
	Cement	Fly ash	Limestone powder	Sand	Pumice	Tuff	Diatomite	Water	SP*	AE*	
SCLC 1	450	50	100	722	492	–	–	180	15·6	3·0	0·28
SCLC 2	450	50	100	700	478	–	–	198	13·8	3·0	0·31
SCLC 3	450	50	100	678	462	–	–	216	11·4	3·0	0·34
SCLC 4	450	50	100	664	452	–	–	228	10·2	3·0	0·36
SCLC 5	450	50	100	649	443	–	–	240	9·0	3·0	0·38
SCLC 6	450	50	100	722	–	534	–	180	15·6	3·0	0·28
SCLC 7	450	50	100	700	–	518	–	198	13·8	3·0	0·31
SCLC 8	450	50	100	678	–	502	–	216	11·4	3·0	0·34
SCLC 9	450	50	100	664	–	491	–	228	10·2	3·0	0·36
SCLC 10	450	50	100	649	–	480	–	240	9·0	3·0	0·38
SCLC 11	450	50	100	722	–	–	436	180	15·6	3·0	0·28
SCLC 12	450	50	100	700	–	–	423	198	13·8	3·0	0·31
SCLC 13	450	50	100	678	–	–	410	216	11·4	3·0	0·34
SCLC 14	450	50	100	664	–	–	401	228	10·2	3·0	0·36
SCLC 15	450	50	100	649	–	–	392	240	9·0	3·0	0·38

* SP: superplasticiser; AE: air-entraining admixture.

all the aggregates were used as saturated and dry surface. An air-entrained admixture was used in the production of SCLC to prevent segregation. LWAs were used in the mixes as saturated and dry surface. The composition of the mixes is presented in Table 4.

Experiments

On the fresh SCLC produced with three different aggregates, experiments, presented in Table 5, were carried out to determine the workability of the SCLC according to the EFNARC Committee (EFNARC, 2002). All tests were performed at 20°C. The slump flow test is used to determine the ability of the concrete to flow in a non-restricted condition. To determine the slump flow the traditional hollow Abrams cone is placed on a slump-flow plate with an edge length of 1000 × 1000 mm and is filled with SCC and lifted slowly. In order to prevent any thixotropic effect, the Abrams cone was lifted immediately after having been filled with the SCC. The slump-flow of the final deformed, or slumped, SCC was measured from two perpendicular diameters 2 min after cone lifting (Figure 1). During the slump-flow test, the time required for SCC to reach a slump-flow radius (T_{500}) of 500 mm length was measured.

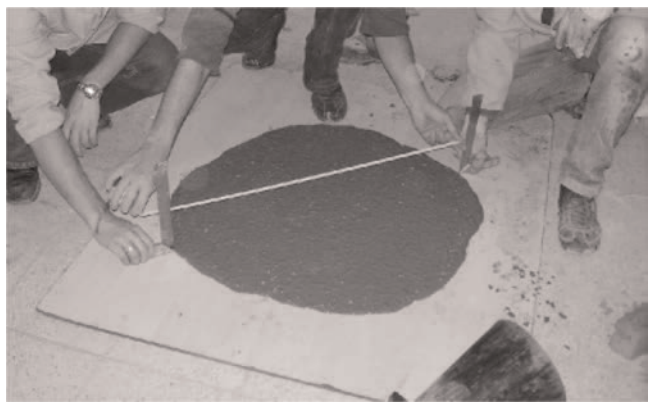
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Table 5 Experiments for evaluating the workability of SCLC

SCLC property	Experiment	Limit*
Filling ability	Slump-flow	650–800 mm
	Time to T_{500} at slump-flow	2–5 s
	V-box flow time	6–12 s
Passing ability	J-ring	0–10 mm
	U-box	0–30 mm
	Filling box	90–100%
	L-box	(h_2/h_1) 0·8–1·0
Segregation resistance	V-box flow at T_{5min}	+3 s
	Sieve segregation (GTM screen stability)	0–15%

* According to EFNARC (2002).

Figure 1 Slump-flow tests



The flow time of SCC was measured with a V-funnel (Figure 2). With the outlet flap closed the funnel is filled to the top with the sample of SCC. The flap is then opened. The time taken by the concrete to flow out of the funnel is measured. Filling ability of SCLC was evaluated with the V-funnel flow time. Then, the passing ability of SCLCs was defined with a V-funnel, again, as $V_{T5minutes}$ value. With the outlet flap closed the funnel is filled with the sample of SCC to the top. SCLC was kept in the V-funnel for 5 min. Then, the flap was opened, and, the flow time was measured as the $V_{T5minutes}$ value.

A J-ring test was used to asses the passing ability of the concrete in restricted condition. To determine the slump flow in restricted condition the traditional hollow Abrams cone was

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Figure 2 V-funnel test apparatus



placed centrally inside a J-ring on the slump flow plate with an edge length of 1000 × 1000 mm, filled with SCC and lifted slowly. The diameter of the ring of vertical bars was 300 mm, and the height 100 mm. Similar to the slump-flow test, T_{500} time was measured during the slump-flow of SCLC in restricted condition. The slump-flow of the final deformed SCLC was measured from two perpendicular diameters 2 min after cone lifting. Furthermore, the difference in height between the concrete just inside the bars and that just outside the bars was measured (Figure 3(a)). Four measurements were taken on the outside of the J-ring as k_1, k_2, k_3, and k_4 around the ring at a perpendicular angle (Figure 3(b)). The arithmetic average of k values (k_{av}) was used for the outside height ($h_{outside}$) in the J-ring. Then, step-height (st_j) was determined with the difference of outside ($h_{outside}$) and inside (h_{inside}) concrete height in the J-ring by Equation 1 (Figure 3(c))

$$st_j = (h_{outside} - h_{inside}) = \left[\left(\frac{k_1 + k_2 + k_3 + k_4}{4}\right) - h_{inside}\right] \quad (1)$$

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Figure 3 Measuring of (a) h_{inside} value and (b) $h_{outside}$ value; (c) determination of step-height ratio in J-ring



(a)



(b)



(c)

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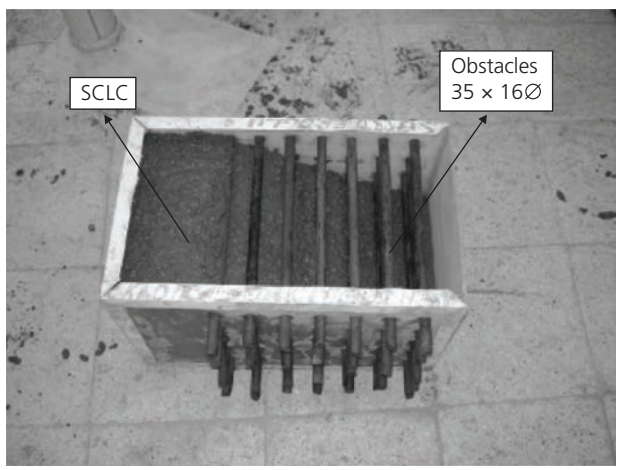
Fill-box test apparatus was used to measure the passing ability of SCLC with a different type of LWA. There are 35 steel obstacles with a diameter of 16 mm and a distance centre to centre of 50 mm. SCLC was poured into the filling pipe at the top side (Figure 4(a)). The apparatus was filled with about 40 litres SCLC through the filling pipe, and the difference in height between two sides of the container was measured to determine the passing ratio according to EFNARC (Figure 4(b)).

To assess the passing ability of SCLC, the L-box test method was used. The height of the fresh SCC after passing through the specified gaps of steel bars and flowing within

Figure 4 A view of fill-box



(a)



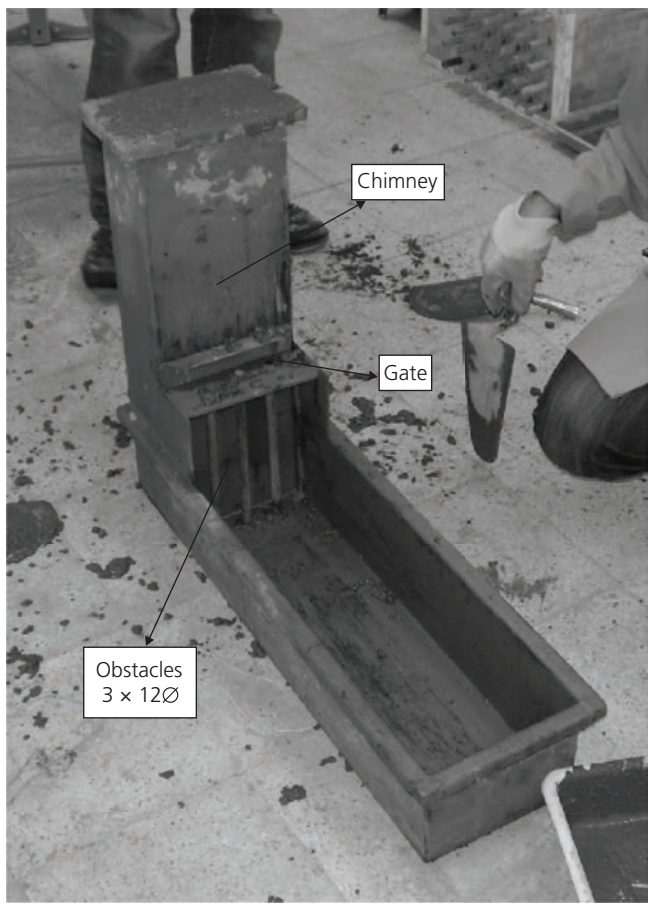
(b)

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a defined flow distance in the L-box (Figure 5) was measured. Once the concrete flow stopped, the height of concrete in the chimney was recorded as h_1, and the height of the concrete at the end of the horizontal section was recorded as h_2. With this reached height, the blocking behaviour of SCLC was determined by h_2/h_1. During the L-box test, the time required for SCLC to reach 200 (T_{200}), 400 (T_{400}) and 600 (T_{600}) mm length flow time was measured.

The U-box test was used to measure the filling ability of SCLC. The U-box consists of a vessel that is divided by a middle wall into two compartments. An opening with a sliding gate was fitted between the two sections. Reinforcing bars were installed at the gate with centre-to-centre spacing of 50 mm. One section is filled with about 20 litres of concrete then the gate lifted and concrete flows upwards into the other section. The height of the concrete in both sections is measured at the end of the test.

Figure 5 L-box test apparatus



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Figure 6 Stability test



In order to check the screen stability self-compactability, segregation resistance tests were performed with a sieve that conformed with the standard procedures given by EFNARC (2002). A sieve with square holes of 5 mm, frame diameter 350 mm and height 75 mm was used through stability experiments (Figure 6). Segregation resistance was determined by Equation 2

$$S = (W_h/W_b) \times 100 \quad (2)$$

where S is segregation resistance; W_h is concrete passing through the sieve; and W_b, is the weight of concrete poured onto the sieve.

Results and discussions

This study focused on those fresh properties of SCLC with different types of lightweight aggregates. However, it should be mentioned that the mechanical properties of hardened SCLC decreased as the w/p ratio increased for each series regardless of aggregate type. When the compressive strength of SCLC with pumice varied between 18 and 25 MPa, the compressive strength varied between 16 and 22 MPa and between 12 and 20 MPa for the SCLC series with tuff and diatomite, respectively, at age 28 days depending on the w/p ratio. The hardened concrete properties of the SCLC series with pumice, tuff and diatomite can be found in the study by Topçu and Uygunoğlu (2010).

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Fresh unit weight

The fresh unit weights of SCLCs were measured after the workability tests. It can be seen from Table 6 that the fresh unit weight of the concretes decreased as the w/p ratios increased. While the unit weights of SCLC with pumice were changed between 1750 and 1670 kg/m^3, the unit weight of SCLCs of those made up with tuff ranged between 1810 and 1720 kg/m^3 for 0·28–0·38 w/p ratio, respectively. On the other hand, the unit weights of SCLC with diatomite varied between 1750 and 1640 kg/m^3 for the same w/p ratios. This is attributable to the increase of porous structure in SCLC with high water content. Furthermore, Table 6 shows that the unit weights of SCLCs decreased with increasing density of lightweight aggregates for mixtures with the same w/p ratio. The fresh unit weight reached the maximum value when tuff was used in the production of SCLC. The bulk density of tuff is higher than that of diatomite and pumice; therefore the unit weight of the mix increased when the tuff took the place of pumice and diatomite lightweight aggregates. The density is much lower when compared with the density of normal SCC, namely 2400 kg/m^3.

Filling ability of SCLC

The slump-flow test is a value system for the ability of SCLC to deform under its own weight against the friction of the surface with no external restraint present. The slump flow results in Table 6 indicate that the diameter of SCLC slump flow was 525–840 mm. It is clearly seen that the slump flow diameter increased as the w/p ratio increased for each series regardless of

Table 6 Fresh properties of SCLC

Series	Unit weight: kg/m^3	Slump-flow: mm	V-funnel flow time: s	V_{T5}-flow time: s	V_{T5}-V: s	U-box height difference: mm
SCLC 1	1747	618	6·07	6·31	0·24	22·0
SCLC 2	1701	683	5·85	6·56	0·71	16·0
SCLC 3	1695	723	3·78	4·80	1·02	15·0
SCLC 4	1685	765	2·93	3·66	0·73	9·0
SCLC 5	1657	767	3·19	3·72	0·53	4·0
SCLC 6	1814	529	5·78	6·32	0·54	48·0
SCLC 7	1811	578	4·67	6·06	1·39	48·0
SCLC 8	1754	670	3·48	3·87	0·39	16·0
SCLC 9	1727	728	2·72	3·82	1·10	12·0
SCLC 10	1723	755	2·42	3·68	1·26	4·0
SCLC 11	1737	655	4·19	4·66	0·47	13·0
SCLC 12	1716	770	4·14	4·59	0·45	10·0
SCLC 13	1673	778	2·92	3·35	0·43	5·0
SCLC 14	1655	817	1·87	2·33	0·46	5·0
SCLC 15	1640	834	1·32	1·75	0·43	2·0

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aggregate type. This was attributed to the increase in lubrication between the fine particles with an increase of w/p ratio (Chia and Zhang, 2004). The slump-flow value of tuff, pumice and diatomite was 525, 620 and 650 mm, respectively, with a 0·28 w/p ratio. When the w/p ratio was 0·38, the slump-flow value reached 750, 760 and 840 mm for SCLC with tuff, pumice and diatomite respectively. This is because the higher water content in mixes increased the lubrication between the aggregate particles and thus decreased the yield stress and eased the flow ability of concrete (Roussel *et al.*, 2005). The slump-flow reached the maximum value when diatomite was used in the production of SCLC regardless of the w/p ratio. This is due to the lighter weight structure of diatomite than pumice and tuff LWA in SCLC. When the slump-flow values given by EFNARC were considered (650–800 mm), a good filling ability was obtained on SCLCs in 0·28–0·35 w/p ratio, 0·30–0·38 w/p ratio, and 0·34–0·38 w/p ratio for diatomite, pumice and tuff respectively.

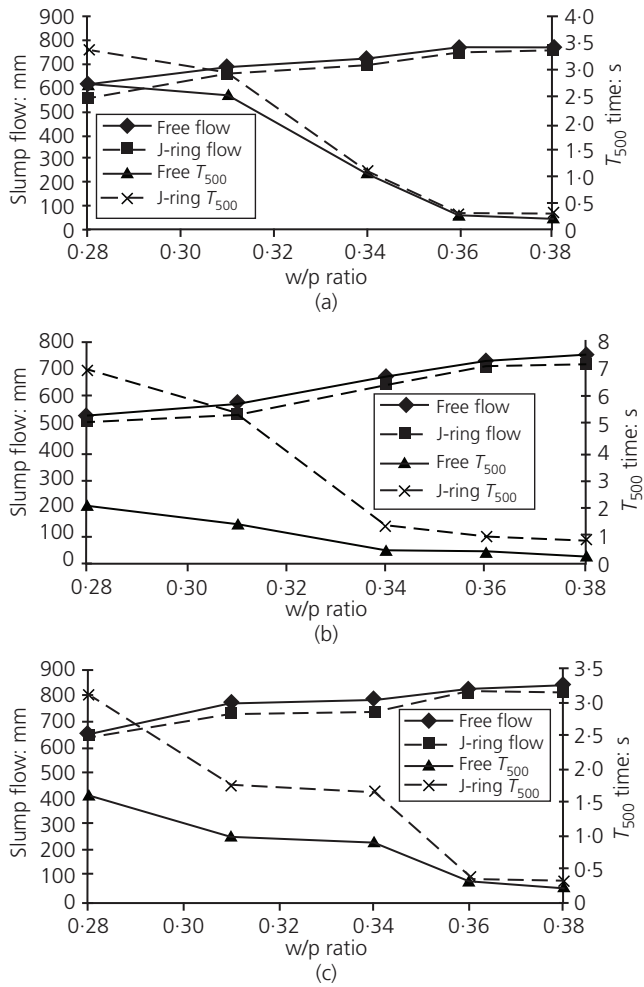
The change of the V-funnel flow time of SCLCs with different types of LWA is shown in Table 6 depending on the w/p ratio. The V-funnel flow time is an indicator of viscosity. In other words, viscosity increases with increase of V-funnel flow time. However, it must be borne in mind that V-funnel flow time is often used to estimate the apparent viscosity of a mixture. Many factors influence the results of the V-funnel test: the amount, shape and size distribution of aggregates and also the viscosity and amount of paste and so on. This means that the V-funnel flow time does not necessarily correspond with the viscosity of a mix measured, for example, by a rheometer. The results indicate that the lowest V-funnel flow time was obtained on SCLC with diatomite regardless of the w/p ratio. On the other hand, the highest viscosity was observed on SCLC with pumice in all the w/p ratios. Even though air-entrained admixture was used, the viscosity of SCLCs with diatomite, pumice and tuff in all the w/p ratios was too low according to the limit values given by EFNARC (6–12 s); the exception was SCLC with pumice produced in w/p ratio of 0·28.

Passing ability of SCLC

The variations of slump-flow and T_{500} in free and restricted conditions are compared in Figures 7(a)–(c) for SCLC with pumice, tuff and diatomite respectively. As seen, the T_{500} time value was higher in the J-ring slump flow test than free slump-flow owing to obstacles. It can be noted from Figure 7 that the greatest T_{500} time difference between free and J-ring slump-flow was obtained in the lowest w/p ratio, regardless of aggregate type. The passing ability of SCLC with all the aggregate types was too high in the w/p ratio of 0·38. However, the T_{500} time difference with and without restriction increased as the w/p ratio decreased for each series regardless of aggregate type. This was because the SCLC in the low w/p ratio was blocked between the obstacles because of low viscosity. When aggregate type is considered, it can be clearly seen that the greatest T_{500} time difference was obtained in SCLC with tuff aggregates due to the shape and bulk density of tuff. Even though diatomite has a lower bulk density than other LWAs, the lowest T_{500} time differences were observed in SCLC with pumice in each w/p ratio because pumice has a relatively spherical shape when compared with diatomite and tuff. The shape of crushed aggregates is often more angular with a rougher surface than natural aggregates. Plain and self-consolidating concrete with crushed aggregate often requires higher cement and water content in order to reach the same workability as a concrete with spherical aggregates. When the T_{500} time difference values of SCLC with pumice have changed between 0·7 and 0·1 s, it was ranged between 5 and 0·7 s, and 1·4–0·1 s in SCLC with tuff and diatomite, respectively, depending on the w/p ratio.

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Figure 7 Comparison of free and restricted slump flow of SCLC with (a) pumice, (b) tuff and (c) diatomite

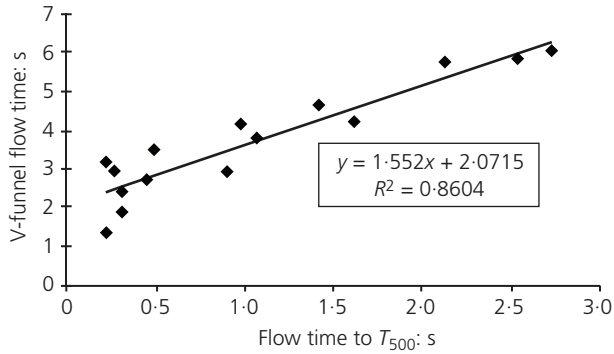


An SCLC mixture with 10 mm slump flow difference between free and restricted condition can be desirable in a good SCLC mixture from the passing ability point of view (Chia and Zhang, 2004). In general, the slump flow difference in the free and J-ring decreased as the w/p ratio increased from 0·28 to 0·38. However, this difference was restricted. It ranged between 63–13 mm, 38–19 mm and 47–9 mm in SCLC with pumice, tuff and diatomite respectively, depending on the w/p ratio.

Since the flow time to T_{500} in free slump-flow and V-funnel flow time is an indicator of viscosity, the relationship between these parameters was examined by statistical methods (Figure 8), and a good correlation coefficient was found ($R = 0{\cdot}927$). The flow time to T_{500} increases by increase of the V-funnel flow time.

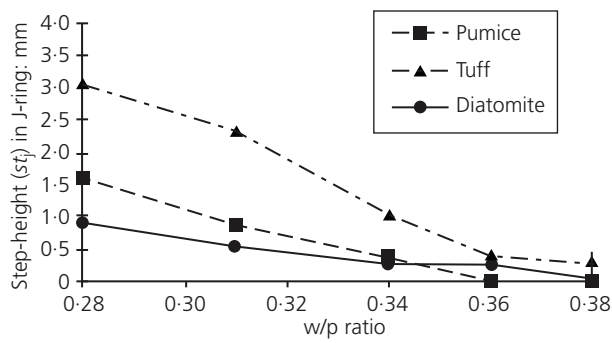
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Figure 8 Relationship between V-funnel flow time and flow time to T_{500} in slump flow



The influence of aggregate type on step-height in the J-ring of SCLCs depending on w/p ratio is shown in Figure 9. There is a substantial decrease in step-height with the increase in w/p ratio, and this decrease is substantial between 0·34 and 0·38 w/p ratios. It is evident that for a given aggregate type, a lower w/p ratio leads to a lower passing ability of SCLC, owing to the low lubrication between the aggregate particles. The high step-height value is an indication of the blocking risk of SCLC. When aggregate type is considered, it can clearly be seen from Figure 9 that the step-height (st_j) of SCLC with diatomite was lower than that of SCLC with pumice and tuff for all w/p ratios. The st_j value of SCLC with diatomite with a w/p ratio of 0·28, 0·31, 0·34, 0·36 and 0·38 was 0·9, 0·6, 0·3, 0·3 and 0 respectively. The highest height value was observed in SCLC with tuff. It was ranged from 3 to 0·3 depending on the w/p ratio. The SCLC mortar moved the diatomite aggregates as its bulk density is lower than that of tuff, and thus SCLC was not blocked. The blocking risk of SCLC with tuff is three times greater than that of SCLC produced with tuff in the lowest w/p ratio. Another blocking factor – the blocking ratio – was measured in the L-box; test results are presented in Figure 10. Similar to st_j, the highest blocking risk occurred in the lowest w/p ratio for SCLC with all types of

Figure 9 Step-height of SCLC in J-ring



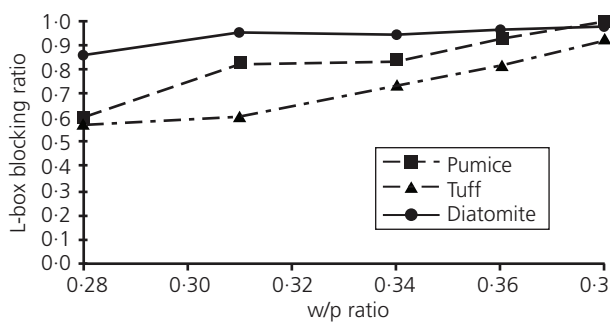
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LWA. For a good passing ability of SCLC, the L-box blocking ratio must be between 0·8 and 1 according to EFNARC (2002). As seen from Figure 10, the most appropriate w/p ratio for passing ability of SCLC with pumice, tuff and diatomite is 0·31, 0·36 and 0·28 respectively, in the L-box test.

The effect of a different LWA and w/p ratio on the time required for SCLC to reach T_{200}, T_{400} and T_{600} length flow time during the L-box test is shown in Figures 11(a) to (c) for pumice, tuff and diatomite respectively. Actually, the flow time of SCLC can be associated with viscosity. It is also an indicator of passing ability. There is a substantial increase in the L-box flow time of SCLC produced with all types of LWA with the increase in L-box length from 200 to 600 mm, regardless of the w/p ratio. While the flow time of SCLC with pumice for 0·28 w/p ratio ranged between 1·13 and 7·19 s, the unit weight of SCLC comprising tuff and diatomite for 0·28 w/p ratio was in the range 1·26–10·29 and 0·6–3·89 s respectively. For a w/p ratio of 0·38, the L-box flow time of SCLC with pumice, tuff and diatomite was in the range 0·26–1·08, 0·44–1·64 and 0·24–1·33 respectively. This is probably due to the increase of viscosity in SCLC with increase of flow length, and thus the flow of SCLC stops in a shorter distance, and the passing ability of SCLC mortar decreases. This phenomenon shows that aggregates with low unit weight (or low bulk density) can be moved easily by SCLC mortar. It can be clearly seen that the lowest L-box flow time for lengths of 200, 400 and 600 mm were obtained on SCLC with diatomite which has a lower unit weight than pumice and tuff. On the other hand, the highest flow time in the L-box was noted on SCLC with tuff which has a higher bulk density than pumice and diatomite.

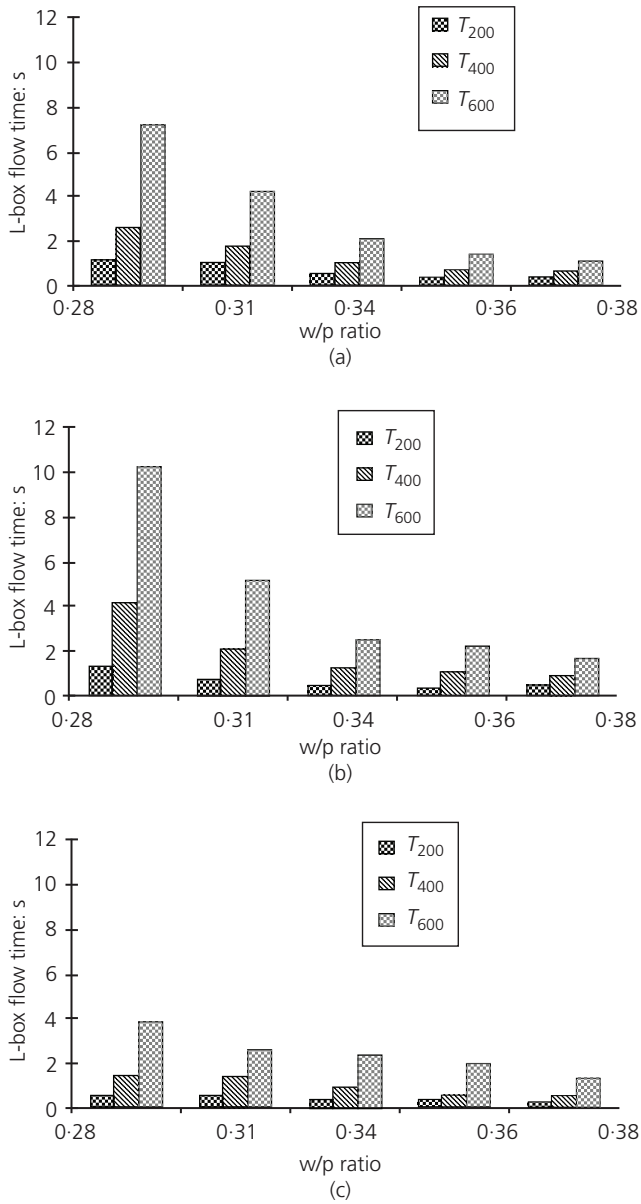
When the effect of the w/p ratio was considered on L-box flow time with length, it could also clearly seen that there was a substantial decrease in T_{200}, T_{400} and T_{600}, respectively, with the increase in w/p ratio from 0·28 to 0·38. It is evident that for a given SCLC type, a lower w/p leads to a higher flow time, owing to the lack of lubrication between the aggregates. The short flow time is an indication of good passing ability achieved by the concrete self-weight.

Figure 10 Blocking ratio of SCLC in L-box



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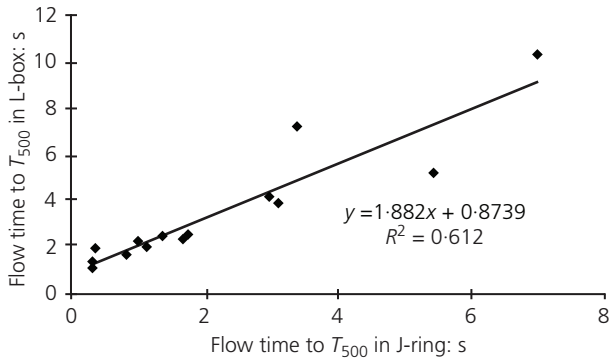
Figure 11 T_{200}, T_{400} and T_{600} flow time of SCLC with (a) pumice, (b) tuff and (c) diatomite



The relationship between L-box flow time (T_{600}) and J-ring flow time to T_{500} is given in Figure 12. It can be noted that there is a good relationship between both parameters with a high correlation coefficient ($R = 0{\cdot}928$). Moreover, the L-box flow time (T_{600}) and J-ring flow time are directly proportional to T_{500}. In other words, the blocking risk of SCLC decreased with the increase of flow time in both the L-box and J-ring.

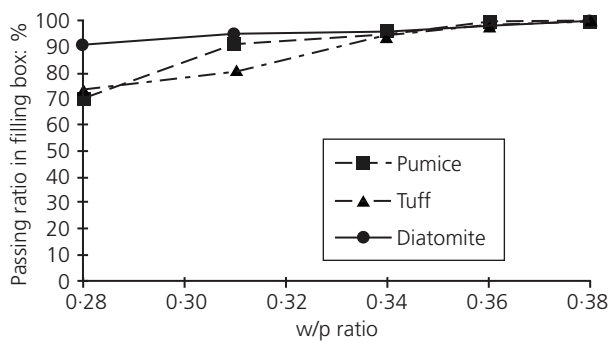
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Figure 12 Relationship between L-box flow time (T_{600}) and J-ring flow time to T_{500}



The passing ratio of SCLC with different LWAs was determined with a filling box, and results, depending on the w/p ratio, are given in Figure 13. The passing ratio of SCLC produced with tuff and pumice is 70%, whereas it was 90% on SCLC with diatomite. When the w/p ratio was increased to 0·38, the passing ratio was 100% for all types of SCLC. For good passing ability, the target range is in the range 90–100% in the filling box. SCLC with diatomite has a high passing ability in all of the w/p ratios. However, SCLC produced with pumice and tuff LWA has a good passing ability after w/p ratios of 0·31 and 0·34 respectively. Another passing ability indicator is the height difference in the U-box. The highest height difference was observed in SCLC with tuff in the lowest w/p ratio as 48 mm (Table 6). On the other hand, the height difference was 12 and 22 mm for SCLC with diatomite and pumice, respectively, for the same w/p ratio. An acceptable range for height difference in the U-box test is between 0 and 30 mm. While all the w/p ratios are appropriate for SCLC with pumice and diatomite for good passing ability, it was over 0·33 for SCLC with tuff. The results show that the importance of the aggregate characteristics, such as the shape, surface texture and bulk density, becomes less important with increasing w/p ratio.

Figure 13 Passing ratio of SCLC in filling-box



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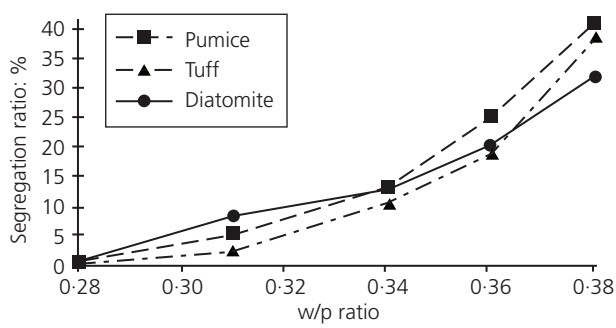
Segregation resistance of SCLC

Another important factor for workability of SCLC is segregation resistance. The segregation resistance of SCLC was evaluated using the wet sieve test for different w/p ratios (from 0·28 to 0·38); the test results are presented in Figure 14. The segregation resistance of the SCLC incorporating the pumice, tuff and diatomite with a w/p ratio of 0·28 was about 0%. The target range was between 0 and 15% for the segregation ratio. The segregation resistance of SCLC containing all the types of LWA was under 15% in the case of a w/p ratio up to 0·34. For a given w/p ratio, it can be noted that the segregation ratio values were close to each other for all the types of SCLC. SCLC with pumice, tuff and diatomite has a segregation ratio of 41, 38 and 33% respectively, in the case of 0·36 w/p ratios. However, for a 0·38 w/p ratio, the segregation ratio of SCLCs was 25, 18 and 20%, respectively, for pumice, tuff and diatomite. It was interesting that SCLC incorporating the diatomite aggregate has a lower segregation value than pumice and tuff in the highest w/p ratio. This can be explained by the increase of the air-entraining effect in high w/p ratios. Air bubbles restricted the exit of LWAs, specifically lower unit weight aggregates, from the SCLC mortars, thus segregation in highly flowable mixtures was prevented.

The V-funnel in the T_5 minutes test is used to determine the segregation resistance of the SCLC. The increase in V-funnel flow time after 5 min is an indicator of the presence of segregation in SCLC. Table 6 shows the difference between V-funnel flow time and V_{T5} flow time. This difference must not exceed 3 s for an acceptable segregation resistance. All the SCLC types had a desirable segregation resistance according to Table 6. The highest difference was obtained on SCLC with tuff as 1·25 s in the highest w/p ratio. The V-funnel time difference was not changed in SCLC with diatomite. On the other hand, in SCLC with pumice, the V-funnel time difference was increased with the increase of w/p ratio up to 0·34. It was then reduced because of air-entraining admixture effect. It must be borne in mind that the air-entraining admixture has a more significant effect on lighter aggregates than weight aggregates for the prevention of segregation. It can be clearly seen that the V-funnel flow time difference in SCLC incorporating the tuff was higher than other SCLC types owing to weightier bulk density of tuff than pumice and diatomite.

In Table 7, statistical analyses of workability test result were presented. For each test, another test was plotted, and correlation and equations for the relationship between the test results were

Figure 14 Segregation ratio of SCLC with different aggregates



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Table 7 Statistical analyses of SCLC workability results

X axes *Y* axes	Slump-flow: mm	V-funnel flow time: s	Segregation ratio: %	L-box (h_2/h_1)	Filling-box: %
Filling-box: %	$y = 0{\cdot}095x + 24{\cdot}42$	$y = -5{\cdot}56x + 112{\cdot}7$	$y = 6{\cdot}12\ln(x) + 79{\cdot}34$	$y = 60{\cdot}06x + 41{\cdot}8$	–
Correlation, *R*	0·86	0·82	0·90	0·89	–
U-box: mm	$y = -0{\cdot}15x + 121{\cdot}6$	$y = 6{\cdot}9x - 10{\cdot}16$	$y = 24{\cdot}33e^{-0{\cdot}054x}$	$y = -69{\cdot}6\ln(x) + 1{\cdot}94$	$y = -1{\cdot}2x + 126$
Correlation, *R*	0·91	0·67	0·81	0·90	0·81
L-box (h_2/h_1)	$y = 0{\cdot}0015x - 0{\cdot}25$	$y = -0{\cdot}074x + 1{\cdot}11$	$y = 0{\cdot}67x^{0{\cdot}103}$	–	–
Correlation, *R*	0·93	0·74	0·79	–	–
J-ring step-height: mm	$y = -0{\cdot}0096x + 7{\cdot}62$	$y = 0{\cdot}46x - 0{\cdot}89$	$y = -5{\cdot}3\ln(x) + 1{\cdot}9$	$y = 12{\cdot}36x^2 - 25{\cdot}12x - 12{\cdot}93$	$y = -0{\cdot}0026x^2 + 0{\cdot}366x - 10{\cdot}5$
Correlation, *R*	0·93	0·73	0·84	0·93	0·91
V-funnel flow time: s	$y = 0{\cdot}014x + 13{\cdot}3$	–	$y = -0{\cdot}83\ln(x) + 5{\cdot}43$	–	–
Correlation, *R*	0·82	–	0·83	–	–

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obtained. Each column shows the '*x* axes' values; however, each line shows the '*y* axes' values for equations that are given in Table 7. The lowest relation was obtained between the V-funnel flow time and U-box height difference with a correlation coefficient (R) of 0·67.

Conclusions

In this paper, results from a study of the influence of aggregate type on the workability of self-consolidating lightweight aggregate concrete have been presented. The experimental results showed that the workability of SCLC strongly depends on characteristic properties of light-weight aggregate such as unit weight (or bulk density), shape and surface texture. However, the importance of the aggregate characteristics becomes less important as the w/p ratio increases. The highest passing ability and filling ability were obtained in SCLC with diatomite aggregates owing to the shape and low bulk density of diatomite in low w/p ratios. On the other hand, segregation of SCLC incorporating diatomite aggregates was prevented by using air entraining admixtures in the high w/p ratios. A high ratio of w/p also contributes to the increase of passing ability and filling ability by increasing the lubrication between aggregate particles and decreasing the viscosity. However, an increase in the w/p ratio resulted in a decrease in segregation resistance. In general, it can be deduced that the optimum w/p ratio is 0·28, 0·31 and 0·34 for good workability of SCLC containing the diatomite, pumice and tuff lightweight aggregates respectively.

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