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Effect of silica fume and polyepoxide-based polymer on electrical resistivity, mechanical properties, and ultrasonic response of SCLC

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Abstract. This study focused on the influences regarding the use of polyepoxide-based polymer and silica fume (SF) on the fresh and hardened state properties of self-compacting lightweight concrete (SCLC) along with their impacts on electrical resistance and ultrasonic pulse velocity (UPV). To do so, two series of compositions each of which consists of twelve mixes, with water to binder (W/B) ratios of 0.35 and 0.4 were cast. Three different silica fume/binder ratios of 0, 5%, and 10% were considered along with four different polymer/binder ratios of 0, 5%, 10%, and 15%. Afterwards, the rupture modulus, tensile strength, 14-day, 28-day, and 90-day compressive strength, the UPV and the electrical resistance of the mixes were tested. The results indicated that although the use of polymer could enhance the passing and filling abilities, it could lead to a decrease of segregation resistance. In addition, the interaction of the SF and the polymeric contents enhanced the workability. However, the impacts regarding the use of polymeric contents on fresh state properties of SCLC were more prevalent than those regarding the use of SF. Besides the fresh state properties, the durability and mechanical properties of the mixes were affected due to the use of polymeric and SF contents. In other words, the use of the SF and the polymer enhanced the durability and mechanical properties of SCLC specimens.

Keywords: polyepoxide-based polymer; silica fume; self-compacting lightweight concrete; mechanical properties; durability; ultrasonic pulse velocity

1. Introduction

In recent years, due to economic, environmental, and technical benefits of SCLC, researchers paid more attention to this generation of high-performance concrete (Holschemacher *et al.* 2017, Brooks *et al.* 2000, Kaffetzakis and Papanicolaou 2016, Karamloo *et al.* 2016a, Karamloo *et al.* 2016b, Karamloo *et al.* 2017, Mazloom 2008, 2013, Mazloom and Hatami 2016, Mazloom and Mahboubi 2017, Mazloom and Miri 2017, Mazloom *et al.* 2004, 2015, Mazloom and Yoosefi 2013, Mazloom and Yoosefi 2011, Roudak *et al.* 2017a, b, Vakhshouri and Nejadi 2017). However,

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more studies are needed for better understanding of the behavior of SCLC. In addition, more attention should be paid to the concept of green architecture and construction (Zarghami *et al.* 2017), in which lightweight materials such as SCLC could play an important role (Karamloo *et al.* 2017). For instance, Hanif *et al.* (2017) experimentally assessed the suitability of fly ash cenosphere, a waste residue from coal fired power plants, for use in lightweight ferrocement construction. Apart from the advantages and disadvantages regarding the use of SCLC, in general, practical implications necessitate the use of additives and admixtures such as silica fume, superplasticizers, and polymers in concrete. Therefore, conducting researches in this field is inevitable. For instance, Ghoddousi and Saadabadi (2017) considered the effects of metakaolin and silica fume on chloride transport and electrical resistivity of self-compacting concrete (SCC). Brooks *et al.* (2000) investigated the effects of admixtures on the setting time of high-strength concrete. Mazloom *et al.* (2004) considered the influences regarding SF usage on mechanical properties of high-strength concrete. Ardalan *et al.* (2017) studied the effects of pumice powder and SF on fresh and hardened state properties of SCC along with their influence on workability retention.

According to the literature, a patent in 1923 for a concrete floor with natural latex was the onset of polymer usage in concrete (Pacheco-Torgal and Jalali 2009). Polymer-modified concrete (PMC) is developed by imposing a polymer dispersion to concrete to enhance the properties of concrete (Frigione 2013). As stated by Wang *et al.* (Wang *et al.* 2012), the polymer could lead to an increase in the concrete flexibility. However, depending on the polymer type (such as polyvinyl alcohol), they could lead to incorporation of air in concrete (Mehta and Monteiro 2006). In this regard, in commercial polymers, air detraining agents are usually included (Wang *et al.* 2005). Effects of polymer incorporation on the behavior of normal concrete (NC), SCC, and mortars were studied by many researchers. For example, Issa and Assad (2016) studied the stability and bond properties of polymer-modified SCC. They reported that the incorporation of polyvinyl acetate (PVA) and styrene-butadiene (SBR) in SCC improved the modulus of elasticity, tensile strength, and bond properties of SCC. Besides, it improved the static stability of SCC and decreased the bleeding (Issa and Assaad 2016). However, they claimed that the polymer incorporation did not affect the compressive strength of SCC. Ma and Li (2013) studied the microstructure and mechanical properties of polymer modified mortars under distinct mechanisms. To do so, they used two types of polymer (polyacrylate and polyurethane modified polyacrylate). Their results indicated that incorporation of the polymer could lead to a decrease of mortar compressive strength along with the reduction of its modulus of elasticity (Ma and Li 2013). Aliabdo and Abd_Elmoaty (2012) conducted an experimental survey on the properties of polymer modified SCC. They considered the interactions between the constituents of SCC (chemical admixtures and filler) and polymer. In the mentioned study, it is claimed that the use of styrene butadiene rubber and polyvinyl acetate modifies the workability of SCC and leads to a decrease of SP dosage. In addition, it is reported that the use of polyvinyl acetate increases the compressive strength of SCC. However, the use of styrene butadiene did not change the compressive strength of concrete (Aliabdo and Abd_Elmoaty 2012). Of course, it should be mentioned that they clearly reported that the 90-day compressive strength of polymer modified SCC was 25% higher than SCC. According to the study of Aliabdo and Abd_Elmoaty (2012), the dynamic elastic modulus of polymer modified SCC is lower than NC and SCC. Moreover, tensile strength and bonding properties of polymer modified SCC were improved in comparison with NC and SCC (Aliabdo and Abd_Elmoaty 2012). Pacheco-Torgal and Jalali (2009) investigated the sulfuric acid resistance of polymer modified concrete. They reported that the use of the polymer in concrete pipes increases the resistance of concrete against sulfate

Table 1 Chemical analysis of cement and silica fume

Material	Chemical analysis (%)										
Constituents	CaO	SiO2	Al2O3	Fe2O3	MgO	SO3	Na2O	K2O	Cl	L.O.I	Residue
Cement	63.35	21.05	4.55	3.46	3.21	1.52	0.19	0.84	0.01	1.6	0.22
SF	1.08	92.3	0.97	0.9	1.8	0.87	-	-	0.08	2	-

Table 2 Mix compositions

Mix	Constituents (Kg/m^3)							
	W	C	SF	P	LECA	Fine aggregate	SP	LP
1SCLC	157.5	450	0	0	296	792	10.8	170
1SF5	157.5	427.5	22.5	0	296	792	8.55	170
1SF55	157.5	405	22.5	22.5	296	792	8.55	170
1SF510	157.5	382.5	22.5	45	296	792	8.55	170
1SF515	157.5	360	22.5	67.5	296	792	8.55	170
1SF10	157.5	405	45	0	296	792	8.55	170
1SF105	157.5	382.5	45	22.5	296	792	8.55	170
1SF1010	157.5	360	45	45	296	792	8.55	170
1SF1015	157.5	337.5	45	67.5	296	792	8.55	170
1P5	157.5	427.5	0	22.5	296	792	8.55	170
1P10	157.5	405	0	45	296	792	8.55	170
1P15	157.5	382.5	0	67.5	296	792	8.55	170
2SCLC	180	450	0	0	266	802	5.4	190
2SF5	180	427.5	22.5	0	266	802	4.05	190
2SF55	180	405	22.5	22.5	266	802	4.05	190
2SF510	180	382.5	22.5	45	266	802	4.05	190
2SF515	180	360	22.5	67.5	266	802	4.05	190
2SF10	180	405	45	0	266	802	4.05	190
2SF105	180	382.5	45	22.5	266	802	4.05	190
2SF1010	180	360	45	45	266	802	4.05	190
2SF1015	180	337.5	45	67.5	266	802	4.05	190
2P5	180	427.5	0	22.5	266	802	4.05	190
2P10	180	405	0	45	266	802	4.05	190
2P15	180	382.5	0	67.5	266	802	4.05	190

attacks. As it can be seen, a few studies can be found about the behavior of polymer modified SCLC, if there is any. However, the self-compactness, low density, and its other advantages make this generation of high-performance concrete an interesting volunteer for the in-depth study. In this regard, in the present study, the influences regarding the incorporation of polyepoxide-based polymers along with the incorporation of silica fume were investigated. To reach this aim, 24 mix compositions with two groups of water/binder ratios of 0.35 and 0.4 were prepared. In each series, effects of replacement of 5%, 10%, and 15% polymer by binder weight and 5% and 10% SF by binder weight were considered. In addition, the effects of using both SF and polymer in SCLC were investigated.

2. Materials and mix compositions

2.1 Materials

An ordinary type I Portland cement was used whose chemical analysis is reflected in Table 1. The used cement was provided from Tehran cement factory. The specific gravity of the provided cement was 3.15 gr/cm^3. Silica fume, whose specific gravity was 2.12 gr/cm^3, was used as a pozzolanic material. Table 1 shows the chemical properties of the used SF. To enhance the workability of the mixes, a polycarboxylic ether based superplasticizer (SP) was used along with ultrafine limestone powder, whose maximum nominal size was about 0.25 mm. Light expanded clay aggregate (LECA) was provided to use as coarse aggregate, whose 30-min, 1-hour, and 24-hours water absorption were 6.7%, 11.5%, and 14.3%, respectively. The maximum nominal size of the coarse aggregate was 19 mm. Crushed natural river sand was used as fine aggregate, whose water absorption was about 3.4%. Moreover, to assess the advantages or disadvantages regarding the use of the polymer in SCLC mixes, a synthetic, single-component polyepoxide-based polymer was used, whose density was 1.04 g/cm^3, and PH was 6.5.

2.2 Mix compositions

In the present study two series of mixes, whose water/binder ratios were 0.35 and 0.4 have been prepared. Each series consisted of twelve different mix compositions each of which had different contributions of SF and polymer. Three polymers to binder (P/B) ratios of 0.05, 0.1, and 0.15 were chosen along with two silica fumes to binder (SF/B) ratios of 0.05 and 0.1. Besides, for all mixes, limestone powder was used as neutral filler. It is worth noting that all cases of binary (C+ limestone powder (LP)), ternary (C+LP+SF or C+LP+P), and quaternary (C+LP+SF+P) were considered in the mixes. Table 2 shows the designed mix compositions.

3. Experimental procedure

3.1 Fresh state experiments

In the present study, EFNARC guidelines (EFNARC 2002) were used to assess the workability of mixes. Slump flow, flow time (T_{50}), V-funnel time, and L-box ratio tests were carried out to determine the effects of mix compositions on the fresh state properties of SCLC mixes.

3.2 Mechanical properties

In order to evaluate the effects regarding the use of silica fume or polymer on mechanical properties of self-compacting lightweight concrete, 100×100×100 mm^3 cubic compressive strength of each mix was determined in three ages of 14 days, 28 days, and 90 days in accordance with BS-EN-12390 (BS EN 12390 2000). In addition, 150×300 mm standard cylinder specimens were cast

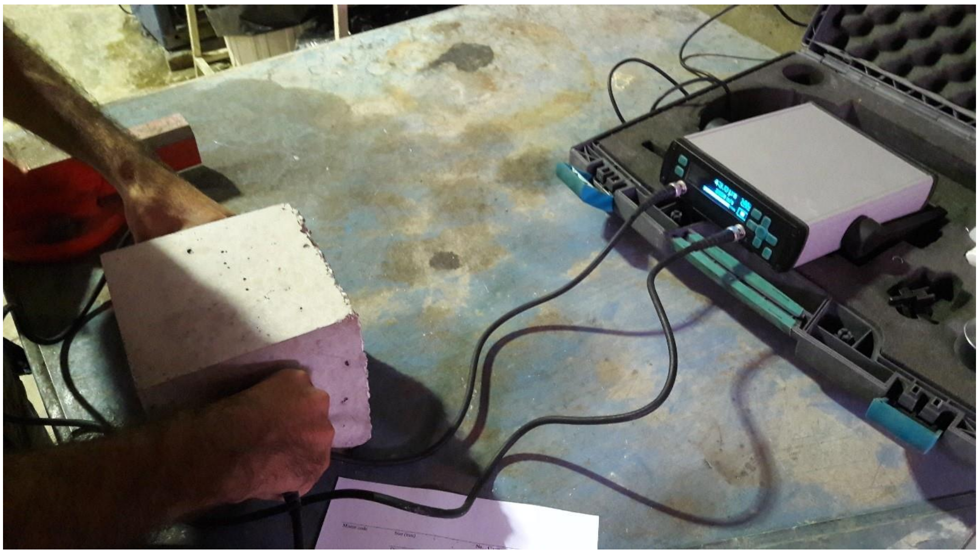

Fig. 1 Ultrasonic testing of an SCLC specimen

and cured to determine the indirect tensile strength of each mix at the age of 28 d. These tests were carried out according to the ASTM C496 (ASTM C 496 2002). Rupture modulus of each mix was determined by using ASTM C78 standards (ASTM C 78 2002). To do so, three 100×100×400 mm^3 beam specimens were cast and cured for 28 days. Then they were tested under 4-point bending configuration in such manner that it was stated in (ASTM C 78 2002).

3.3 Durability tests

Two types of non-destructive test methods (e.g., electrical resistivity and ultrasonic test) have been conducted in order to preliminary assess the durability of mix compositions. The ultrasonic and electrical resistivity tests have been conducted in accordance with ASTM C597 and ASTM C1202. Fig. 1 shows the ultrasonic testing configuration.

4. Results and discussion

4.1 Fresh state properties

Workability of concrete, especially in self-compacting generations of concrete, is of great importance. However, there is a few recommendations or guidelines for SCLC, if there is any. Therefore, the EFNARC guidelines (EFNARC 2002), which was recommended for SCC mixes was used in order to assess the workability of the mixes. Since the SCLC is a new generation of concrete, the studies pointing to its properties are still rare. Amongst the conducted researches, those whom attributed to the fresh state properties of SCLC are of interest and could be helpful to discuss the results in this section. Table 3 shows the results of slump flow, T_{50}, V-funnel, and L-box tests. As it can be seen, the constituents have a prominent effect on the workability of the mixes. In the first series of mixtures, whose water/binder ratio is 0.35, the amounts of coarse and

Table 3 Fresh state properties of mixes

Mix	slump flow (mm)	T50(sec)	V funnel	L-box (h2/h1)
1SCLC	695	2.6	9.6	0.91
1SF5	670	3.6	10.4	0.85
1SF55	685	3.1	10.1	0.86
1SF510	690	3	9.5	0.86
1SF515	695	2.7	8.7	0.88
1SF10	650	4.4	12.8	0.81
1SF105	660	3.8	11.9	0.82
1SF1010	675	3.5	11.1	0.84
1SF1015	690	3.1	9.8	0.87
1P5	695	2.7	9.5	0.89
1P10	710	2.5	8.9	0.91
1P15	730	1.8	7.5	0.92
2SCLC	760	2.2	8.9	0.94
2SF5	710	3.5	9.5	0.87
2SF55	725	2.8	9.1	0.88
2SF510	740	2.7	8.8	0.88
2SF515	750	2.1	7.8	0.91
2SF10	685	3.7	11.7	0.84
2SF105	700	3.1	10.8	0.85
2SF1010	710	3	10	0.86
2SF1015	720	2.4	9.2	0.89
2P5	720	2.3	8.2	0.93
2P10	750	1.7	7.5	0.94
2P15	780	1.3	6.4	0.96

fine aggregate were kept constant equal to 296 and 792 kg/m^3, respectively. Moreover, the amounts of limestone powder were kept equal to 170 kg/m^3. This trend was kept for the second series of mixes such that the amounts of coarse aggregate, fine aggregate, and limestone powder be equal to 296, 802, and 190 kg/m^3. This proportioning makes it possible to assess the effects of the inclusion of silica fume and polymer on the properties of SCLC. By using the EFNARC guidelines, the workability grades of the mixes are indicated in Fig. 2. Of course, it is worth noting that the boundaries specified in EFNARC are allocated to SCC mixes. However, some researchers stated that there is a strong need to reconsider the guidelines for SCLC mixes (Papanicolaou and Kaffetzakis 2011).

In order to consider the effects of SF/B and P/B ratios on the workability of SCLC mixes, Figs. 3-10 have been drawn. Fig. 3 shows the effects of P/B and SF/B ratios on the L-box ratios of mixes with W/B=0.35. As it can be seen, they were all of the grade PA_2 based on EFNARC recommendations. Moreover, the increase of polymeric contents increased the L-box ratio, though the increase of silica fume decreased the L-box ratio. The minimum L-box ratio was seen in the contribution of 10% SF and without polymer. In other words, silica fume diminished the passing

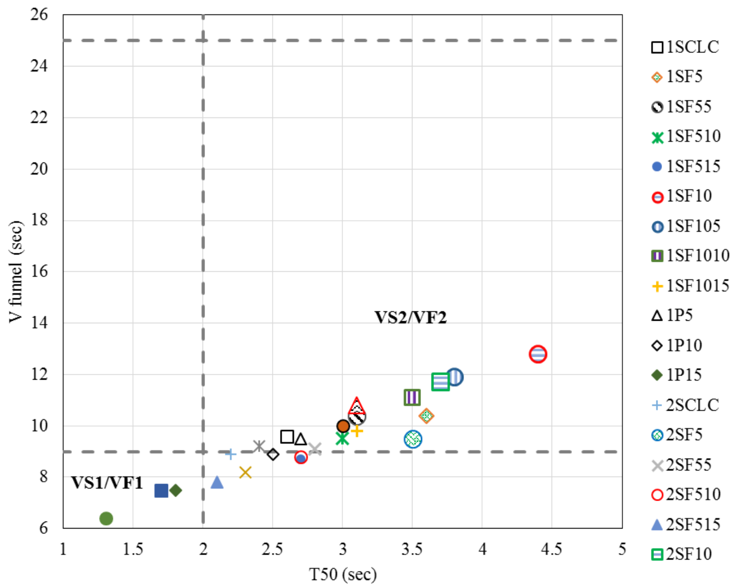

Fig. 2 Fresh state grade of mixes based on EFNARC

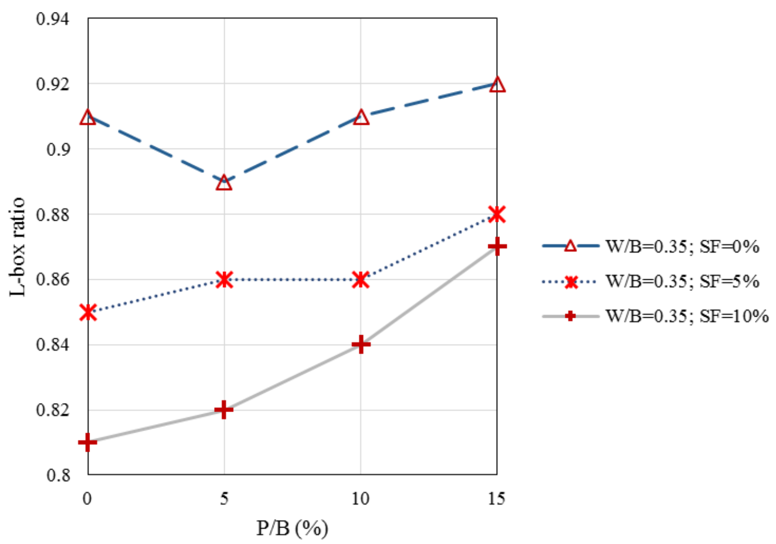

Fig. 3 Variation of L-box ratio versus P/B ratio and SF/B ratio for mixes with W/B=0.35

and filling ability, but the increase of P/B ratio enhanced these abilities. One can attribute these findings to the water retention of silica fume and a decrease of friction between the constituents of the fresh mix due to use of polymers. These findings are in line with those reported by Issa and Assaad (2016) for SCC. They found out that the incorporation of PVA and SBR improved the static stability and increased the bleeding resistance of SCC. In another research it is reported that the use of SBR and PVA could lead to an enhancement of the workability of SCC (Aliabdo and Abd_Elmoaty 2012).These trends can also be seen in Fig. 4, which belongs to the mixes with water/binder ratio of 0.4.

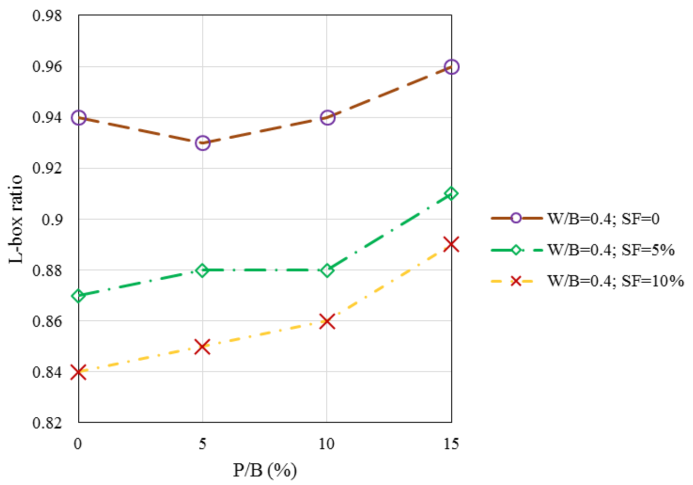

Fig. 4 Variation of L-box ratio versus P/B ratio and SF/B ratio for mixes with W/B=0.40

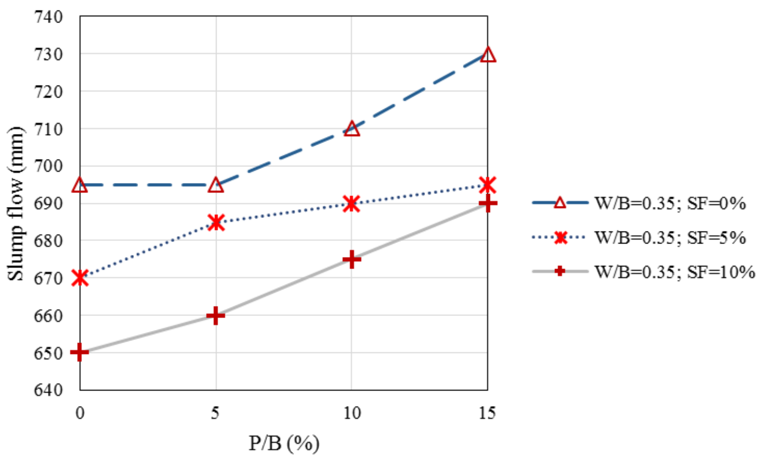

Fig. 5 Variation of slump flow diameter versus P/B ratio and SF/B ratio for mixes with W/B=0.35

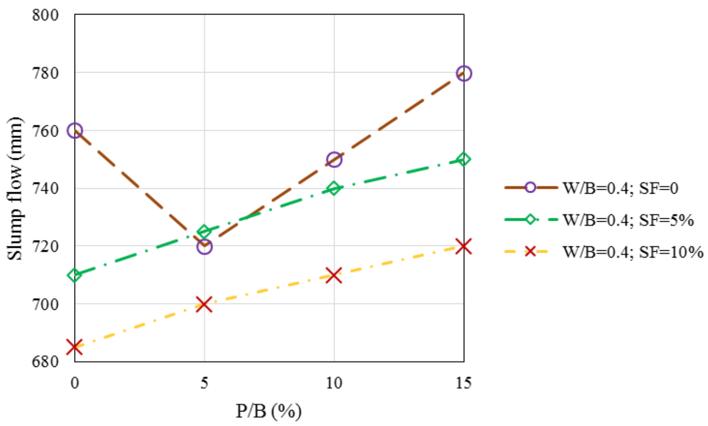

Fig. 6 Variation of slump flow diameter versus P/B ratio and SF/B ratio for mixes with W/B=0.40

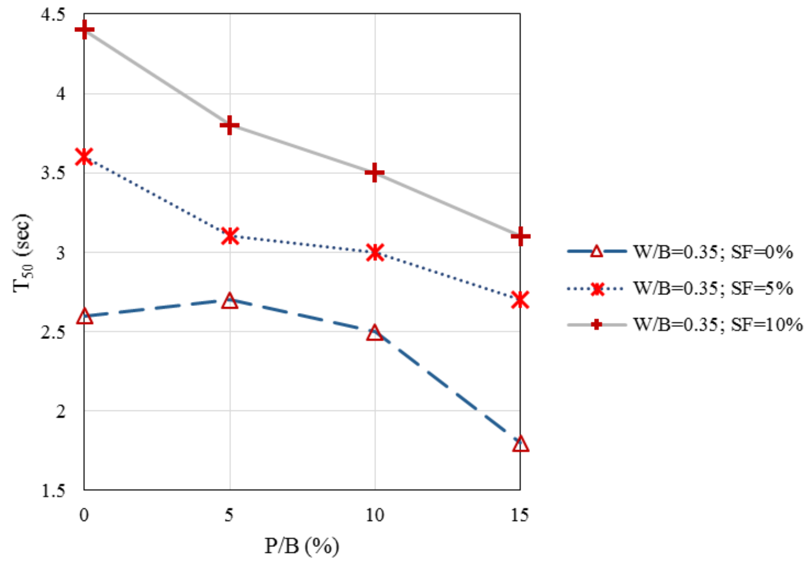

Fig. 7 Variation of T50 versus P/B ratio and SF/B ratio for mixes with W/B=0.35

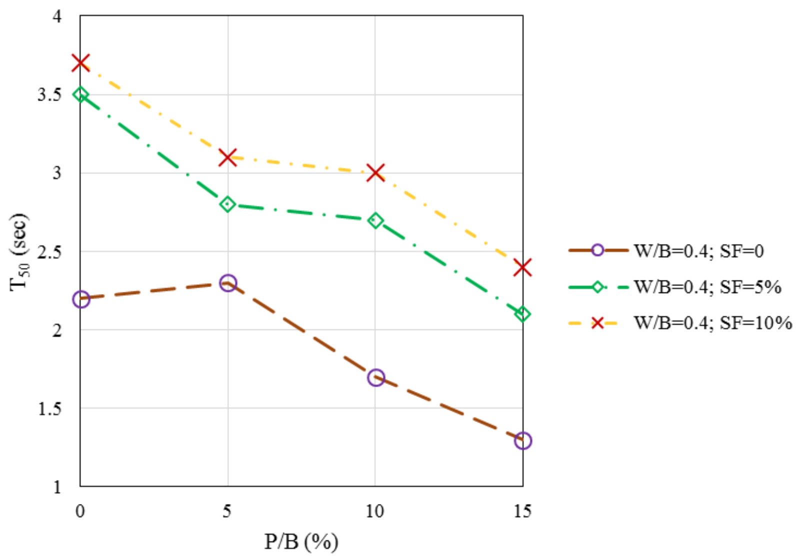

Fig. 8 Variation of T_{50} versus P/B ratio and SF/B ratio for mixes with W/B=0.40

Figs. 5 and 6 indicate the variation of slump flow diameter versus the variations of SF/B and P/B ratios in mixes with W/B ratios of 0.35 and 0.4, respectively. It is apparent that the use of silica fume decreases the slump flow diameter. However, the use of polymer increases this diameter. These observations could be attributed to those mentioned reasons for L-box ratio variations. Moreover, the values of T_{50} and V-funnel time, which are shown in Figs. 5-10 for both cases of W/B=0.35 and 0.4, are highly related to the contribution of silica fume and polymeric contents. These findings are in agreement with those reported for polymer modified SCC (Issa and Assaad 2016).

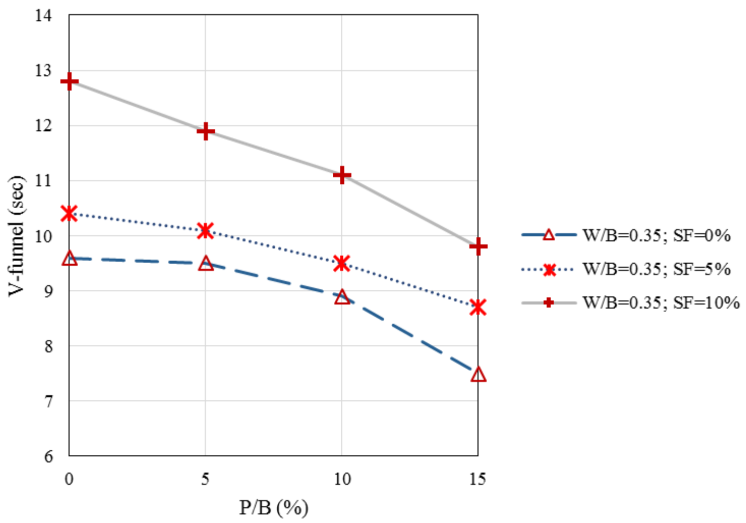

Fig. 9 Variation of V-funnel time versus P/B ratio and SF/B ratio for mixes with W/B=0.35

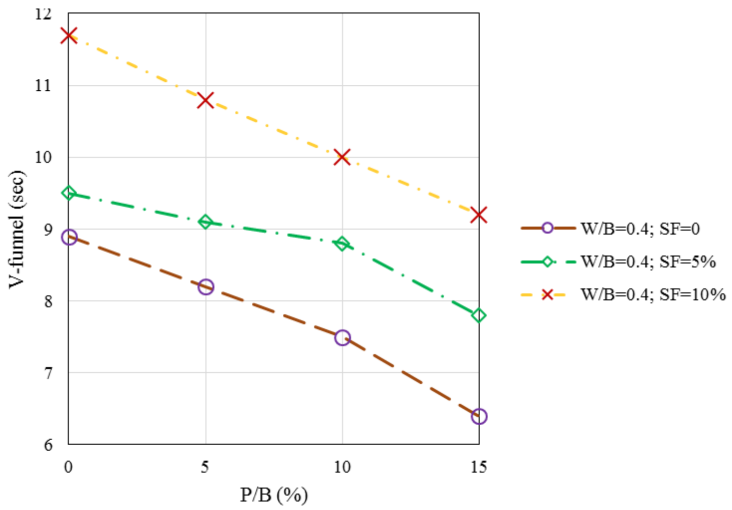

Fig. 10 Variation of V-funnel time versus P/B ratio and SF/B ratio for mixes with W/B=0.40

4.2 Mechanical properties

As mentioned earlier, studies about the behavior of SCLC is still too rare. This lack of knowledge could be attributed to two important issues: A. SCLC is a new generation to be developed in research and practice; B. the constituents used in SCLC are of a variety of kinds. For example, some researchers use different types of ultra-fine particles as a filler such as fly ash, rice husk ash, limestone powder, granite powder, etc. Some researchers use different types of lightweight aggregate such as light expanded clay aggregate, expanded perlite, pumice, etc. These differences in constituents lead to different macro and micro level behavior in SCLC. As a result, there is an essential need for in depth study about this beneficial generation of high-performance concrete. In this section, effects of SF/B and P/B ratios on 14-day, 28-day, and 90-day

Table 4 Mechanical properties of the mix compositions

Mix	14-day compressive strength (MPa)	28-day compressive strength (MPa)	90-day compressive strength (MPa)	Rupture modulus (MPa)	Tensile strength (MPa)
1SCLC	24.90	28.30	29.85	4.97	2.67
1SF5	27.6	31.42	32.83	5.2	2.84
1SF55	31.33	34.98	35.83	5.96	3.24
1SF510	33.50	37.56	38.26	6.59	3.58
1SF515	34.81	37.85	38.70	6.62	3.65
1SF10	31.57	35.12	37.64	5.47	3.28
1SF105	39.49	41.08	42.11	6.97	3.9
1SF1010	43.62	45.21	46.16	8.38	4.55
1SF1015	43.31	45.19	45.45	8.38	4.69
1P5	28.29	29.99	32.19	5.71	3.12
1P10	30.82	32.75	33.67	6.4	3.43
1P15	30.31	32.83	33.43	6.44	3.33
2SCLC	21.32	24	26.86	4.59	2.16
2SF5	23.38	25.97	28.43	4.87	2.36
2SF55	27.51	29.07	30.86	5.65	2.67
2SF510	30.66	32.08	32.89	6.31	2.99
2SF515	29.72	31.41	33.30	5.96	2.89
2SF10	26.31	29.08	30.89	5.20	2.96
2SF105	30.55	32.89	34.46	6.75	3.23
2SF1010	33.35	35.97	37.26	8.12	3.82
2SF1015	32.79	35.20	36.62	7.80	3.65
2P5	26.16	27.50	29.08	5.45	2.56
2P10	27.07	28.87	29.99	6.18	2.84
2P15	26.83	28.28	29.82	5.57	2.58

compressive strength, 28-day tensile strength, and rupture modulus of SCLC have been considered. Table 4 shows the results of the experiments in detail. As it could be seen, all mentioned mechanical properties were tested for both groups of water to binder ratios of 0.35 and 0.4. It is clear that the contribution of SF and P, as well have affected the mechanical properties of SCLC mixes as time. Fourteen figures (Figs. 11-24) have been brought herein to indicate the effects of P/B and SF/B ratios on mechanical properties, along with the influences of the age on compressive strength of SCLC.

Fig. 11 illustrates the effects of P/B and SF/B contribution on the growth of 14-day compressive strength. The vertical axis indicates $\frac{f_c^{14d}}{\left(f_c^{14d}\right)_{1SCLC}}$, and the horizontal axis shows P/B ratio. As it can be seen, changing the P/B ratio from 10 to 15% did not enhance the compressive strength of specimens of mixes with W/B=0.35. On the other hand, the increase of silica fume increased the 14-day compressive strength of specimens. In other words, silica fume alone

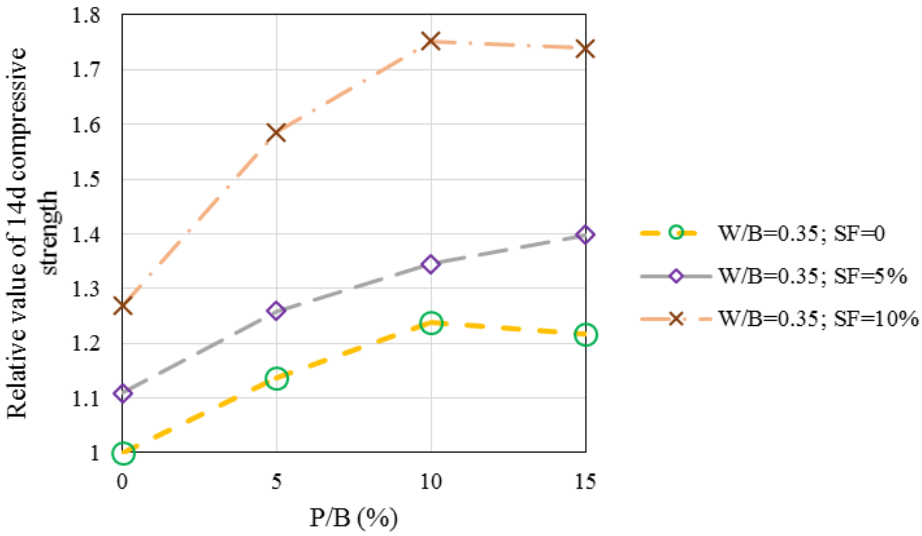

Fig. 11 The growth of 14-day compressive strength due to use of SF and polymer in comparison to the mix 1SCLC

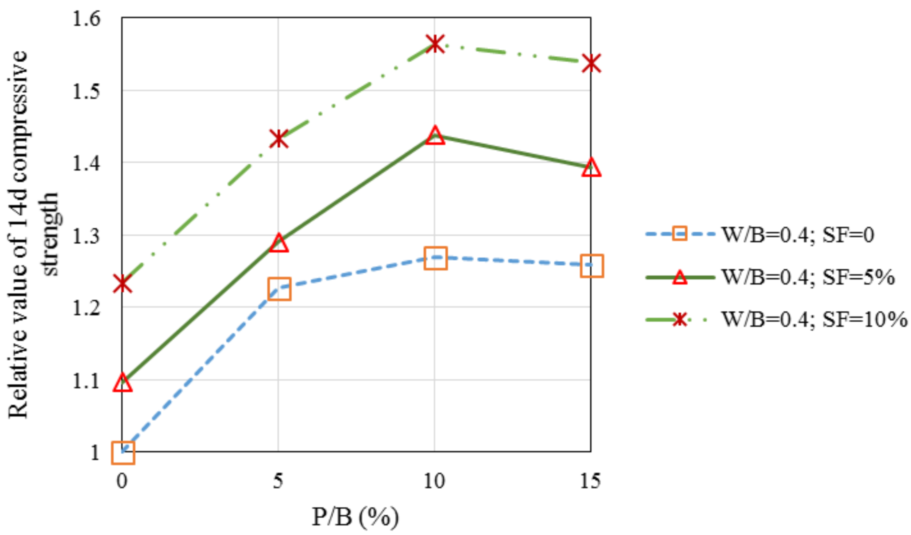

Fig. 12 The growth of 14-day compressive strength due to use of SF and polymer in comparison to the mix 2SCLC

increased the 14-day compressive strength of concrete by 11 and 27% for the SF/B ratios of 5% and 10%, respectively. However, the use of polymeric contents alone increased the 14-day compressive strength of SCLC for 24% at P/B=10%. Besides, the increase of P/B ratio from 10 to 15% when SF=0, led to 2% decrease of 14-day compressive strength. It is evident that a contribution of both silica fume and polymer improved the 14-day compressive strength of concrete. Quaternary mixes show better 14-day compressive strength. The efficient case of contribution of silica fume and polymer at W/B=0.35 was seen when 10% SF was used along with 10% of polymeric contents. However, one may ask the reason of decreasing in 14-day growth in

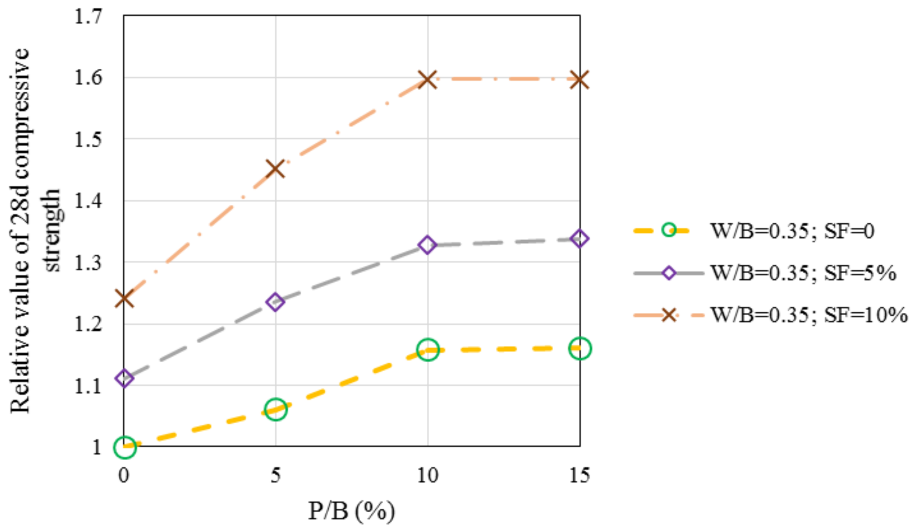

Fig. 13 The growth of 28-day compressive strength due to use of SF and polymer in comparison to the mix 1SCLC

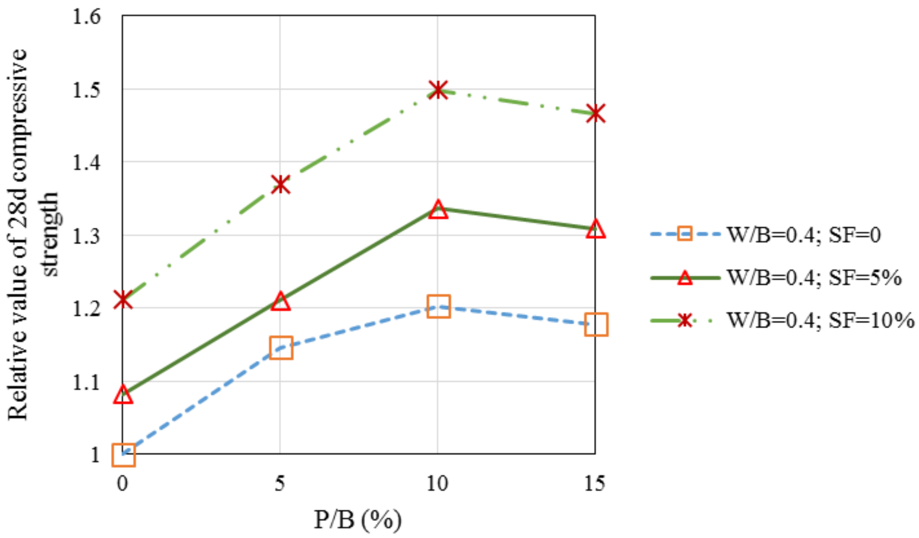

Fig. 14 The growth of 28-day compressive strength due to use of SF and polymer in comparison to the mix 2SCLC

the case when P/B=15%. This observation can be explained by decrease of constituents interlocking due to the use of the polymer. In the cases in which W/B was 0.4, the same trend was observed. However, the decline of strength growth was more evident. In other words, when the SF/B was 5%, the 14-day compressive strength was averagely decreased by 5%. Besides, in the absence of polymers, the increase in 14-day strength of mixes with W/B=0.35, due to the use of silica fume, was more than mixes with W/B=0.4. This finding could be attributed to more limestone powder in series with W/B=0.4 along with higher porosity of them, than the mixes with W/B=0.35. Actually, various trends were reported in the literature about the effects of polymer on

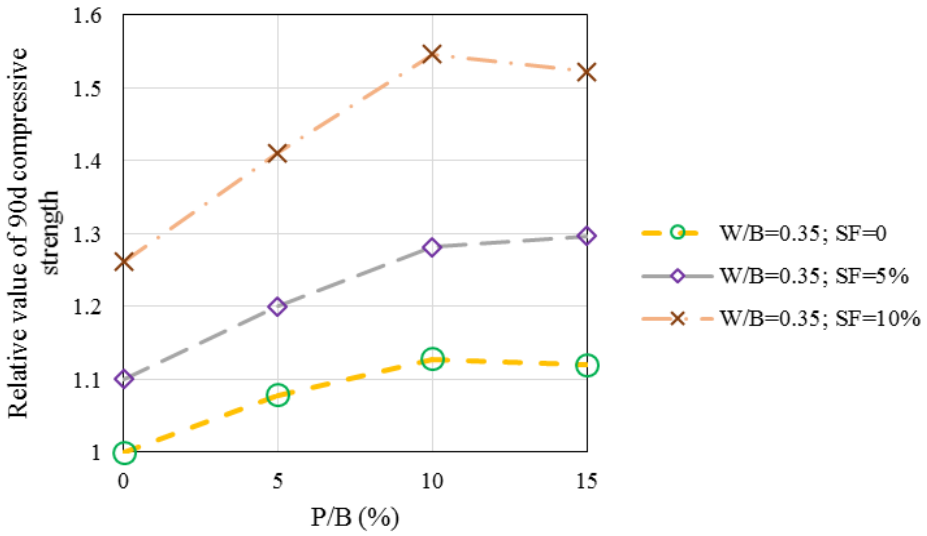

Fig. 15 The growth of 90-day compressive strength due to use of SF and polymer in comparison to the mix 1SCLC

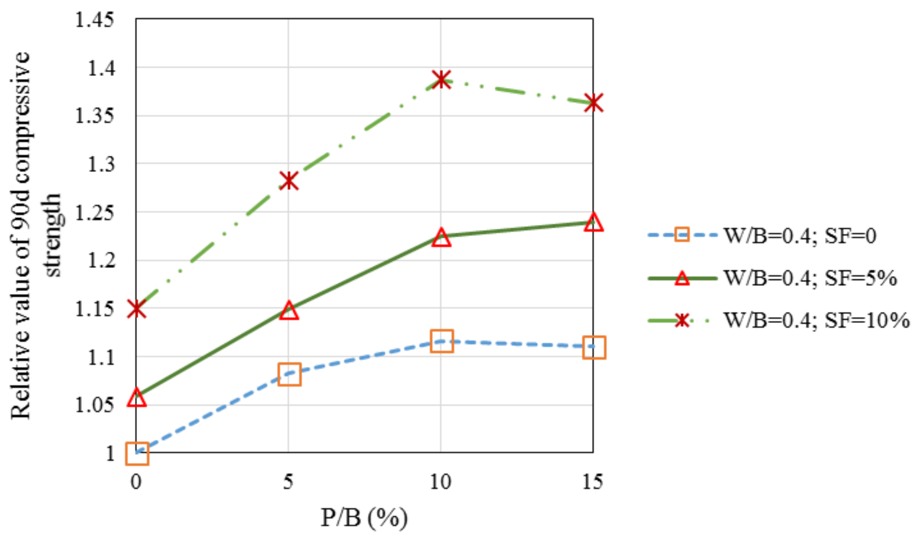

Fig. 16 The growth of 90-day compressive strength due to use of SF and polymer in comparison to the mix 2SCLC

compressive strength of cementitious composites. For instance, Issa and Assadd (2016) did not observe any change in the compressive strength of SCC due to use of the polymer. However, Aliabdo and Abd_Elmoaty (2012) used two different types of polymer and reported that styrene butadiene rubber did not affect the 28-day compressive strength of SCC. Nevertheless, polyvinyl acetate increased the mentioned compressive strength. They also reported that the effectiveness of polymer on the compressive strength of SCC depends on the age of concrete. Ma and Li (2013), however, reported that the polymer contents (polyacrylate and polyurethane modified polyacrylate) decrease the compressive strength of mortar.

Figs. 13 and 14 show the influences of P/B and SF/B ratios on the growth of 28-day

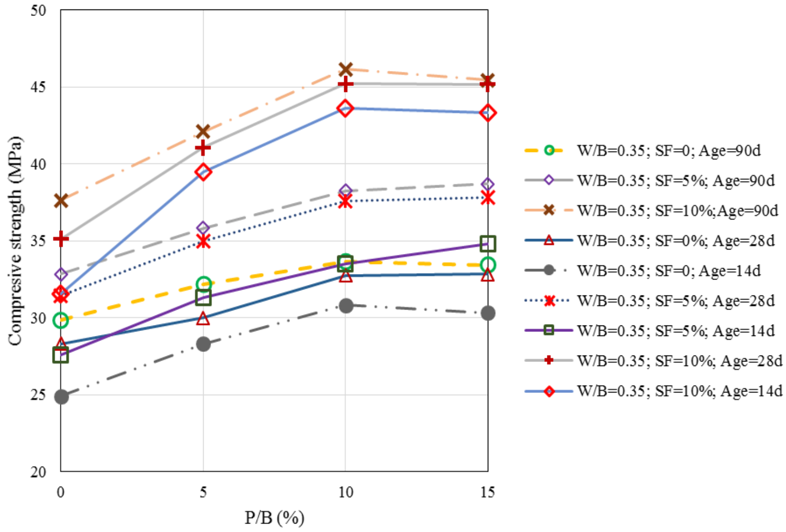

Fig. 17 Consideration of the effects regarding age, SF/B, and P/B ratios for mixes with W/B=0.35

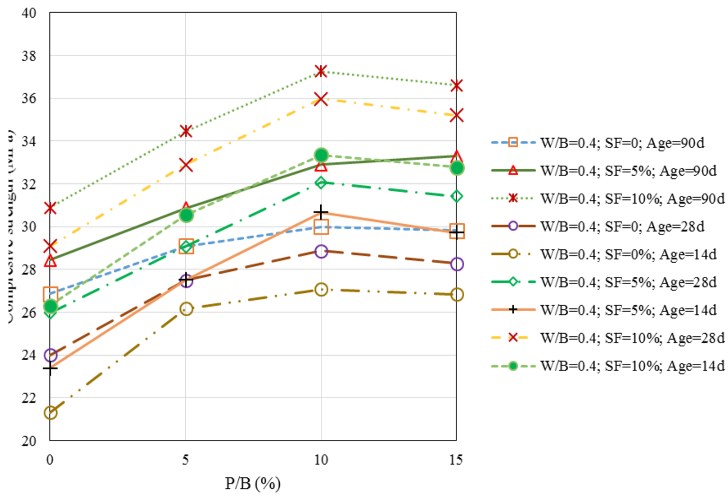

Fig. 18 Consideration of the effects regarding age, SF/B, and P/B ratios for mixes with W/B=0.40

compressive. In other words, vertical axis of Fig. 13 shows the values of $\frac{f_c^{\ 28\mathrm{d}}}{\left(f_c^{\ 28\mathrm{d}}\right)_{1\mathrm{SCLC}}}$ and vertical axis of Fig. 14 shows the values of $\frac{f_c^{\ 28\mathrm{d}}}{\left(f_c^{\ 28\mathrm{d}}\right)_{2\mathrm{SCLC}}}$. According to these figures, at the age of 28 days, the effect of silica fume alone on the compressive strength of mixes with W/B=0.35 is more considerable. In other words, at P/B=0 and SF/B=5%, the increase of compressive strength in comparison with the SF=P=0 specimen showed 11% and 8% increase for W/B=0.35 and 0.4, respectively. In addition, the effect of the polymer alone on the compressive strength of SCLC was weaker than silica fume. The other point, which should be noticed is that the optimum P/B ratio is about 10% and it is seen from Figs. 13 and 14 that further use of polymer could lead to a decrease

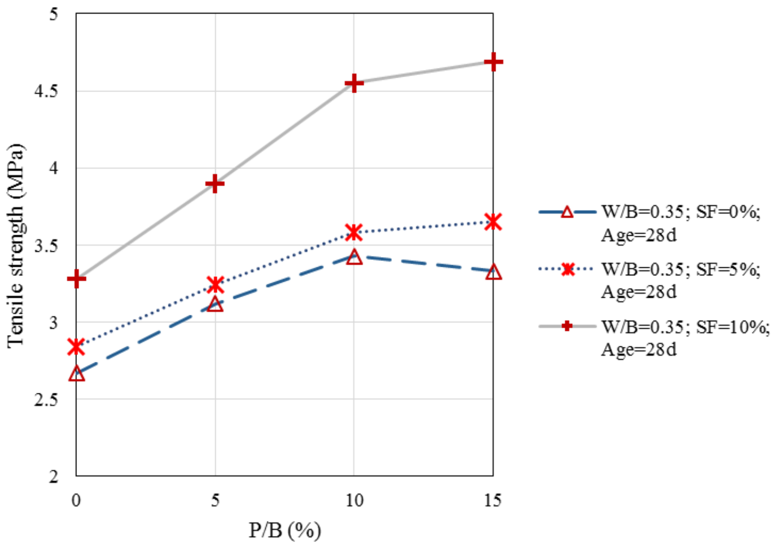

Fig. 19 Effects of P/B and SF/B ratios on Tensile strength of mixes with W/B=0.35

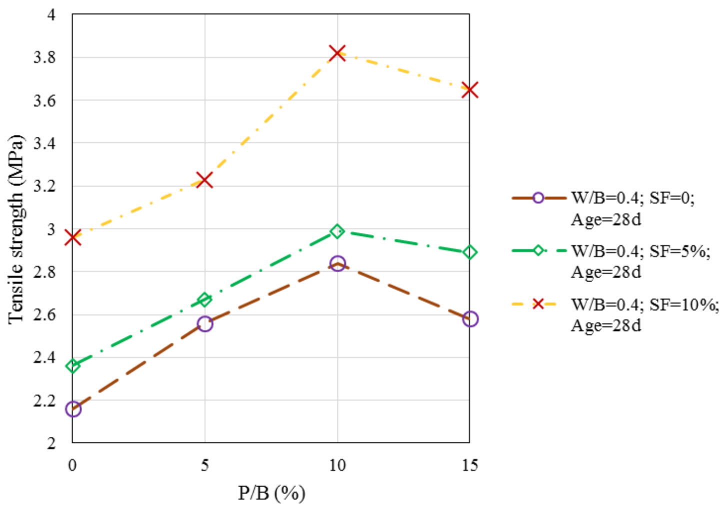

Fig. 20 Effects of P/B and SF/B ratios on Tensile strength of mixes with W/B=0.40

of compressive strength. Figs. 15 and 16 indicate the effect of silica fume and polymer on strength development of SCLC after 90 days. It is clear that the effects of these admixtures were more prominent after 90 days. This finding could be attributed either to the pozzolanic activity of silica fume or effect of polymer on retardation of hydration (Khalid *et al.* 2015, Kong *et al.* 2015). Actually, it could be claimed that it is better to use polymeric admixtures for lower values of water/binder ratio, since they cause reduction of the constituents interlock. Hence, the combination of high water/binder ratio and high amounts of polymeric contents could lead to a development of a poor-quality concrete.

To efficiently illustrate the effects of aging, P/B ratio and SF/B ratio on compressive strength of mixes with W/B=0.35 and 0.4, Figs. 17 and 19 are brought here in which the variation of the

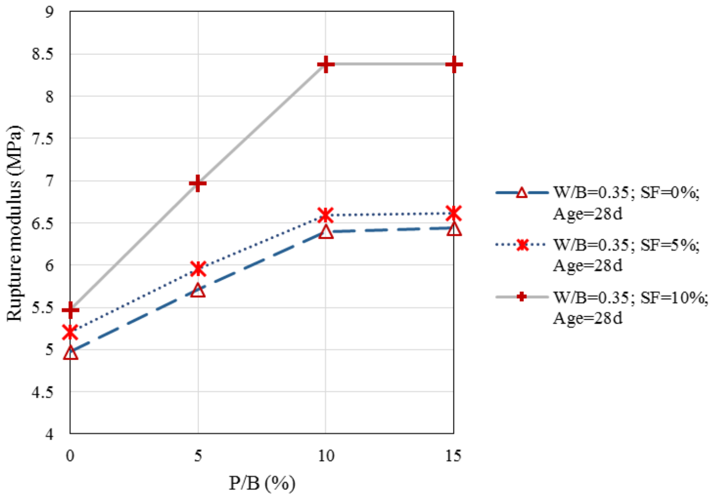

Fig. 21 Effects of P/B and SF/B ratios on rupture modulus of mixes with W/B=0.35

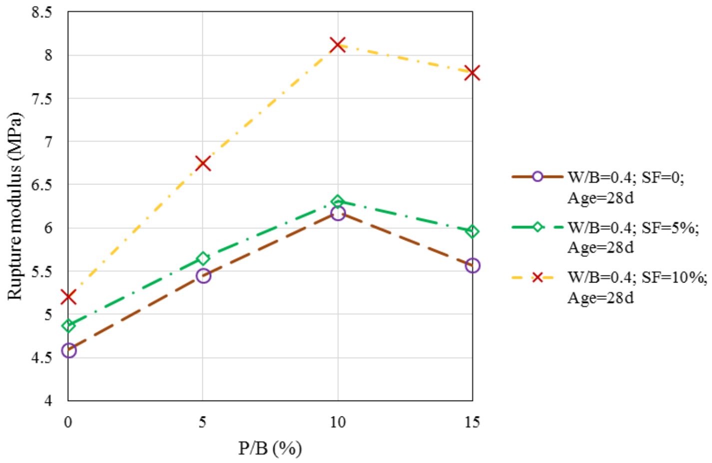

Fig. 22 Effects of P/B and SF/B ratios on rupture modulus of mixes with W/B=0.40

compressive strength of mixes with the mentioned parameters has been shown.

The other mechanical property, which was determined for 24 designed mixes, was an indirect tensile strength. Fig. 19 indicates the variation of tensile strength due to the use of silica fume and polymer in mixes with water/binder ratio of 0.35. As it can be observed, both the silica fume and polymer could enhance the indirect tensile strength of SCLC. However, the contribution of excessive amounts of the polymer could lead to a decrease of tensile strength. The finding is in agreement with those reported in (Aliabdo and Abd_Elmoaty 2012). It is evident that in W/B=0.35, P/B=0, contributions of 5% and 10% silica fume could enhance the tensile strength of SCLC by 6% and 23%. In addition, in the case W/B=0.35, SF=0, the contribution of 5, 10, and 15% polymer could lead to an improvement of tensile strength by 17, 29, and 25% in comparison to mix 1SCLC. Actually, the use of excessive amounts of polymers would not be beneficial and could lead to a decrease of tensile strength. In the domain of this study, the optimum P/B ratio was 10%. The detrimental effect of excessive usage of the polymer is more obvious in Fig. 15.

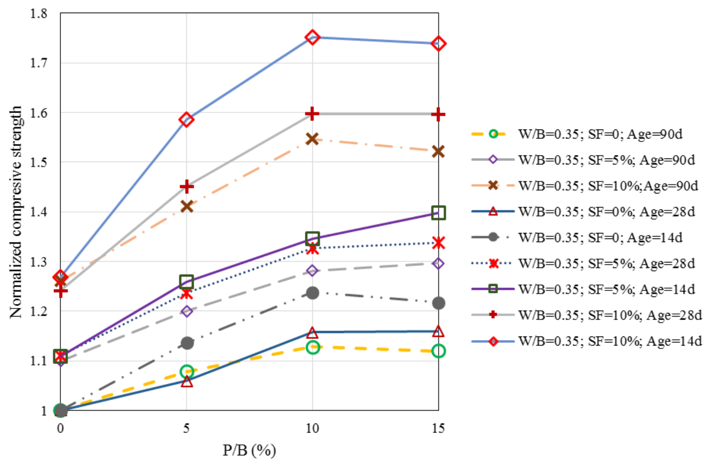

Fig. 23 Consideration of the effects regarding age, SF/B, and P/B ratios for mixes with W/B=0.40

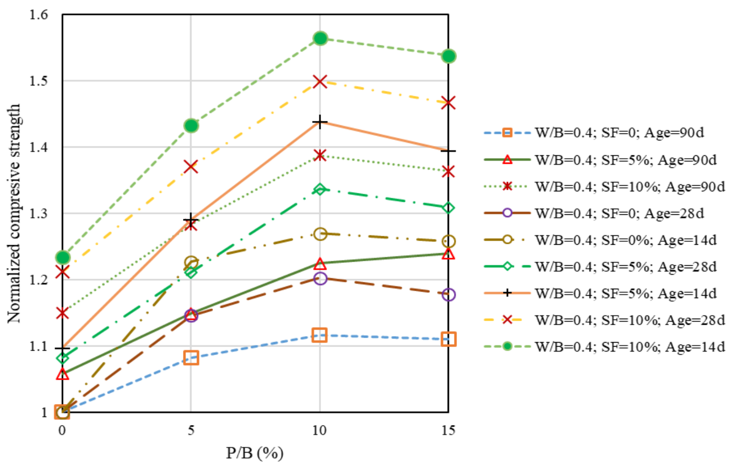

Fig. 24 Consideration of the effects regarding age, SF/B, and P/B ratios for mixes with W/B=0.40

The other mechanical property, which was determined for all mixes, was rupture modulus. As it can be observed from Figs. 21 and 22, the optimum dosage of polymer occurred, where the P/B was equal to 10%. In addition, in the absence of polymer, an increase of SF/B ratio from 0 to 10%, increased rupture modulus by 10% and 13% for W/B=0.35 and 0.4, respectively. On the other hand, in the absence of silica fume, the maximum variations of rupture modulus were 30 and 35%, for W/B ratios of 0.35, and 0.4, respectively. This implies that the effect of polymeric contents was more prominent than that of silica fume. It is clear that contribution of both SF and P could lead to a better SCLC.

Figs. 23 and 24 show the growth of compressive strength of mixes due to the variation of age, silica fume, and polymeric contents.

4.3 Durability tests

The durability of concrete mixes was always of great interest. Therefore, many research studies

Table 5 Ultrasonic pulse velocity and electrical resistivity of mixes

Mix	Ultrasonic pulse velocity (m/s)	Electrical resistivity (ohm.m)
1SCLC	3921	47
1SF5	3968	67.4
1SF55	4068	134.2
1SF510	4077	145.2
1SF515	4028	168.2
1SF10	3989	112.2
1SF105	4074	152.2
1SF1010	4096	175.4
1SF1015	4031	181.6
1P5	4060	149.2
1P10	4087	187.8
1P15	3994	201.9
2SCLC	3890	42.5
2SF5	3940	59.1
2SF55	4042	112.5
2SF510	4051	124.6
2SF515	4053	154.2
2SF10	4016	101.3
2SF105	4077	134.1
2SF1010	4100	149
2SF1015	4031	168.4
2P5	4067	168.2
2P10	4081	195.6
2P15	3996	215.4

have been carried out to realize the durability behavior of a new generation of concrete (Dave *et al.* 2017, Kabir *et al.* 2017, Mohammadhosseini *et al.* 2017, Onuaguluchi and Banthia 2017, Zeyad *et al.* 2017). However, a few studies could be found regarding durability of SCLC. For instance, Karahan *et al.* (2012) investigate the effects of metakaolin on porosity, sorptivity index, and chloride penetration resistance of SCLC. Hwang and Tran (2016) investigated the durability properties of foamed lightweight aggregate SCLC. In the present study, in order to preliminary estimate the effects of SF/B and P/B ratios on the durability of self-compacting concrete, two methods of testing i.e., ultrasonic pulse velocity test and electrical resistivity test have been conducted for all specimens. Test results are reflected in Table 5. Moreover, Fig. 25 to Fig. 28 were brought here to illustrate the effects of SF/B and P/B ratios on ultrasonic pulse velocity and electrical resistivity of the mixes.

As it can be seen from Figs. 25 and 26, the P/B and SF/B ratios have a prominent effect on the ultrasonic response of the mixes. On the other hand, the higher amounts of pulse velocity mean that the tested specimen had lower porosity. Hence, the higher amounts of pulse velocity infer that the mixture was more durable. Accordingly, it can be concluded that the contribution of 10%

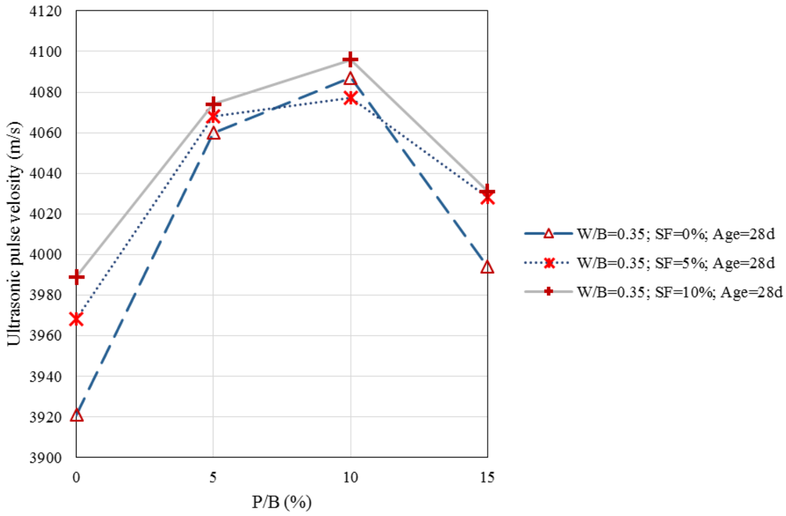

Fig. 25 Effects of P/B and SF/B ratios on ultrasonic pulse velocity of mixes with W/B=0.35

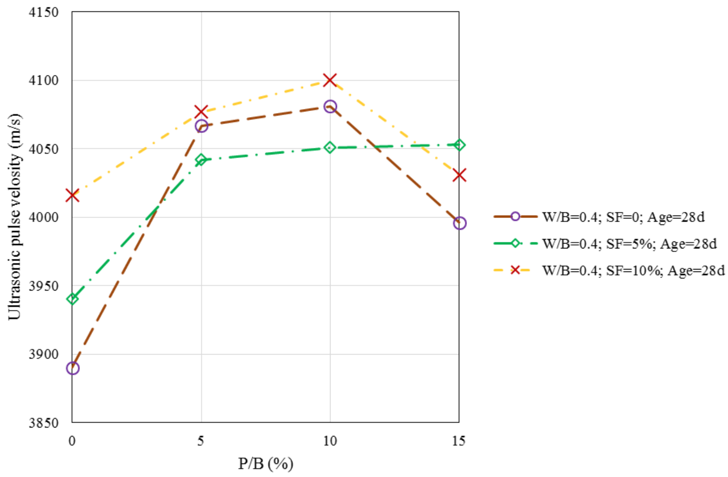

Fig. 26 Effects of P/B and SF/B ratios on ultrasonic pulse velocity of mixes with W/B=0.40

polymer along with 10% silica fume could lead to a more durable mix in both water to binder ratios of 0.35 and 0.5. Besides, the use of excessive amounts of the polymer could lead to a reduction of durability. This finding could be explained by the increase of porosity in P/B=15%. Figs. 27 and 28 illustrates the influences of SF/B and P/B ratios on the electrical resistivity of SCLC mixes with W/B ratios of 0.35 and 0.4, respectively. As stated by Layssi *et al.* (2015), there are robust correlations between electrical resistivity and chloride penetration resistance, diffusion coefficient, corrosion, setting time measurement, and moisture contents. Estimation of the service life of new structures and assessments of the structure for maintenance or rehabilitation necessitates the assessment of diffusion coefficient (Layssi *et al.* 2015). According to the Nernst-Einstein equation, the diffusion coefficient is linearly dependent to the electrical resistivity (Layssi *et al.* 2015). Besides, based on the study of Hornbostel *et al.* (2013), who extensively reviewed the literature to find out the correlation between the electrical resistivity and the corrosion rate, the

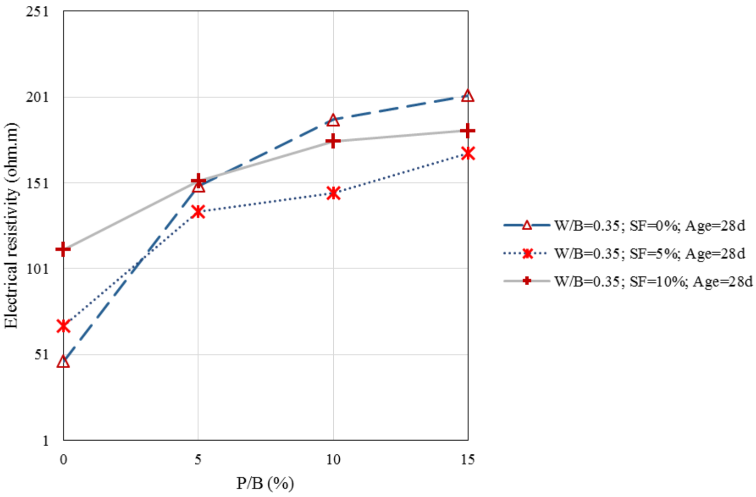

Fig. 27 Effects of P/B and SF/B ratios on electrical resistivity of mixes with W/B=0.35

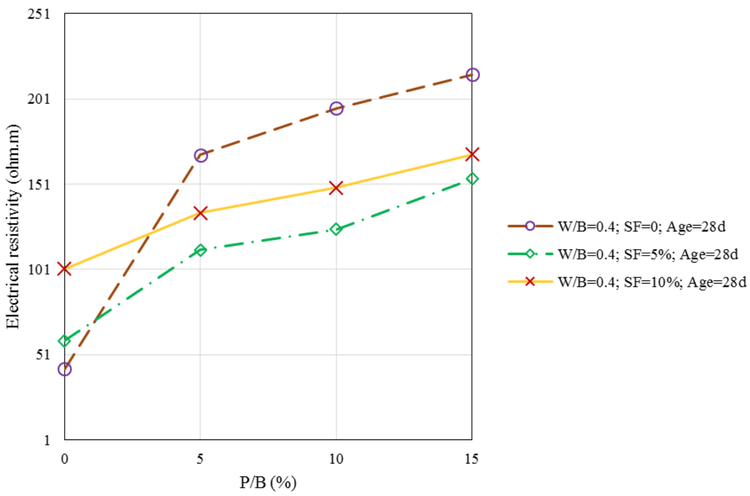

Fig. 28 Effects of P/B and SF/B ratios on electrical resistivity of mixes with W/B=0.40

corrosion rate is often inversely in proportion with the electrical resistivity of concrete. According to the study of Ranade *et al.* (2014), the electrical resistivity is also related to the tensile strain and could be used as a technique to monitor the development of micro-cracks in cementitious composites. In addition, Bentz *et al.* (2015) used this technique in order to predict setting time of the cement paste and concrete, since depercolation and capillary pores spaces increased by hardening of the concrete (Layssi *et al.* 2015). The other potential advantage of electrical resistivity is the determination of moisture contents of concrete (Layssi *et al.* 2015). Rajabipour and his co-authors (Rajabipour *et al.* 2004) used electrical resistivity to determine the moisture contents of concrete. However, the methods need more assessment (Layssi *et al.* 2015). Based on these explanations, the chloride penetration resistance, diffusion coefficient, and micro-cracking of SCLC mixes are highly dependent on the SF/B and P/B ratios. However, it is apparent from Figs. 27 and 28 that the polymers alone yielded better electrical resistivity.

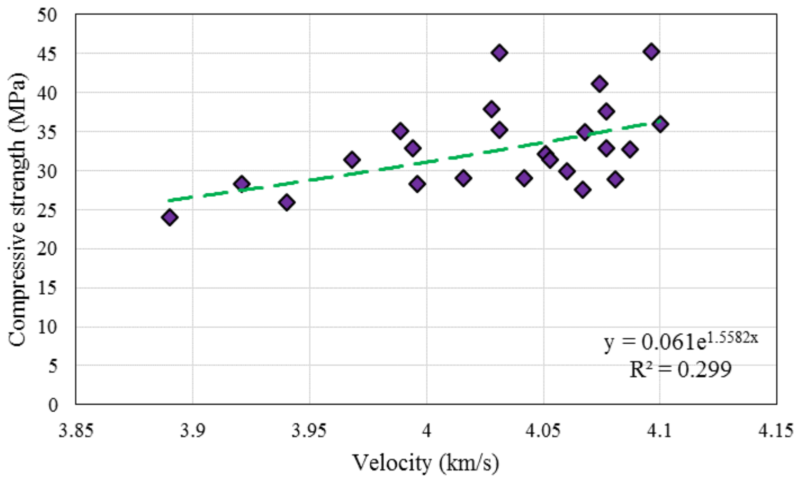

Fig. 29 Correlation between ultrasonic pulse velocity and compressive strength

The other potential usage of the ultrasonic test is to estimate the compressive strength of concrete for preliminary purposes. Fig. 29 shows the correlation between the compressive strength of SCLC mixes and ultrasonic pulse velocity. However, the value of R^2 infers that the correlation is not good enough to be used for practical purposes and could be used only for preliminary estimations.

5. Conclusions

The following conclusions could be drawn from the study:

1. The use of polymers alone could lead to a better electrical resistivity than using both silica fume and polymer.
2. The electrical resistivity of the mixes with polymer/binder ratio of 15% and silica fume/binder ratio of zero, were averagely 4.3 and 5.07 times more than that of the control mix with water/binder ratios of 0.35 and 0.4, respectively.
3. The use of 5 and 10% silica fume alone led to an increase of electrical resistivity by 43% and 139% compared to the control mixes, respectively, for mixes with water/binder ratio of 0.35. Moreover, for water/binder ratio of 0.4, those contributions of silica fume increased the electrical resistivity of mixes by 39% and 138% in comparison to the control mixes, respectively.
4. According to the ultrasonic pulse velocity and mechanical tests, the use of polymer contents should be limited to 10% by weight of the binder.
5. The workability and mechanical properties of mixes with both silica fume and polymer were better than those ternary mixes.
6. Polymer and silica fume enhanced the compressive strength, modulus of rupture, durability, and indirect tensile strength of SCLC mixes.
7. In mixes with water/binder ratio of 0.35, the use of 10% silica fume enhanced the tensile strength of mix by 23% compared to the control mix.
8. In general, the best contribution for quaternary mixes was observed to be 10% for both polymer and silica fume.

9. Effects of silica fume and polymers are time dependent. The increase of compressive strength in the experiments has been seen to be higher after 90 days than those of 28 or 14 days.

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