Utilization of Limestone Quarries Powder Waste to Develop Sustainable Self-Compacting Concrete

Ahmed Azzam, Ahmed Rashad, Ahmed F. Abdel Aziz

Abstract— In limestone quarries, Large quantities of limestone powder (LP) waste are accumulated annually during the operation of these quarries. The utilization of this LP waste for a clean production of low cost and sustainable self-compacting concrete (SCC) represents significant environmental and economic leap. This research is aimed to investigate the influence of using different levels of LP (20%, 30% and 40% of cement weight) as a partial substitution of fine aggregate on the fresh, hardened, and durability characteristics of the developed SCC mixtures. The addition of silica fume (SF) with the best LP content was also investigated. Test results showed that the inclusion of LP significantly improved the fresh, hardened, and durability characteristics of the produced SCC mixtures. Furthermore, the improvement in the mechanical and durability characteristics was more pronounced when 10% SF was added considering its relatively high cost. A simple material cost analysis revealed that the cost of 1 m3 of SCC incorporating LP is almost the same as that of the control SCC mixture. However, the material cost per unit compressive strength was significantly reduced in the order of 22.0 to 33.2 %.

Index Terms— Limestone Powder Waste; Self-Compacting Concrete; Fresh Properties; Hardened Properties; Durability Characteristics.

1 Introduction

In Egypt, limestone quarries are spread across the entire country where they are the principle source of crushed stone aggregates and limestone building units. In these quarries, considerable amounts of LP are being accumulated as by-product waste during crushing, cuttin and sawing processes. These wastes represent a burden from the environmental point of view causing serious health hazards. Therefore, the collection and successful utilization of these powder waste represent a major challenge and turn these by-product materials into a valuable resource. Many researchers have tried to utilize the LP wastes in the development of conventional concrete [1], [2], self-compacting concrete (SCC) [3], [4], [5], high performance concrete [6], and lightweight concrete [7].

SCC is high flowable, non-segregated concrete that can spread in place, fill the molds, and encased the reinforcement without mechanical compaction [8]. In order to attain such behavior, the main requirements of fresh SCC are filling and passing abilities besides high-segregation resistance. The first and second characteristics can be acquired using high range water reducer admixtures (HRWRA). To secure cohesion and stability of the SCC mixture, a large amount of fine materials and/or viscosity-modifying admixture (VMA) is required [9]. However, VMA are too expensive and can increase the SCC cost. This new class of high performance concrete has been employed in cast in place and precast applications. Recently, SCC has been used for repair applications, where it ensured sufficient filling of constrained areas and provided high surface quality [8].

Many investigations have been performed on the utilization of different mineral additions in SCC manufacture such as fly ash [10], [11], [12], [13], SF [14], bagasse ash [15,16], metakaolin [9,17,18], blast furnace slag [13], [14], [17], [19], [20] and marble powder [20], [21], [22], [23] to produce inexpensive SCC. The mineral admixtures significantly enhance the flowability of SCC and they can be efficiently used as viscosity enhancement agents [24]. In addition, these mineral additives can decrease the amount of superplasticizers needed to achieve a specific fluidity. This decrease depends significantly on particle size distribution, particle shape and surface properties of mineral additives [13], [20].

Numerous researches are available on the use of LP in SCC production. Most of researches conducted in this area investigated the fresh and hardened characteristics of SCC [3], [4], [13], [15], [20], [25], [26], [27], [28] while, limited studies have been investigated the time dependent deformation [3], [5], [29]. In addition, the durability characteristics of SCC including LP have been studied in very limited investigation [13], [25], [30], [31]. Till date, there is a lack of information about the durability performance of SCC including LP waste in Egypt and around the world.

This study aims to study the feasibility of utilizing the by-product LP waste from local limestone quarries in developing low cost and sustainable SCC. Thus, an experimental investigation was designed and accomplished to assess fresh properties (through the slump flow, J ring, L box, GTM screen stability and V funnel tests), the hardened properties (compressive strength, splitting tensile strength, flexural strength, bond strength and drying shrinkage), and the durability characteristics (water penetration depth, rapid chloride ion penetration, water sorptivity as well as the sulfuric acid resistance) of the SCC mixtures developed using various contents of LP waste

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(20%, 30% and 40% of cement weight). Moreover, the viability of adding specific dosage of SF (10%) to the high LP replacement level is also evaluated in the present research.

2 Experimental Program

2.1 Material Characterization

CEM I (42.5R) ordinary Portland cement (OPC) conforming to EN 197-1 [32], has been used in all concrete mixtures. LP waste was obtained from El-Menya quarry, Egypt. The chemical composition of cement and LP are listed in Table 1. The LP mineralogical composition was determined using x-ray diffraction as shown in Fig. 1, where the main phase was calcite The particle size distribution for aggregates, cement and LP are illustrated in Fig. 2.

The fine aggregate used was natural sand and the coarse aggregate was crushed dolomite limestone. The fineness modulus and specific gravity of fine aggregate were measured to be 2.54 and 2.67, respectively. The coarse aggregate has a maximum size of 14 mm. Its specific gravity was 2.68 and water absorption was 1.80 %. A polycarboxylate based HRWRA was used in all concrete mixtures.

TABLE 1
Chemical Composition of Cement and LP

Composition	CEM I (42.5R)		LP
	Results	Limits*	
CaO	61.54	------	51.2
SiO_2	19.31	------	------
Al_2O_3	4.59	------	------
Fe_2O_3	3.12	------	------
MgO	2.59	≤ 5%	------
SO_3	3.35	≤ 3.5%	------
K_2O	0.03	------	------
Na_2O	0.10	------	------
Cl	0.05	≤ 0.1 %	------
IR	1.72	≤ 5%	2.73
LOI	3.73	≤ 5%	43.79

* European standard EN 197-1 [32].

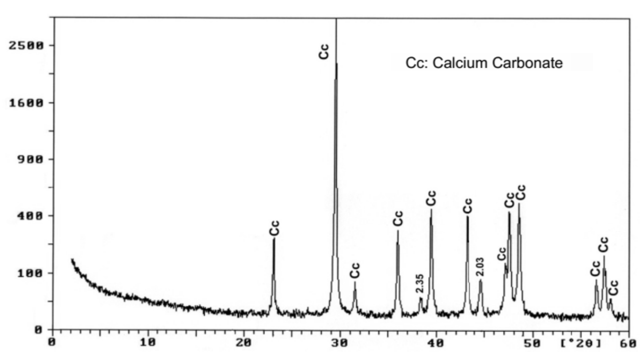


Fig. 1. XRD for Limestone Powder

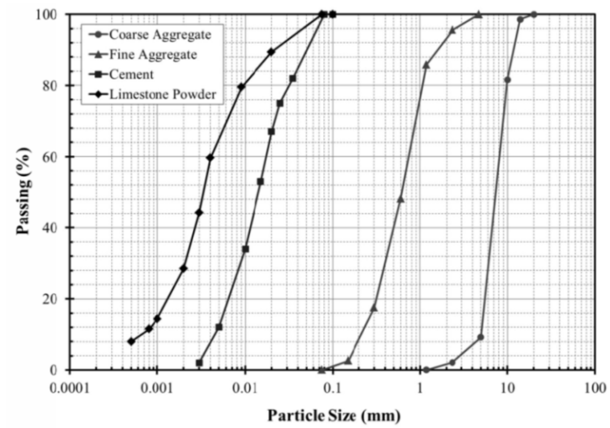


Fig. 2. Particle size distribution of Aggregates, Cement and LP

2.2 Mixture Proportions

SCC mixtures were prepared with different fine aggregate compositions. The cement content has been unified as 400 kg/m³ for the developed mixtures and the coarse aggregate content has been kept constant at 810 kg/m³ for all mixtures. LP has been incorporated to mixtures as a partial substitution of fine aggregate in various replacement levels (0%, 20%, 30% and 40% of cement weight). In the last mixture, 10% of cement was replaced with SF. The 10% SF was selected based on previous study [33] where SF showed a greater improvement in strength compared with other SCMs and the strength was marginally higher when the replacement ratio was more than 10%. The water content and w/cm ratio for all mixtures were kept constant while the HRWRA dosage was adjusted to maintain a flow diameter of 650 ± 50 mm. Details of concrete mixture proportioning are given in Table 2.

TABLE 2
Mixture Proportions of Tested Mixtures

Mixture Code	Cement (kg/m³)	Water (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	LP (kg/m³)	SF (kg/m³)	Super plasticizer (kg/m³)	W/CM
LP0	400	170	810	810	0.0	0.0	8.6	0.425
LP20			730		80		7.2	
LP30			690		120		7.2	
LP40			650		160		7.2	
LP40-SF10	360		650		160	40	8.0	

2.3 Specimens Preparation and Testing Procedures

Each SCC mixture was batched and mixed in the laboratory following the procedure established by Khayat et al. and Madandoust et al. [9], [34]. In this method, fine and coarse aggregates were homogenized for 30 seconds at normal mixing speed. Thereafter, adding about half of the mixing water into the mixer and the mixing process continues for one minute. The mixture was rested for another one minute. Subsequently, cement and LP were added and mixed for one more minute. The remaining water and HRWRA were introduced to the wet mixture, while mixing was going on for three minutes. Finally, after 2 minutes resting, mixing sequence resumed for additional 2 minutes.

A plan of five different types of fresh concrete testing was adopted to assess the three key properties of SCC (filling and passing abilities and segregation resistance) according to EFNARC [35]. Slump flow, J ring, L box, GTM screen stability and V funnel tests were implemented. The workability of SCC mixtures was controlled as the flow diameter of all mixtures was adjusted to be within the range of 650 ± 50 mm. The J ring and L box tests were conducted to assess the mixtures passing ability. Filling ability and segregation resistance of the mixtures were examined through the V funnel test. Moreover, the GTM screen stability test was implemented to assess the stability of mixtures.

The specimens were cast into molds and stored for the first 24 hours under a plastic sheet in the laboratory environment. The specimens were then demolded and wet-cured till test date. For durability test specimens, specific treatment conditions have been applied.

Concrete cubes of 150×150×150 mm dimensions were cast and tested in compression after 1, 3, 7, 28, 56, and 90 days. Concrete cylinders of 150×300 mm dimensions were cast for 28-day splitting tensile strength. Concrete beams of 100×100×500 mm dimensions were produced for 28-days flexural test. "Lollipop" specimens were prepared to determine the 28-day bond strength. The specimens consisted of concrete cylinders of 100×200 mm, in which 12 mm diameter steel rebars were embedded. In all tests, three specimens were tested and the average was reported.

To determine the drying shrinkage, prismatic specimens with dimensions 100×100×285 mm were used. The test was conducted according to ASTM C 157 [36]. The specimens were cast and left in molds for one day. The prisms comprised two stainless steel studs at the middle of both ends of the specimen. After demolding, the specimens were put in a lime-saturated water for 30 minutes and then initial reading was recorded. Then, specimens were put again in the curing solution for 27 days. Specimens were taken out of the solution and stored in a controlled chamber with relative humidity 50 % and a temperature of 23 °C. Comparative readings were recorded and the length change is computed for test specimens.

Water penetration test (WPT) was performed, using a setup prepared at Ain Shams University [37], according to BS EN 12390-8 [38] for cube specimens of 150×150×150 mm. Test specimens were water cured for 28 days, then air dried under laboratory conditions for 24 hours. A concrete surface with 100 mm diameter was exposed to 0.5 N/mm² (5 bar) water pressure for three days. Each specimen was divided into two halves, immediately after the test, and the water depth was determined at five different positions and the mean was reported. Fig. 3 represents a schematic diagram for the test idea.

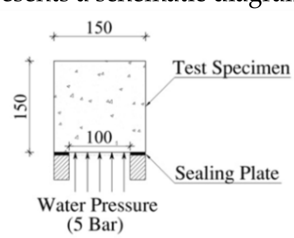


Fig. 3. The Test Idea of WPT

The rapid chloride penetration test (RCPT) was performed at 28 days following ASTM C1202 [39]. The electrical current amount, passing through 50 mm thick slices of 100 mm nominal diameter cylinders, were monitored during a test period of 6 hours. A 60 V D.C. potential difference was sustained across the ends of the specimen, one end is exposed to 0.3 N NaOH solution and the other to 3% NaCl solution. The RCPT setup is shown in Fig. 4. The total charge passed across the test specimen through the test period (6 hours) was determined and used to categorize the chloride ion penetrability of concrete [39].

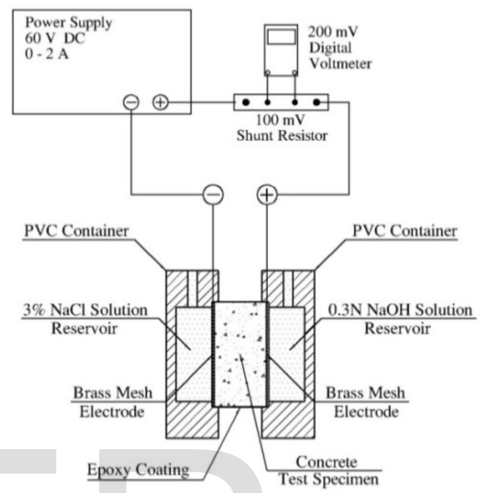


Fig. 4. Test Setup of RCPT

In sorptivity test, the rate of drawn water into the specimen pores is determined. Sorptivity coefficient is determined as an indicator for capillary water suction of concrete. The test was performed as stated by ASTM C1585 [40], after 28 days, on concrete cylinder specimens of diameter 100 mm and height 50 mm. Test specimens were dried for three days at 50° C and then allowed to cool, in a closed container, to ambient temperature. After the specimen sides were coated with epoxy, while the upper surface was covered with a plastic sheet, the sorptivity test was conducted by placing the specimens on pin supports in a shallow water container where the specimen bottom surface was immersed in water up to a height of 3 mm. Specimens were removed from the water container and weighed at specific intervals up to 6 h to calculate the mass gain. The volume of absorbed water was determined by dividing the mass acquired by the specimen surface area by the water density. These values were then plotted against the square root of the time. The best fit line slope is determined to represent the sorptivity coefficient.

The sulfuric acid attack test was performed on 100×100×100 mm concrete cubes. Test specimens were water cured for 28 days and then immersed in a plastic tank containing sulfuric acid solution, at room temperature, for 56 days. The solution consisted of 5.0 % sulfuric acid (H_2SO_4) to produce a solution with comparatively high concentration to accelerate the sulfuric acid effect. The compressive strength reduction and weight loss as a result of sulfuric acid attack were determined at the end of exposure (the compressive strength for control specimens was determined before immersing the exposed specimens).

3. Discussion of Test Results

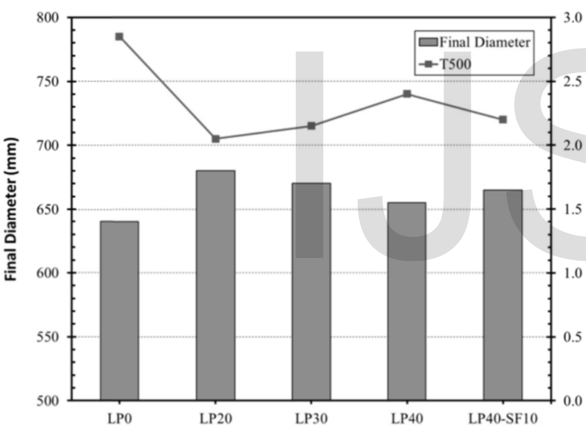
3.1 Fresh Properties

The fresh concrete test results for slump flow, J ring, L box, GTM screen stability and V funnel tests for all SCC mixtures are presented in Table 3 and plotted in Fig. 5.

TABLE 3
FRESH CONCRETE TEST RESULTS

Mixture Code	Slump Flow Test		J ring Test	L Box Test	GTM Screen Stability Test	V Funnel Test	
	T_{500} (sec)	D_{final} (mm)	Blockage (mm)	H_2/H_1	M_b/M_a (%)	T_0 (sec)	T_5 (sec)
LP0	2.85	640	13.1	-----	5.86	6.80	7.92
LP20	2.05	680	7.3	0.67	4.08	6.04	7.12
LP30	2.15	670	6.6	0.71	3.80	6.12	6.83
LP40	2.40	655	6.0	0.73	3.54	6.51	6.91
LP40-SF10	2.20	665	5.0	0.76	3.20	6.41	6.62
Limits*	VS1≤ 2 VS2> 2	SF1 (550 – 650) SF2 (660 – 750) SF3 (760 – 850)	-----	≥ 0.80	SR1 ≤ 20 SR2 ≤ 15	VF1 ≤ 8 VF2 (9-25)	-----

* EFNARC [35].



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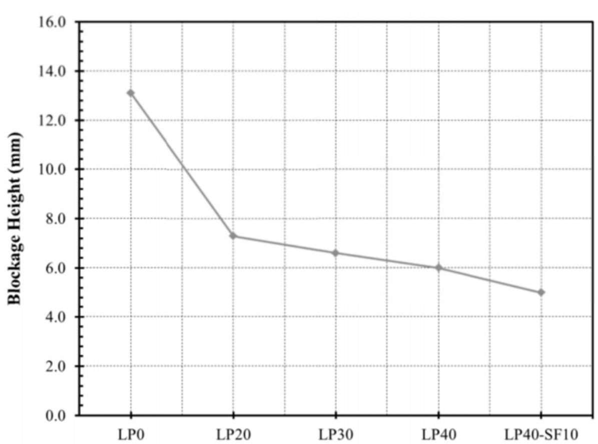

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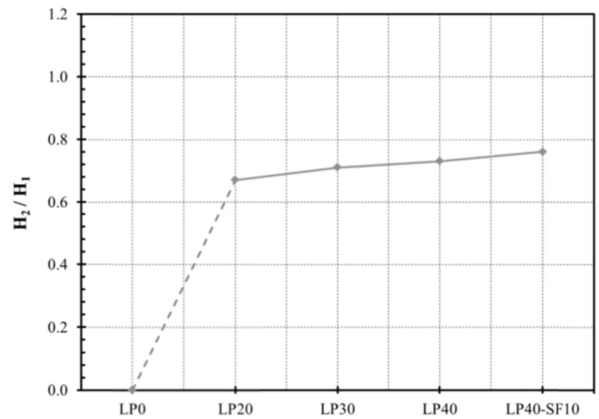

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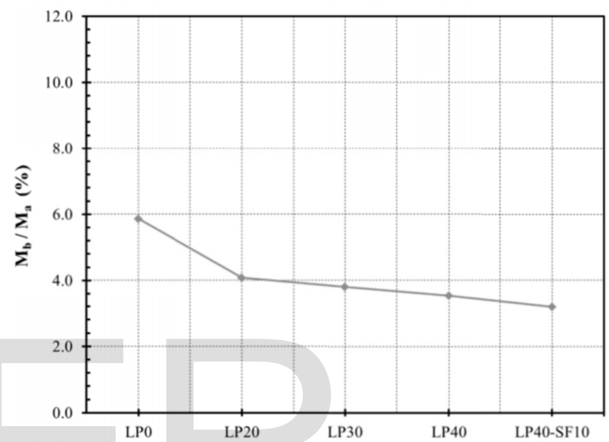

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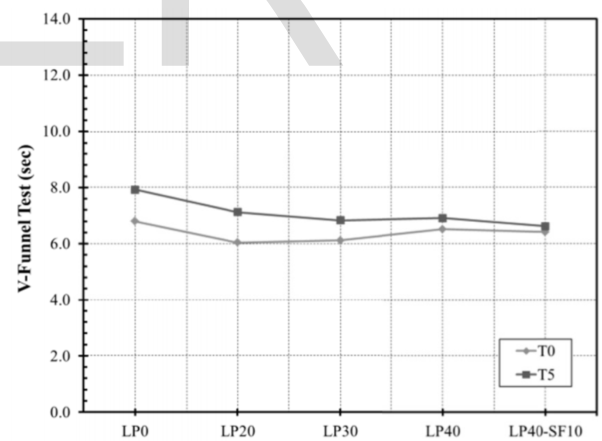

(e)

Fig. 5. Fresh Properties Test Results: (a) Slump Flow Test, (b) J ring Test, (c) L-Box Test, (d) GTM Screen Stability Test, and (e) V Funnel Test

As shown in Table 3 and Fig. 5a, the slump flow values of different SCC mixtures were ranged from 640 to 680 mm. According to EFNARC [35], all mixtures except LP0 can be categorized as slump flow class 2. It should be noted that, inclusion of LP in SCC mixtures decreased the HRWRA demand to achieve the same consistency. However, the flowability of the mixtures was reduced with the LP content increase while, the addition of 10% SF slightly enhanced the flowability with minimal increase in the HRWRA demand.

As presented in Table 3 and Fig. 5a, the slump flow time (T_{500}) for different SCC mixtures were within the range of 2.05 to 2.85 Sec. Test results exhibited that the SCC mixtures with LP had low flow times while for the higher LP content, high T500 times were recorded. However, the addition of 10% SF reduced the T_{500} time as a result of viscosity enhancement. The T500 time was higher for the mixture LP0 which indicates higher internal friction due to the lack of lubricant effect of LP. Test results demonstrate that, all SCC mixtures were classified as VS2 in terms of viscosity according to EFNARC [35].

From the results presented in Table 3 there was a small degree of blockage, within the range of 6.0 to 7.3 mm, in all mixtures incorporating LP (LP20, LP30, and LP40). The LP40-SF10 mixture experienced a minimal blockage (5.0 mm). The J ring flow results for LP0 mixture exhibited extreme blockage (13.1 mm) that indicated inadequate passing ability.

The results from the L box test are presented in Table 3 and Fig. 5c. The L box blocking ratio of SCC incorporating LP changed from 0.67 to 0.76. Although these values were out of the EFNARC [35] recommended blocking ratio (0.80), It should be noted that Felekoğlu et al. [41] reported that the blocking ratio of 0.6 was sufficient to achieve an appropriate filling ability. From the L box test results, It was noticed that the addition of 10% SF slightly enhanced the filling ability of SCC mixture. Conversely, the LP0 mixture did not reach the other end of the horizontal shaft.

The GTM screen stability test was implemented to assess the segregation resistance for developed mixtures. Test results revealed that the segregation resistance increased with the increase of the LP content and the inclusion of SF improved the segregation resistance. However, the LP0 mixture exhibited the lowest segregation resistance.

Regarding the EFNARC [35], V funnel flow time higher than 25 sec was not recommended. As shown in Table 3, the V funnel times of the developed mixtures satisfy the EFNARC requirement. The results indicated that, for mixtures incorporating LP, V funnel time shows a slight tendency to increase with increasing LP content due to viscosity increase. All mixtures can be grouped as VF1 in terms of viscosity in accordance with EFNARC. The difference between T0 and T5 showed a small decrease with the LP content increase which indicates good segregation resistance.

An overview of the fresh properties of SCC mixtures incorporating different LP levels reveals that the mixtures generally satisfy the EFNARC requirements related to filling and passing abilities and segregation resistance. Moreover, the cement replacement with 10% SF enriches the fresh characteristics of SCC mixtures, taking into account the slightly higher HRWRA demand.

3.2 Hardened Properties

The hardened concrete test results of all SCC mixtures (compressive strength at 1, 3, 7, 28, 56 and 90 days, splitting tensile strength, flexural strength, and bond strength) are summarized in Table 4 and presented in Figs. 6 and 7. The dry shrinkage test results (at 28, 32, 35, 42, 56 and 84 days) are summarized in Table 5 and plotted in Fig. 8.

TABLE 4
HARDENED CONCRETE TEST RESULTS

Mixture Code	Compressive Strength (MPa)						Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Bond Strength (MPa)
	1	3	7	28	56	90			
LP0	7.6	16.5	26.1	30.1	31.2	31.8	2.59	3.72	6.32
LP20	12.6	22.3	31.9	36.9	37.9	38.6	3.47	4.94	8.20
LP30	18.8	28.7	37.7	41.7	42.8	43.6	4.31	6.11	9.65
LP40	24.6	36.3	39.5	44.2	45.1	46.0	4.92	6.45	10.20
LP40-SF10	16.4	25.5	38.3	48.2	51.8	54.4	5.39	6.93	11.10

TABLE 5
DRY SHRINKAGE TEST RESULTS

Mixture Code	Drying Shrinkage Strains ($\times 10^{-6}$)					
	28	32	35	42	56	84
LP0	220	870	1040	1150	1215	1320
LP20	210	630	790	915	980	1095
LP30	185	340	505	620	750	840
LP40	140	295	390	530	620	710
LP40-SF10	110	180	220	275	345	405

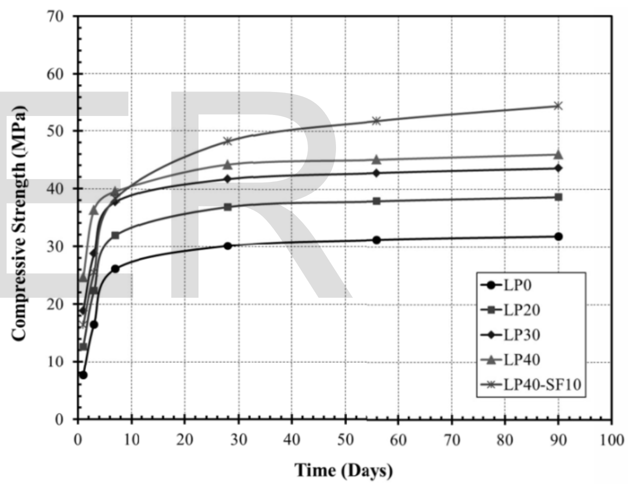

Fig. 6. Compressive Strength Development for SCC Mixtures

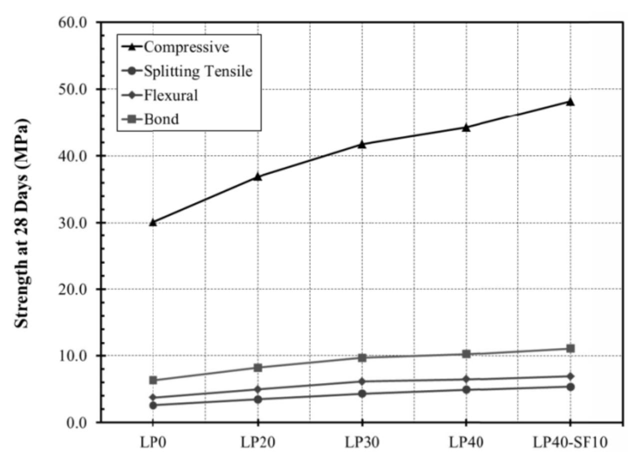

Fig. 7. Hardened Properties for SCC Mixtures

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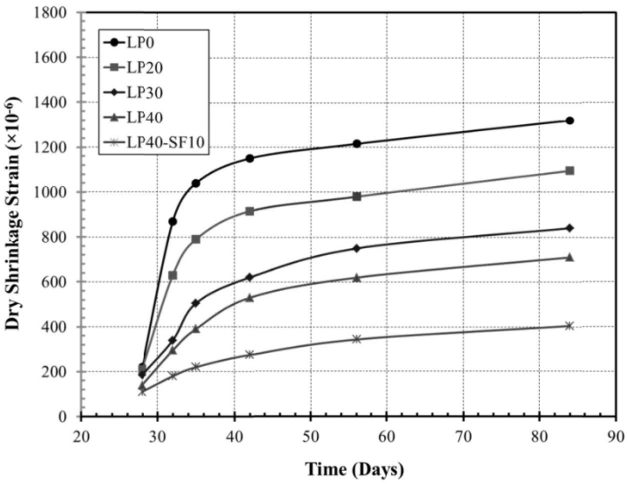


Fig. 8. Dry Shrinkage Development for SCC Mixtures

As shown in Table 4 and Fig. 6, the incorporating of LP results in significant enhancement in compressive strength. For instance, the increase in compressive strength at 28-days was 22.6%, 38.5%, and 46.8% for LP20, LP30, and LP40 mixtures, respectively, due to the paste enrichment as a result of filling effect of LP particles. This agrees with the findings of other researches [1], [15], [21]. As shown in Fig. 6, LP inclusion increased early-age strength (1, 3, and 7 days) as well as the long-term strength (28, 56, and 90 days). Although the addition of SF significantly boosted the long-term compressive strength (28, 56, and 90 days) due to the pozzolanic action of SF, it was noticed that the compressive strength decreased at early ages (1 and 3 days). The strength decrease was less pronounced for 7-day strength. However, the LP0 mixture showed the lowest compressive strength due to lack of filling effect.

The test results, as presented in Table 4 and Fig. 7 showed, that the 28-day strengths (splitting tensile strength, flexural strength, and bond strength) had similar behavior to the compressive strength. The highest strengths were obtained by the LP40-SF10 mixture, whereas the lowest strengths were acquired by LP0 mixture.

The drying shrinkage strains for developed SCC mixtures are reported in Table 5 and plotted in Fig. 8. The LP0 mixture showed the highest drying shrinkage at different ages. The drying shrinkage significantly decreased with the incorporation of the LP. The increase in the proportion of LP resulted in a considerable decrease in the drying shrinkage. Furthermore, the LP40-SF10 mixture exhibited the lowest drying shrinkage. This trend can be attributed to the improvement of the pore structure of the mixtures comprising higher replacement levels of LP. Moreover, the addition of SF further improved the pore structure [42].

3.3 Durability Performance

The durability performance tests [water penetration depth (WPD) , rapid chloride penetration (RCP), sorptivity and sulfuric acid resistance] for all concrete mixtures are summarized in Table 6 and plotted in Fig. 9.

TABLE 6

DURABILITY TEST RESULTS

Mixture Code	WPD (mm)	RCPT Total Charge Passed (Coulombs)	Sorptivity Initial Absorption (mm/sec$^{0.5}$) (×10^{-3})	Sulfate Resistance	
				Strength Loss (%)	Weight Loss (%)
LP0	8.8	1145	17.8	39.77	18.35
LP20	6.7	890	14.8	31.56	17.27
LP30	6.1	835	13.9	29.69	17.03
LP40	5.0	760	13.4	26.41	16.39
LP40-SF10	3.1	510	10.6	24.36	15.56

The WPD results of SCC mixtures are presented in Table 6 and plotted for different mixtures in Fig. 9. It is evident that at the same w/cm ratio, the penetration depth decreased as the LP content increased. From the test results, it is also evident that the LP40-SF10 mixture had the lowest penetration depth whilst the LP0 mixture had the highest one. The decrease of penetration depth is related to the filler effect and heterogeneous nucleation. The results of previous studies [1], [2], [31] showed a similar trend.

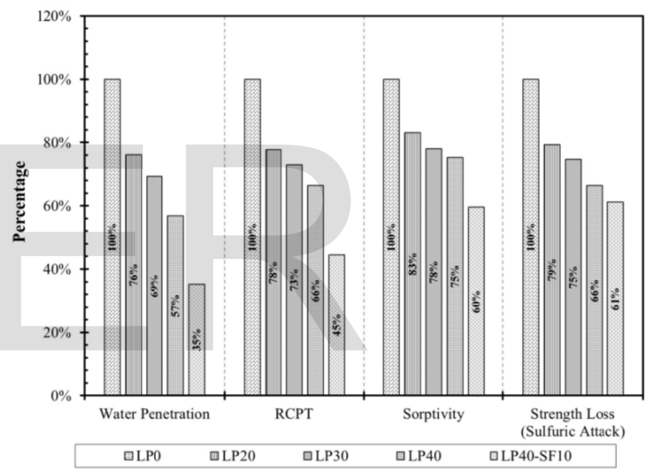


Fig. 9. Durability Test Results for SCC Mixtures

The results of RCPT are given, in terms of the total electrical charge (TEC) that passed through the SCC specimens in coulombs, in Table 6 and Fig. 9. The test results showed that the chloride ion permeability of SCC mixtures decreased through LP incorporation. The increase in the LP content resulted in a remarkable reduction in the total electric charge passed values. For instance, the reduction was 22%, 27%, and 34% for mixtures LP20, LP30, and LP40, respectively. Moreover, The LP0 mixture had the highest chloride ion permeability whilst the LP40-SF10 mixture had the lowest value (55% reduction). The results showed also that, the TEC passed through all SCC mixtures incorporating LP ranged between 500 and 1000 Coulombs which characterized as very low permeability of chloride ion as reported in ASTM C1202 [39]. However, the LP0 mixture can be characterized as low chloride ion penetrability

The sorptivity test results as measured in terms of initial absorption rate are demonstrated in Table 6 and Fig. 9. The test results revealed that, the highest initial sorptivity of 17.8 × 10-3 mm/sec0.5 was obtained by LP0 mixture. The incorporation of LP were remarkably effective in decreasing the initial sorptivity coefficients of SCC mixtures. The reduction was 17%, 22%, and 25% for mixtures LP20, LP30, and LP40, respectively. This reduction in the initial sorptivity coefficients reflects the pore structure refinement. Furthermore, by inclusion of SF, further reduction in initial sorptivity coefficients of the SCC was attained (40% reduction).

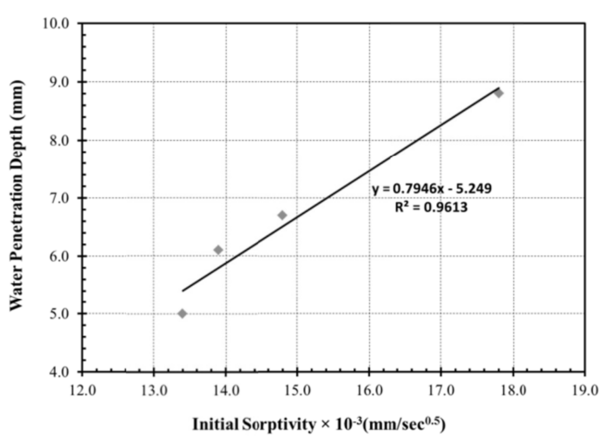
The sulfuric acid attack test results, measured in terms of compressive strength loss and weight loss, are presented in Table 6 and plotted in Fig. 9. The test results showed that, the LP0 mixture showed the highest compressive strength and weight losses (40% and 18%, respectively). The strength reduction and weight loss, for SCC mixtures, decreased with the LP incorporation. The increase in LP content caused a slight decrease in the compressive strength reduction and weight loss. The inclusion of SF caused a minimal compressive strength reduction and weight losses due to sulfuric acid attack.

In general, inclusion of LP in SCC mixtures significantly improved the durability and transport characteristics as a result of its filling effect leading to the pore structure refinement of the developed mixtures. Furthermore, the improvement was more pronounced when 10 % of cement was replaced with SF.

4. Correlation between Durability and Transport Properties

Based on the experimental test results from different durability tests, the relationships between different transport characteristics (WPD, TEC passed, and initial sorptivity) of SCC mixtures with different LP content are presented in Fig. 10.

The test results, as presented in Fig. 10, indicated a very strong positive linear correlation between different transport characteristics as the correlation coefficients (R) ranged between 0.980 and 0.997.



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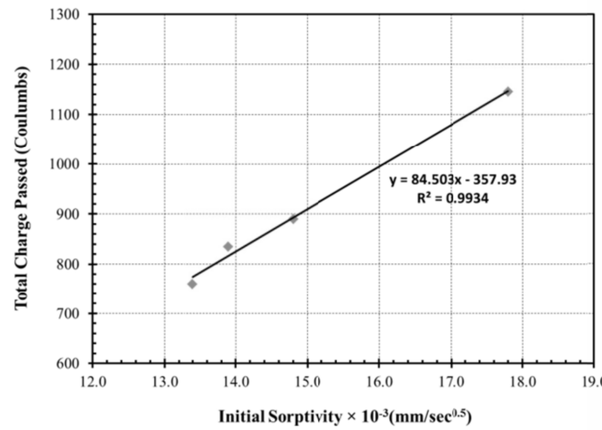

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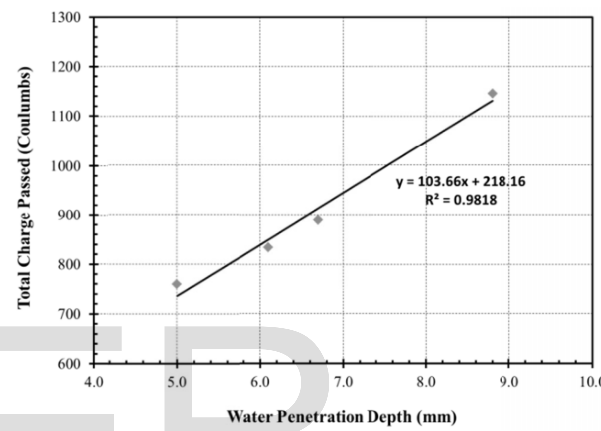

(c)

Fig. 10. Relationships between Different Transport Characteristics: (a) WPD versus Initial Sorptivity, (b) TEC Passed versus Initial Sorptivity, and (c) TEC Passed versus WPD

5. Material Cost Effectiveness of SCC Mixtures Incorporating LP

A simple material cost study for 1 m3 of the developed SCC mixtures was performed to assess the effect of using LP on the SCC cost. The material cost and the unit compressive strength cost (UCSC) (the material cost of 1 MPa) for different SCC mixtures were calculated and presented in Fig. 11.

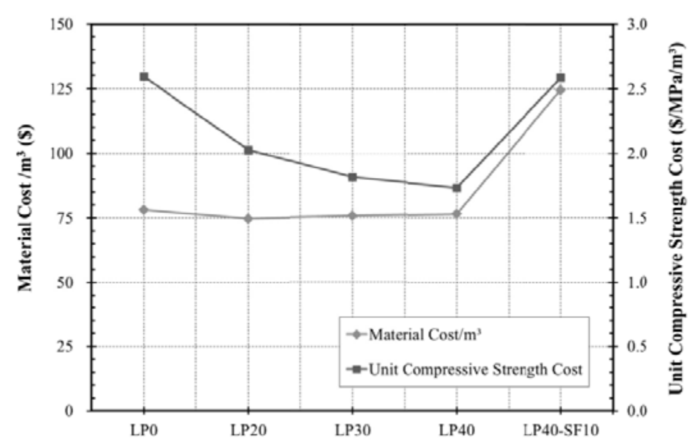

Fig. 11. Material Cost for SCC Mixtures

The comparison of the material cost as presented Fig. 11 revealed that the minimum cost among the studied mixtures was the cost of mixtures incorporating LP (taking into consideration the significant improvement in the durability performance of these mixtures). The reduction in the cost was very slight at the range of 4.4%, 3.2% and 2.0% for mixtures LP20, LP30 and LP40, respectively, compared with LP0 mixture. Furthermore, the cost of LP40-SF10 mixture was the highest (59.5% increase) compared with LP0 mixture.

Furthermore, the UCSC as shown in Fig. 11 indicated that, the increase in LP content significantly reduced the UCSC of SCC mixtures. The UCSC was 2.59, 2.02, 1.81, and 1.73 $/MPa/m3 for mixtures LP0, LP20, LP30, and LP40, respectively. As the percentage of LP increases, the UCSC considerably decreases (22.0%, 30.1%, and 33.2% for mixtures LP20, LP30, and LP40, respectively). Besides, It was found that the UCSC of LP40-SF10 mixture was almost the same as that for LP0 mixture (2.58 $/MPa/m^3). Moreover, the UCSC of LP40-SF10 mixture was considerably high (49.1%) compared to LP40 mixture. It should be noted that the improvement in the performance of LP40-SF10 mixture is not commensurate with the large increase in its UCSC.

6. Conclusions

This study was performed to evaluate the fresh, hardened, and durability characteristics of SCC incorporating limestone quarry powder waste with different ratios as a partial substitution of fine aggregate. Based on the findings of the current study, the following conclusions can be drawn:

1. All the developed SCC mixtures achieved the required self-compacting fresh properties (except for the L box height ratios). The presence of LP had positive effects on the flowability and segregation resistance. The increase of LP content increased the cohesion, viscosity, and segregation resistance.
2. SCC mixture LP0, which does not contain LP, required an extra amount of HRWRA than that incorporating LP to achieve the specified fresh properties. Moreover, it exhibited lower filling and passing abilities as well as segregation resistance.
3. The inclusion of LP enriched the paste as a result of filling effect consequently, improved the early age as well as the long term compressive strength of SCC mixtures. The improvement increases as the LP content increases. Furthermore, the incorporation of SF significantly enhanced the long-term compressive strength, however, it had a negative effect on the early ages compressive strength.
4. The 28-day splitting tensile, flexural, and bond strengths of SCC mixtures showed a relatively similar trend to that of the compressive strength.
5. SCC mixture LP0 had the highest drying shrinkage; however, as LP content increased the drying shrinkage values, at different tested ages, decreased. Furthermore, the inclusion of SF with LP remarkably reduced the drying shrinkage.
6. Generally, the LP inclusion increased the packing density and refined the pore structure and consequently, improved the durability and transport characteristics of the developed SCC mixtures.
7. The increase of LP contents significantly reduced the WPD, the total charge passed in the RCPT, and initial sorptivity. Additionally, the inclusion of SF with LP exhibited a more pronounced reduction.
8. Strong positive linear correlations were found between the three durability aspects (water penetration, total charge passed and sorpitivity) for the developed SCC mixtures with the same w/cm ratio; this shows that these durability aspects are related and changes in one consequentially affect the others.
9. The increase of LP content improved the sulfuric acid resistance of developed SCC mixtures and the addition of SF slightly enhanced the sulfuric acid resistance.
10. The Inclusion of LP reduced the material cost of unit compressive strength for all developed SCC mixtures. The reduction was in the order of 22.0 to 33.2 %. However, the addition of SF significantly increased this material cost by 49.1%. Furthermore, the Inclusion of LP significantly improved the durability performance of the developed SCC mixtures which saves the maintenance cost especially in aggressive environments.
11. The successful utilization of limestone quarry powder waste in SCC produced desired characteristics, decreased cost, and also showed an environment friendly removal of LP waste and keeping it free from pollution.

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