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Investigation of the influence of non-pozzolanic filler composition and content on the properties of self-compacting concrete

Vinod C. Panchal[1] and Gaurang R. Vesmawala[1,*]

[1]Applied Mechanics Department, Sardar Vallabhbahai National Institute of Technology, Surat, India
[*]Corresponding author: grv@amd.svnit.ac.in

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Abstract

This study measured the inherent effect of two micro fillers on the young, hardened characteristics of self-compacting concrete (SCC). Disposing of secondary industrial products creates several environmental problems that increase with time, particularly non-pozzolanic reactions. In this experimental study, two industrial by-products of the non-pozzolanic group, limestone powder (LP) and marble powder (MP), were selected. Five diverse compositions and three cement replacement levels of 10%, 15%, and 20% were used. The concrete flow, sieve segregation, and microstructural analysis tests were performed on SCC combination mixes. Based on the results, LP as replacement enhanced the workability of the SCC combination mixes by up to 24% compared with zero filler SCC (SCC0). A higher MP content (15%) boosts the compressive strength, densifies the internal framework, and improves resistance against bleeding and segregation of SCC.

Keywords: Self-compacting concrete, Fine aggregate to total aggregate ratio, Superplasticizer, Marble powder, Lime powder

1. Introduction

Self-compacting concrete (SCC) has been used in the construction industry since its inception. During these years, several new generation materials and methods in the literature have been presented with concerns about the relevance, application, mix composition, strength, flowability, and stability of SCC [1-3]. In modern technological advancements, new-generation materials can substantially affect the characteristic of SCC and can be used as an alternative to producing various cement-based valuable products.

The construction sector always demands and searches for new alternative materials that reduce cost and waste disposal problems with minimum cement content. Marble powder (MP) and lime powder (LP) are among the secondary products generated by stone mines. Alyamac and Ince [4]. stated that during the marble cutting process, the stone mines produce very fine powder waste that easily floats in the atmosphere and creates many environmental problems globally. High-quality materials are costly and not for long-term supply in India. Hence, the rising demand for substitutes for cement and concrete products can be addressed partly by replacing cement with MP [5]. The higher powder content and fine materials in SCC produce a higher paste volume in the range of 390-620 kg/m^3.

The paste volume functions as a carrier to lift and floats coarse aggregate content to reach and fills every space to form dense concrete [6]. Compared with normal vibrated concrete, SCC comprises a higher paste volume because of added minerals, influencing its long-term stability. An abundance of analyses has been performed in this phase on the flowability, viscosity, blend composition, rheology, porousness, and sorptivity of SCC [7]. Mineral micro fillers (marble, lime, and fly ash) are finely dispersed materials (< 125μ) that can enhance the particle size distribution and the physical properties of SCC mixes (water retention and workability) [8].

SCC has been used within the industry for over three decades [9]. In the 1990s, the engineering properties of materials and their structural execution had been assigned minimal importance. The recent and more frequent investigations are committed to the performance-based properties of SCC [10]. Plastic shrinkage cracking, bleeding rate, evaporation, and water-to-cement ratio are specific variables that directly affect tensile stress and capillary pressure at the initial setting stage [11]. Several researchers [7,11,12] have performed reviews on SCC characteristics.

The solid waste by-products of the marble and lime mines industries are MP and LP fillers. Actual and cost-saving energy may begin when by-products are used for cement replacement in concrete-based items [13]. This investigation attempts to study the feasibility of using locally available MP and LP waste as partial replacements for cement when developing a high-quality SCC mix. Several studies reported replacing MP and LP waste with a combination of five diverse parameters and a 16-m maximum aggregate size using the Nan-su method [14]. The objective is to find the optimal doses and combination of two mineral wastes. This experimental study contributes to the use of waste marble and lime to improve SCC properties and prevent environmental problems.

2. Materials and methods

2.1 Raw material properties

This study aimed to investigate the influence of non-pozzolanic filler types on the workability and hardened properties of SCC with different types of replacement levels and compare different replacement combinations with SCC (0%) without filler. For this experiment, two fillers of the same group (mineral type) were selected: LP and MP. The chemical properties of cement and mineral filler are presented in Table 1. The mixed design of SCC adopted for testing and casting the specimen are presented in Table 2.

In this study, all mixtures that satisfy the Indian standard 12269 (53 grade) and ASTM C-150 [15-17] specification, including ordinary Portland cement (OPC), were used. Natural, clean, and dry siliceous sand and crushed granite coarse aggregate of specific gravity and fineness modulus 2.72, 2.66, and 2.80, 2.64 follow IS 383 [15]. The specific gravity of coarse aggregate was determined based on the ASTM C-127 wire basket technique [18]. This study used a 16-mm maximum size of coarse aggregate and potable water with a temperature of 28±1°C for the mix. LP and MP fillers were used after passing through a 125-µm sieve. A formaldehyde-based naphthalene superplasticizer (1.5% weight of powder content) was used to minimize the water requirement in the SCC. A viscosity modifying admixture (VMA) of 0.20% was used to reduce bleeding and segregation in the SCC.

Table 1 Cement and filler (chemical composition).

Component (%)	Cement (%)	LP (%)	MP (%)
CaO	62.35	95.61	89.16
SiO_2	20.76	4.23	1.16
Al_2O_3	4.54	0.87	0.82
Fe_2O_3	2.38	0.46	0.05
SO_3	2.16	1.34	0.63
Loss on ignition	1.33	1.26	2.18

Table 2 Mix proportions of SCC with filler materials.

Type of mix	Cement (kg)	FA (kg)	CA (kg)	Water (kg)	Filler (%)		% Replace	Slump flow (mm)	V-Flow (sec)
					LP	MP			
SCC0	400	997.0	794.0	171.60	0	0	0	525	14
0L-100M	360	997.0	794.0	167.50	0	40	10	610	10
25L-75M	360	997.0	794.0	167.50	10	30	10	615	12
50L-50M	360	997.0	794.0	167.50	20	20	10	630	11
75L-25M	360	997.0	794.0	167.50	30	10	10	605	8
100L-0M	360	997.0	794.0	167.50	40	0	10	640	8
0L-100M	340	997.0	794.0	166.20	0	60	15	610	12
25L-75M	340	997.0	794.0	166.20	15	45	15	620	14
50L-50M	340	997.0	794.0	166.20	30	30	15	590	13

Table 2 (continued) Mix proportions of SCC with filler materials.

Type of mix	Cement (kg)	FA (kg)	CA (kg)	Water (kg)	Filler (%)		% Replace	Slump flow (mm)	V-Flow (sec)
					LP	MP			
75L-25M	340	997.0	794.0	166.20	45	15	15	630	10
100L-0M	340	997.0	794.0	166.20	60	0	15	660	11
0L-100M	320	997.0	794.0	165.30	0	80	20	480	18
25L-75M	320	997.0	794.0	165.30	20	60	20	525	17
50L-50M	320	997.0	794.0	165.30	40	40	20	500	16
75L-25M	320	997.0	794.0	165.30	60	20	20	510	14
100L-0M	320	997.0	794.0	165.30	80	0	20	550	14

Mix proportion M30 (kg/m^3).
W/P = 0.43, FA = fine aggregate, CA = coarse aggregate, LP = lime powder, MP = marble powder.

2.2 Mix design

Based on the European Federation of National Associations Representing for Concrete (EFNARC) guidelines and a new mix design of [14,19], SCC proportioning was conducted with a target compressive strength of 30 MPa. The initial mix for laboratory experiments was produced using a water-to-binder ratio of 0.43. The concrete was designed with 400 kg/m^3 of OPC [15]. The powder content, fine aggregate to total aggregate ratio, and water content were maintained at 360-500 kg/m^3, 0.54, and 150-210 kg/m^3. The SCC specimens were prepared without filler (0%) and with two fillers by 10%, 15%, and 20% replacement with the different combinations. Table 2 lists the mixed proportions of SCC with varied cement replacements of 0%, 10%, 15%, and 20% using LP and MP.

This study aims to identify the acceptable dose of two fillers, LP and MP, that produces higher workability and compressive strength and compare the fresh and hardened properties of SCC with that of normal SCC without filler. Three replacement levels (10%, 15%, and 20%) by mass of cement and five different compositions are used: 0L-100M, 25L-75M, 50L-50M (50% lime filler and 50% marble filler of respective% replacement), 75L-25M, and 100L-0M. The different binary and ternary blended SCC types were prepared by mixing cement, sand, aggregate, filler, and chemical admixture with a 0.43 water-to-powder ratio (per laboratory test trials) based on EFNARC guidelines [19]. The proportion of coarse-to-fine aggregate was adjusted for flowability, passing ability, and filling ability.

3. Results and discussion

3.1 Test on fresh concrete

3.1.1 Marsh cone, slump, slump flow, and V-funnel test

The water-to-powder ratio and superplasticizer doses are determined by the Marsh cone test per ASTM C-939 [20]. The Marsh cone test is conducted to identify the optimal doses required for paste and verify the compatibility of SP [21]. The highest fluidizing impact at the minimum dosage is considered an economic point (Table 3) represents the obtained value for different doses of SP with fort 5 and 30 min for the complete flow of grout measured. The optimal doses were determined at the intersection of two lines at point 1.4% after laboratory trials, so the adopted value of SP is 1.5%.

Table 3 Marsh cone test values.

SP% By weight of cement	0.6	0.8	1.0	1.2	1.4	1.6
Time in sec (T) after 5 min	191	170	153	84	86	87
Time in sec (T) after 30 min	236	211	166	91	85	91

Figure 1A and Figure 2 depict the slump flow and its flow value for all mixes, with the thick horizontal line indicating the limit of the slump flow value below which the mix has a high viscosity and the complete line representing a slump spread of various filler and regular concrete. It is possible to calculate the time required for the concrete sample to expand from its initial cone shape into a predominantly flat “pizza-like” layer.

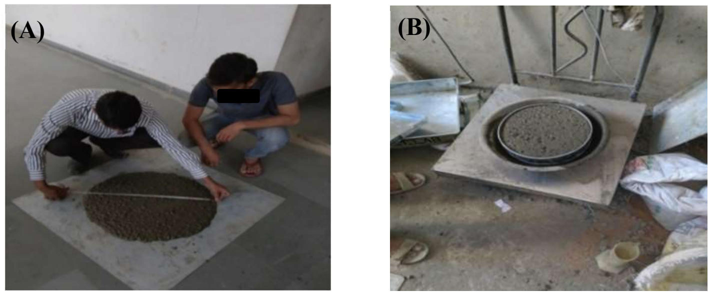

Figure 1 (A) Slump flow and (B) sieve segregation tests for SCC.

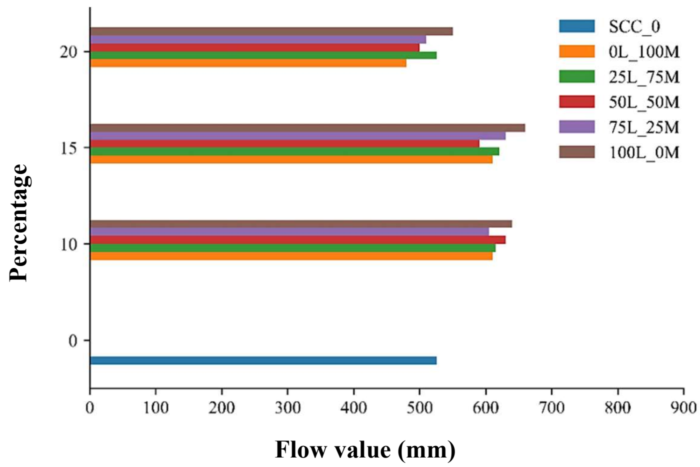

Figure 2 Slump flowability test values of LP and MP for three replacement of SCC mixes.

The higher the flow rate of SCC during installation, the shorter the time 500. Topcu et al. [5]. categorized the slump flow into four different segments of 100 each, starting from 400 to 500 mm and up to 800 mm. Usually, a mixture of less than 500 mm for the slump flow value should be highly sticky and viscous because it does not move freely. Slump flows within 500 to 600 mm exhibit a difference in the mixture's viscosity and changes to produce more fluidity. In this test, there was no laitance or halo of fine mortar in the majority of the SCC mix based on ocular inspection. As the time passed, the flow of the mix reached 400 to 600 mm, the consistency of the mixture was assumed to be highest, and it flowed freely under its weight. Based on the results, all mixes satisfied the workability criteria per [19].

In comparing the results of the slump flow of the mix, of the five LP mixes, 100L of 15% has a maximum value of 660 mm. As the percentage of LP increases in the mix, the flow value increase for 10 and 15% replacement from 600 to 660 mm. When compared with the zero-filler SCC (SCC0) mix with combination mixes, the difference in flow value was observed from 85 to 135 mm. The LP paste covers coarse aggregate and provides more lubrication to mixes because of LP's higher water retention capacity, finer particle size (< 125μ), and rounded shape. Consequently, a combination of SCC mixes produces a higher flow value than SCC0 mixes.

The mix produced with two-grain size materials with different grain size distributions provides a filling ability for smaller particles in the interstitials void of the coarser particles to improve workability. A finer grain size and higher content of CaO in LP provide more lubrication, resulting in higher spreads of 100L-0M, 75L-25M, and 50L-50M in 10% and 15% replacement.

A higher amount of LP (25% to 100%) in the different mixes illustrates a higher spread diameter in the slump flow test, reflecting softer, easier flow, possibly because the continuous grainy skeleton has more paste covering the coarse particle, allowing them to flow more easily. These results have been agreed upon by scholars [6,22].

A V-funnel test is conducted to determine the segregation resistance of fresh SCC produced with MP and LP, with the results presented in Table 2. The viscosities of the 20% replacement sample, 0L-100M, 25L-75M, and 50L-50M, are 18, 15, and 16 sec. The flow time through the V-funnel of this group was above 15 sec, which is considered the above limitations of the SCC mix. Filling the empty area in a compact system may promote the proper grouping of particles in the structure, assuring sufficient participation of the mixing water to obtain enough fluidity in the mixture. The recommended values per the EFNARC committee for lower and upper limits are 8 and 15 sec; the remaining mixes are satisfactory for designing the relevant SCC mixture. Mix 75L-25M and 100L-0M exhibited improved flow within 8 sec for 10%, 15%, and 20% replacement because of the large amount of calcium hydroxide (CH) in the matrix.

3.1.2 Sieve segregation test

A sieve stability test was conducted to measure the segregation resistance of fresh SCC mix, as shown in Figure 1(B). The test is based on deciding how much separation occurs among mortar paste and coarse aggregate in a sample of SCC [19]. After pouring 2.0 liter of concrete from a 4.75 mm sieve with a container below it, the ratio of the mass passing the sieve to the poured mass is a measure of segregation resistance.

The outcome of different replacements with fillers on fresh concrete is depicted in Figure 3. From these results, the filler mixes of different replacement levels with LP and MP improve the stability of concrete and provide higher resistance against segregation compared with normal SCC (0%). For example, 10% replacement SCC mixes have segregated portions of 9.91%, 8.86%, 10.14%, 13.42%, and 11.60%, which are considered satisfactory, and the mass ratio is within the limits of 5% to 15%.

The passing ratio for the LP and MP mixes containing calcium carbonate ($CaCO_3$) powders were higher than SCC0. The presence of $CaCO_3$ increases the fineness of the paste, resulting in a 5% to 15% value. A lower value of percentage passing indicates a healthier paste cohesion. However, the SCC0,0L-100M and 25L-75M mixes exhibited unusually lower values (< 5%) of 4.43%, 4.63, and 4.86%. In the SCC0, a lower value resulted from the absence of smaller filler particles and less lubrication in the mix.

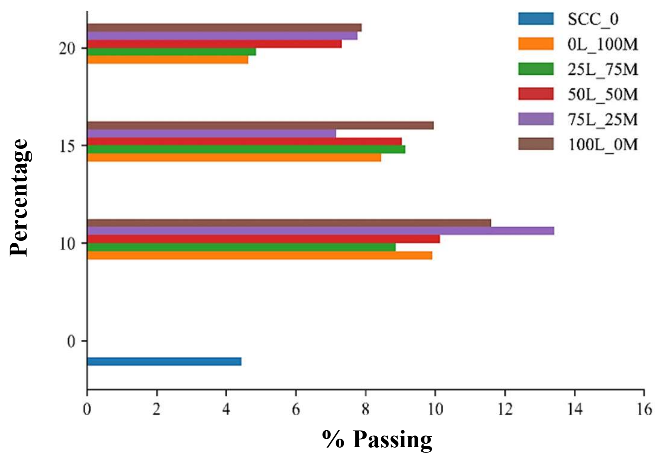

Figure 3 Sieve segregation test results for SCC0, 10%, 15% and 20% replacement levels.

3.2 Hardened SCC test

3.2.1 Compressive strength test

Figure 4 highlights the cube strength development of SCC after a curing period of 28 days for sixteen different mixes. The compression strength results of LP, MP, and SCC0 with a different combination of filler presented in Figure 4 for 0L-100M, 25L-75M, 50M-50L, 75L-25M, and 100L-0M of a mix with cement replacement by filler 0, 10, 15, and 20%. The compression strength for 10% and 15% replacement compared with SCC0 increased by approximately (13%,21%) 0L-100M, (3.60%,20%) 25L-75M, (5%,13%) 50L-50M, (4%,13%) 75L-25M, and (3%,0%) 100L-0M. In contrast, for 20% replacement, the decreases in strength were approximately (0.5%) 50L-50M, (2.5%) 75L-25M, and (6.5%) 100L-0M.

Out of 16 samples of different mixes, 10 mixes have higher strength compared with SCC0. All samples have a strength range from 42.15 to 32.50 MPa considered higher compared with the design strength (M30). The actual effects of various filler percentages in the SCC in hardened concrete characteristics were also obtained. Filler content of 10% and 15% replacement in cases with higher MP content had higher strength. MP had acceptable concrete properties concerning fresh properties and compressive strength.

The underlying cause is that filler is an inert addition that might be interpreted as ultrafine particulates in concrete filling pores, resulting in a greater compressive strength of 42.15 MPa than SCC0. A similar finding has been reported in the literature [22-25]. Based on this study, the effective use of MP and LP as cement replacement substances in the concrete mix with optimal doses of 15% with all five combinations can be considered.

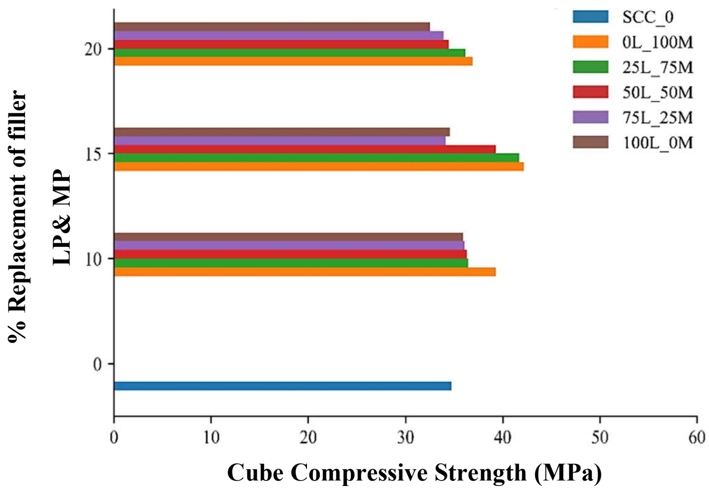

Figure 4 Effect of MP and LP replacement on compressive strength at 28 days of SCC.

3.2.2 Split tensile strength technique

This test was conducted on a 150-mm diameter cylinder of 300-mm height on a compression testing machine according to the specifications of I.S-5816 [22] after 28 days of water curing. Figure 5 illustrates split tensile strength results. Substantial differences were observed when comparing SCC0 with filler SCC of MP and LP, with values of up to 40.37% higher than the SCC0. This result is similar to data analyzed by the researchers [26,27]. For the example 15% filler content, with combinations of 0L-100M, 25L-75M, 50L-50M, 75L-25M, and 100L-0M, the split tensile strength increased 28.41%, 22.64%, 28,41%, 23.38%, and 9.41% compared with SCC0. Similarly, the case of 0L-100M and 100L-0M mixes had a nearly 10% difference in value. For 20% filler mixes, a strength loss was observed compared with SCC0 and 15% filler mixes. Logically, reducing coarse aggregate content in a mix of SCC may reduce the “aggregate interlock” to the strength of plain concrete.

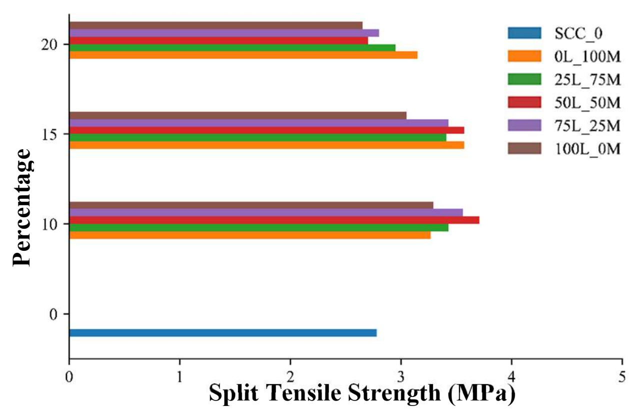

Figure 5 Split tensile strength values.

3.2.3 Microstructure SEM analysis of SCC

The influence of LP and MP on the concrete microstructure was examined with different replacements and content using a scanning electron microscope (SEM). Figure 6(A) and (B) illustrate the SCM images of SCC0. Based on the images, the interlock of aggregate and cement matrix seemed to be unconnected from the initial phase, and the smaller amount of paste between the largest size aggregates resulted in poor bonding and strength. Aggregate particles appear as large, angular, and separated from the cement paste. The CH formed an incoherent layer along with parts of the interfacial zone (ITZ) of the largest aggregates in the images.

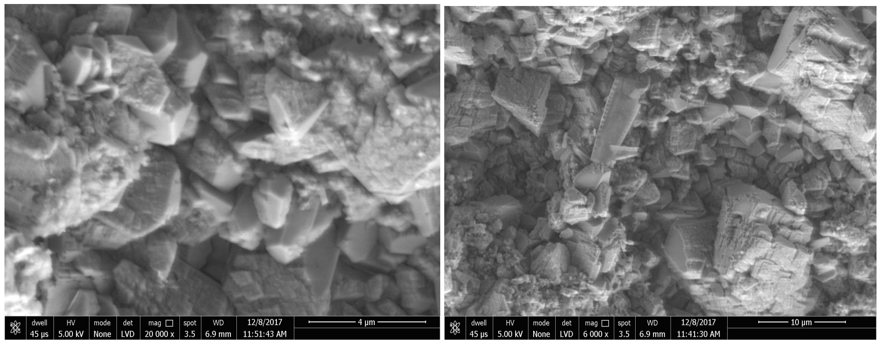

Figure 6 (A) Microstructure of SCC0 at 4 μm, (B) Microstructure of SCC0 at 10 μm

Figure 7(A-F) represent 10% and 20% replacement of MP and LP. For 10% filler mix in 100L and 100M, (Figure 7A-C) indicates that the effect of micro bleeding between aggregate and paste was significantly reduced in the SCC. Even after 28 days of curing and hydration process, no change was observed in the volume of LP and MP; the interface among filler and hydrates improved step-by-step as the percentage of filler increased.

For 20% replacement of SCC in 100L, 50L-50M, and 100M mineral filler, the microstructure of the paste seemed to be homogeneous, and no different ITZ was observed. The association of mineral powder induces improved density of paste, as depicted in Figure 6. The test results reveal that the strength of concrete comprising mineral filler LP and MP matches the strength provision. After 28 days, LP remained unhydrated in the mix and did not take part in a reaction. Hence no pozzolanic activity occurred in the mix, but the small gaps among the aggregate were filled, forming a denser paste matrix [28].

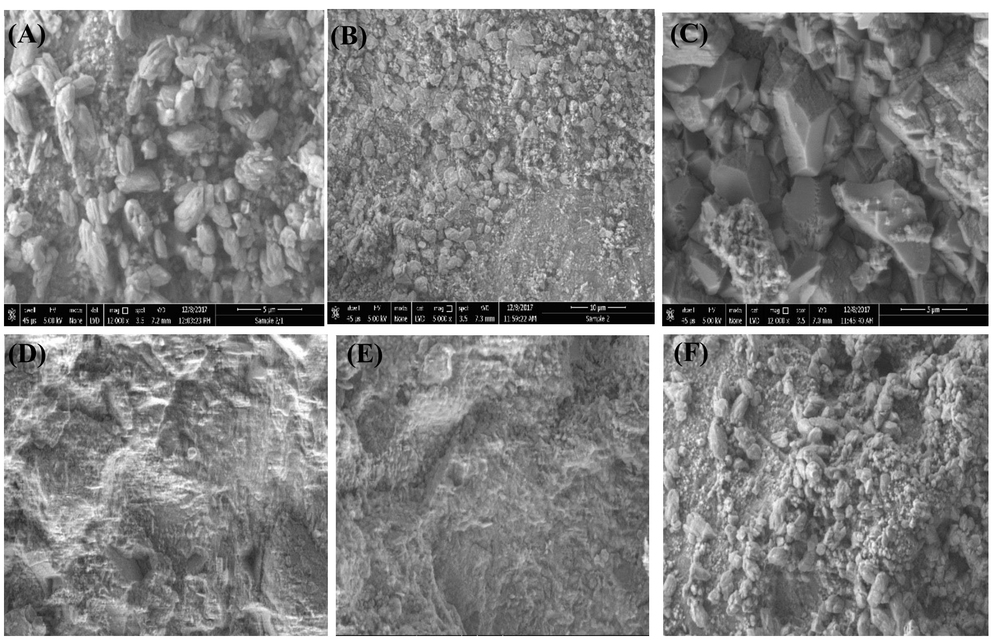

Figure 7 SCM Images of MP and LP for normal, 10% and 20% replacement of SCC (A) 0L-100M (10%), (B) 50L-50M (10%), (C) 100L-0M (10%), (D) 0L-100M (20%), (E) 50L-50M (20%), and (F) 100L-0M (20%).

The LP and MP materials can be interpreted as micro-scale filler in the mix at the core level. This matches with the outcome obtained by some researchers [2,26].

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4. Conclusion

Several conclusions are found based on this investigation and the experimental outcomes of the SCC mix comprising two mineral fillers of a non-pozzolanic group, LP and MP: Based on the different values and visual observations in the test of workability and strength, the rounded LP molecule in the binary and ternary mix was confirmed to form a thin layer of lubrication. Because of its high solubility in water, LP reduces the wall effect and enhances the flow of SCC from 600 to 660 mm. An SCC mix that contains a higher amount of MP provides a higher strength 42.15 Mpa. As expected, the filler composition produces superior results, with higher workability and 23% higher compressive strength than the SCC0.The cost of a superplasticizer is higher in the SCC mix; the use of wastages of marble and LP as filler can save up to 15% (59.70 kg/m^3) cement and balance the cost of the superplasticizer. Furthermore, it saves embodied energy and costs of extracting natural resources, reducing the carbon footprint.The natural filler powder waste (marble and lime) can be used as a cement supplement up to 15% (not limited) with different combinations without compromising the young, hardened properties of SCC. Furthermore, 20% and higher replacement can be investigated in future research to obtain a void-free mass with higher workability and other long-term properties of SCC.

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