

2.1 GENERAL

The hydration of cement, in the presence of water, is an exothermic reaction. The formation of calcium silicate hydrates (C-S-H) and calcium hydroxide (Ca(OH)_2) takes place when C_3S and C_2S react with water. C-S-H acts as a binder. As Ca(OH)_2 is soluble in water, its formation increases the porosity of concrete and thus reduces the strength and durability of concrete. The hydration of C_3S results in the lesser formation of C-S-H gel as compared to Ca(OH)_2 . On the contrary, the amount of C-S-H gel formed in hydration of C_2S is higher than Ca(OH)_2 . Consequently, cement with higher C_2S content is preferred in structures which are highly prone to the leachate attack [38].

The hydration kinetics of cement depends on its C/S ratio (ratio between CaO and SiO_2 content). Moreover, in the hydrated cement paste, the C/S ratio varies between 0.6 and 2.0 [39]. The utilization of pozzolans (as a partial substitute of cement) in mortar or concrete lowers the overall C/S ratio and results in the formation of denser C-S-H gel [40]–[42].

In this chapter, the past literature on the effects of various mineral admixtures (natural and/or synthetic) on the mechanical and durability properties of concrete has been studied. The properties of concrete are greatly influenced by the behaviour of the hydrated cement paste as compared to the aggregates. Therefore, to understand the effects of various mineral admixtures on the properties of concrete, it is crucial to know their impact on cement paste and mortars [38]. The main driving force behind these past studies was to improve the properties of cement paste, mortar and concrete. The analysis of these mineral admixtures will help in understanding the results of the present study to a great extent.

2.2 EFFECTS ON PHYSICAL PROPERTIES OF CEMENT PASTES AND MORTARS

2.2.1 Fly Ash (FA)

FA is a secondary residual product from the combustion of pulverized coal in boilers of thermal power plants. According to ASTM C618-19 [43], FA is classified into two categories based on the variation in chemical composition and on the type of coal burnt: class F and C. 'Class F' FA is siliceous and is produced from bituminous or anthracite coal. At the same time, 'Class C' FA is calcareous and is produced from sub-bituminous or lignite coal.

Shi et al. (2011) [44] studied class N and F fly ash admixed cement mortar for their compressive strength at 1, 7 and 28 days of curing. There was a reduction in compressive strength of Portland Cement (PC) mortar on their admixing. However, when compared with each other, mortars containing class N showed better performance at 1 and 28 days of curing while class F showed better compressive strength after 7 days of curing. They also showed that the usage of fly ash leads to a reduction in the modulus of toughness of mortar. According to them, when 90 days water cured fly ash admixed mortar were subjected to accelerated chloride migration test (ACMT), there was a significant reduction in the diffusion coefficient (D_s) as compared to the control mortar, implying lower chloride migration. In their study, a decrease in compressive strength of the fly ash admixed mortar was due to its slow pozzolanic activity, which requires longer curing periods for positive effects [45], [46]. The reduction in modulus of toughness decreases the chances of shrinkage cracking and chloride and sulphate attacks on concrete. The decrease in D_s was due to the dense microstructure of the mortars because of the addition of fly ash.

Kocak and Nas (2014) [47] found that the water demand required to prepare a cement paste at a standard consistency increases with the increase in the percentage of FA content due to its porous structure and presence of the high amount of unburnt carbon ($> 1\%$). On the contrary, according to Nochaiya et al. (2010) [48], there was a reduction in water demand with an increase in FA content because it had a low amount of unburnt carbon ($< 1\%$) in FA used. However, in both the studies, increase in the setting times of paste and decrease in the compressive strength of mortar with the increase in the ratio of FA was observed as reported by other studies as well [49], [50].

2.2.2 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is a by-product obtained by extinguishing molten iron slag by high-pressure water jet. They are known to improve the performance of concrete. It can replace cement by as high as 70% [51].

Hwang and Shen (1991) [52] evaluated the effect of different amount of GGBFS (10%, 20%, 30%, 40%) on the setting times of the Portland cement paste with varying w/b ratio (0.35, 0.47, 0.59). They concluded that the increase in setting time was more pronounced with increasing GGBFS content and constant w/b ratio as compared to the constant GGBFS content and increasing w/b ratio. It was because an increase in the amount of GGBFS decreased the content of C_3S . Thus, more time was required to achieve the pH equilibrium.

Alhozaimy et al. (2012) [53] studied the effects of GGBFS on the fresh properties of grand dune sand (GDS) admixed Portland cement (PC) pastes and on the compressive strength of GDS admixed mortar. The ratio between binder, sand and water was 1: 3: 0.50. The amount of GDS was fixed to 30% replacement of cement (by weight) in initial testing while the amount of GGBFS was varied (20%, 30%, 40%, 50%

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and 60%). They found out that up to 40% replacement by GGBFS, the standard consistency was more or less equal to the control paste. Upon increasing the replacement level of cement by GGBFS, there was an increase in the normal consistency. It was because of the finer size of the GGBFS particles ($5314 \text{ cm}^2/\text{g}$) as compared to the cement particles ($3012 \text{ cm}^2/\text{g}$) used in the experiment. Also, there was an increase in the initial and final setting times of the cement paste with an increase in the amount of GGBFS. It was due to a delay in the hydration process of higher GGBFS content and lower cement content [54]. They also found that all the GGBFS and GDS admixed mortars showed decreased compressive strength w.r.t the control mortar under water curing. However, under autoclave curing, all the mortars containing a combination of GGBFS and GDS showed improvement in the compressive strength w.r.t control mortar. The reason given behind this phenomenon was the formation of crystalline C-S-H, i.e., tobermorite or xonotlite. The presence of tobermorite or xonotlite is generally connected with higher compressive strength and lower porosity [55]. The mix containing a combination of PC, GGBFS and GDS (50%, 20% and 30% respectively) showed highest compressive strength under autoclave curing (28% higher than the control mortar) because the combination of these cementitious materials had C/S ratio approximately equal to 0.88. When $C/S \leq 1$, it generally represents high compressive strength under autoclave curing [56]. Even the mix containing only 10% cement with 60% GGBFS and 30% GDS showed 4% higher compressive strength w.r.t control mortar under autoclave curing. It implies that as high as 90% replacement of PC was possible with a combination of GGBFS and GDS under autoclave curing without any reduction in the compressive strength.

2.2.3 Metakaolin (MK)

Metakaolin is produced by anhydrous calcination of kaolinite mineral at a high temperature of 700-800 °C. Metakaolin particles are finer than the traditional cement particles but are not as fine as microsilica particles [57]–[60].

Weng et al. (2013) [61] studied the mechanical properties of cement mortar after 28 days of curing admixed with MK at various ratios (5%, 10%, 15%, 20% and 25%). They concluded that the compressive strength of the mortar cubes increases with increase in the ratio of MK up to 15%. Even though the compressive strength at 20% replacement was less than the 15% replacement with MK, it was still higher than the compressive strength of the control mortar. However, at 25% replacement, the compressive strength of MK admixed mortar was less than the compressive strength of control mortar. The increase in the compressive strength of the mortar cubes with MK up to 15% was due to filler effect of particles of MK in the cement paste. It was also because of the formation of secondary C-S-H gel by hydration of cement with MK and the removal of Ca(OH)₂ gel. They also analysed the mortar samples containing a various proportion of MK (15% and 25%) by SEM, as shown in Figure 2.1a, b and c, respectively. The larger capillary pores, the formation of Ca(OH)₂ and connectivity between pores can be seen clearly in Figure 2.1 (a). However, a higher number of pores can be seen in Figure 2.1 (c) of the specimen with 25% MK, which had the least compressive strength. A lot of unreacted particles were observed in the sample with 25% MK. They did not take part in the hydration reaction due to lack of water. Also, chemical admixture was not used, which could compensate for reduced workability. The workability was lower because of usage of MK particles of higher fineness as compared to the cement particles. In the SEM image of the specimen with 15% MK

(Figure 2.1 (b)), dense, compact and homogeneous pore structure was observed, supporting the results of compressive strength test on mortars. However, Weng et al. (2013) did not consider the workability of the paste in their research, which can be an essential factor. It could affect the compacting and casting of the mortar sample. Wang et al. (2019) [62], found that increasing the percentage of MK by more than 10% in cement paste causes a significant reduction in its workability. The reason was because MK particles are highly reactive, have high surface area and non-crystalline structure [63].

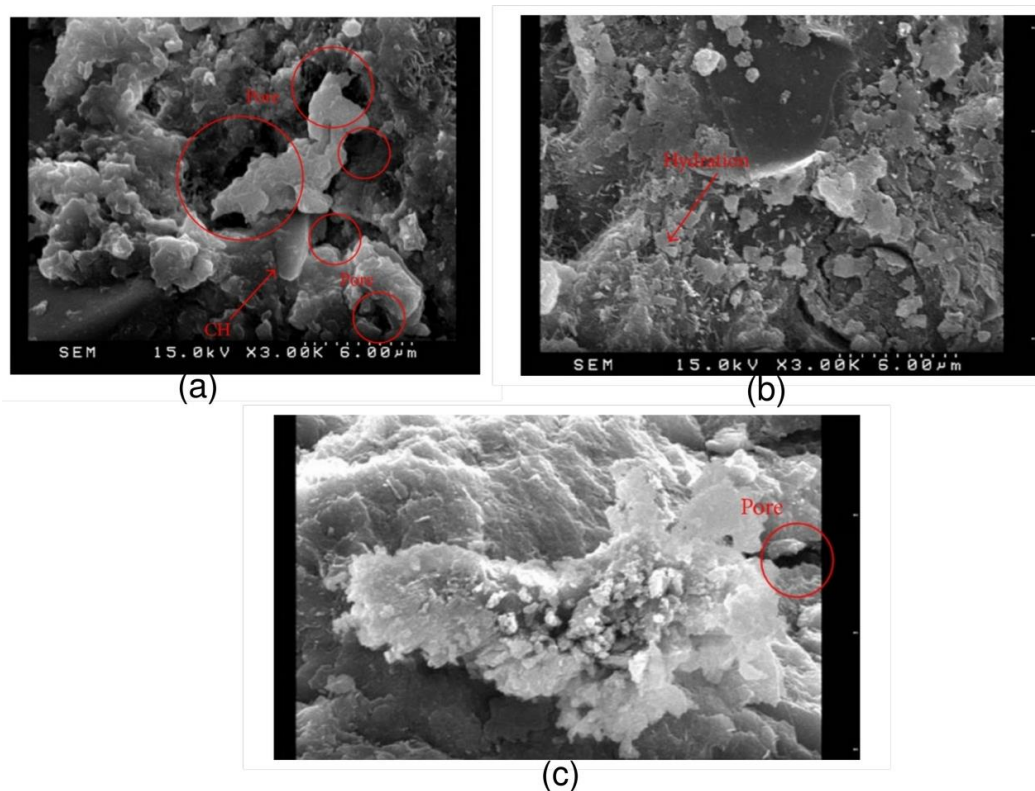


Figure 2.1 SEM images of specimens with (a) 100% PC (b) 85% PC & 15% MK (c) 75% PC & 25% MK [61]

2.2.4 Rice Husk Ash (RHA)

RHA is produced by burning rice husk, a waste by-product of the rice milling industry. RHA is known to have high silica content and finer size than the cement particles [64]–[70].

Singh et al. (2002) [71] studied the effects of replacing cement with RHA by 5%, 10%, 15%, 20%, 25% and 30% on the consistency and setting times of blended cement paste. They concluded that the consistency of the admixed cement paste increases with increase in the content of RHA because of the higher surface area of RHA particles ($28,800 \text{ m}^2/\text{kg}$) as compared to cement particles ($309 \text{ m}^2/\text{kg}$). They also found out that the replacement of cement with 10% RHA was the optimum limit as the initial and final setting times of the cement paste were maximum at 10%. Their results were confirmed in other studies, as well [72], [73]. The increase in water demand with an increase in replacement of cement with RHA was also associated with the porous structure of rice husk ash [72], [74]. The grinding of the original RHA to even finer particle sizes also led to an increase in the water demand due to further increase in the surface area [75]–[78].

Mohseni et al. (2016) [79] studied the effects of replacement of cement with RHA (5%, 10% and 15%) on properties of cement mortar. They investigated compressive strength, water absorption, electrical resistivity (ER), Rapid Chloride Permeability Test (RCPT) and Ultrasonic Pulse Velocity (UPV) test on the admixed cement mortar after 3, 7, 28 and 90 days of curing in water. They found that the compressive strength of all the specimens incorporating RHA has increased w.r.t the control specimen. It was because RHA increases the rate of hydration of the cement. The admixing of optimum RHA also led to an improvement in the microstructure, thereby increasing the compactness in the mortar. Also, reduction in the density of the pores due to formation of secondary C-S-H gel was observed. Figure 2.2 (a) shows the SEM image of the microstructure of the control mix in which high numbers of capillary pores was observed. Figure 2.2 (b) demonstrates denser and compact microstructure and also improved the Interfacial Transition Zone (ITZ) due to the addition of 10%

RHA. The compressive strength at 15% replacement with RHA was less than the 10% replacement; it was still higher than the strength of the control mix. The same phenomenon was observed in other studies, as well [80]–[82]. It was because, due to the formation of excess silica, the homogeneous hydrated matrix couldn't be maintained and surplus silica leaches out. The authors also observed the water absorption of RHA admixed mortar cubes and concluded that with an increase in the ratio of RHA in the mortar, water absorption reduces considerably. It was due to improved and dense microstructure, as mentioned above. Due to the reduction in the number of pores with an increase in RHA content, higher electrical resistivity of the mortars was achieved. Also, the reduction in chloride ion penetration was observed with an increase in the RHA content for the same reason. They also performed the UPV test on the admixed mortar cubes and found out that the more the RHA content was, the higher the UPV came out to be. High UPV value is generally associated with high quality of cementitious materials and thus better durability of the concrete [83].

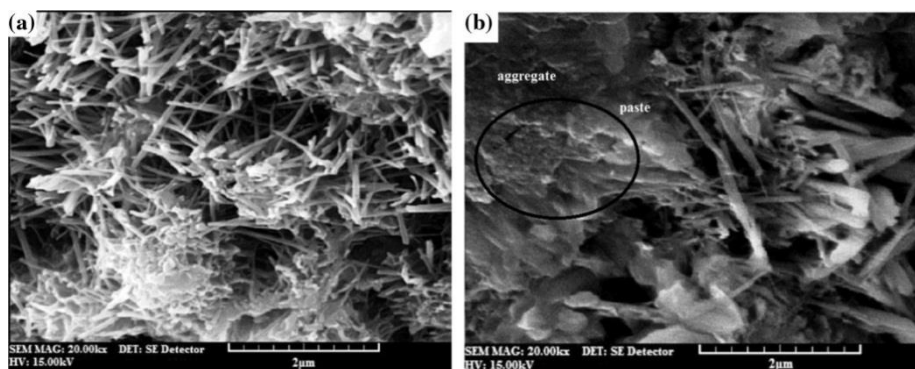


Figure 2.2 SEM images of specimens with (a) 100% cement (b) 90% cement & 10% RHA [79]

2.2.5 Wollastonite

It is a naturally occurring mineral of calcium inosilicate (CaSiO_3) formed due to the subjection of high temperature and pressure on impure limestone or dolomite. It is

finer in size as compared to cement particles and has an approximately equal proportion of CaO and SiO₂ [22], [84].

Mona et al. (2017) [85] studied the effects of wollastonite as a partial replacement (10%, 20% and 30% by wt.) of PC or ISO sand on setting times of cement paste and strength of cement mortar. The w/b ratio for all the mortar cubes was fixed at 0.5, and the loss in workability was compensated by using High Range Water Reducer (HRWR). They observed that an increase in the percentage of wollastonite when used as a cement replacement material, led to marginally higher setting times of the admixed paste. This increase was only 1.33%, 2.67% and 4.67% for 10%, 20% and 30% wollastonite respectively w.r.t control paste. However, the increase was significant when wollastonite was used as a sand replacement material. This increase was 33.33%, 53.33% and 60% for 10%, 20% and 30% wollastonite respectively w.r.t control paste. Since the ratio between cement, sand and water were kept at 1: 3: 0.5 respectively, the amount of wollastonite in the mix, when used as a sand replacement material, was in excess as compared to when used as a cement replacement material. These extra wollastonite particles formed a small carapace around the cement particles, causing a delay in the hydration process. When wollastonite (10%, 20% and 30%) was used as a sand replacement, the flexural strength of the mortar increased by 2%, 10% and 4% respectively at 2 days and by 12%, 28% and 15% respectively at 28 days of curing. However, when wollastonite was used as a cement replacement, the flexural strength of the mortar decreased by 8%, 28% and 36% respectively at 2 days and by 2%, 10% and 17% respectively at 28 days of curing. The increase in the flexural strength when wollastonite was used as a sand replacement up to 20% was because of its fibrous nature. At 30% replacement, the cement paste matrix weakens, and thus there was a decrease in the flexural strength. It was because of the inert behaviour of wollastonite

which does not contribute to the strength at higher replacement percentages. A couple of other studies also showed the same inert behaviour of wollastonite [22], [86]. The authors observed that the results of the compressive strength were similar to that of flexural strength when wollastonite was used as a sand replacement material. However, when wollastonite was used as a cement replacement (10%, 20% and 30%), the compressive strength increased by 24%, 64% and 63% respectively at 2 days and decreased by 12%, 34% and 35% respectively at 28 days of curing in water w.r.t the compressive strength of control mortar. It was attributed to the filling effect of wollastonite, which could not compensate for the loss of strength at 28 days of curing. According to the previous study [87], the addition of wollastonite increases the compressive strength w.r.t the control mortar. The discrepancy was due to the fact that, in the previous study [87], wollastonite microfibers were of smaller size as compared to the size of wollastonite particles used in the study by Mona et al. [85].

2.2.6 Limestone Powder (LS)

Limestone powder is produced from sedimentary carbonate rock, which has high calcium carbonate (CaCO_3) content (>95%) [88]. Limestone is the primary source of calcium (Ca) for cement production, and its aggregates are most commonly used in the base of roads [89]–[92].

Aqel and Panesar (2016) [93] studied the effects of LS on the setting times, the heat of hydration and $\text{Ca}(\text{OH})_2$ content of cement paste and compressive strength of steam cured cement mortars. Three types of LS were used of different particle sizes (17 μm , 12 μm and 3 μm) and Blaine's fineness of 475, 580 and 1125 m^2/kg respectively designated as LS-A, LS-B and LS-C. The cement was replaced by all the three types of LS by weight (5, 10 and 15%). The w/b ratio was kept fixed at 0.37. The compressive

strength of the mortar cubes was tested at 12 h and 16 h (steam curing); 3 days, 7 days and 28 days (lime water curing). It was found that incorporation of LS decreases the setting times of the admixed paste. The reduction in the initial setting time for 15% replacement of cement by LS-A, B and C was 4, 6.1 and 14.3% respectively. The decrease in the setting time with a decrease in the size of the LS particles could be attributed to the excess surface area provided by finer particles for nucleation of hydration products of cement [94], [95]. The higher heat of hydration was observed with decrease in the size of LS particles. It was because the finer LS particles show higher effect on the acceleration of the hydration process. Aqel and Panesar (2016) also investigated the Ca(OH)_2 content of the admixed paste. The higher amount of Ca(OH)_2 was observed with an increase in the replacement of cement by LS at 16 h. It was due to the acceleration of the hydration reaction of cement with water by LS (hydration effect was dominant). However, at 28 days, amount of LS (5% and 10%) and the size of LS particles did not affect the Ca(OH)_2 content. But at 15% replacement by LS, there was a reduction in the Ca(OH)_2 content as dilution effect became dominant. The addition of LS did not affect the compressive strength at 12 h and 16 h w.r.t control mix. However, at 3, 7 and 28 days, there was a 3 to 4% decrease in the compressive strength with a higher reduction in higher LS content.

Bentz et al. (2017) [96] studied the effects of limestone powder on setting times of the admixed paste. The OPC used was Type I/II cement and CaCO_3 content of LS was approximately 98.1%. The OPC was replaced by 5, 10, 20, 40, 50, 60, 80, 90 and 95% LS by volume and not by weight. It was due to a noteworthy difference in the specific gravity of OPC and LS. All the mix showed higher setting times as compared to the control paste because of extra sites for nucleation of hydration products of cement [97], [98]. They concluded that hydration effect was more dominant than the dilution

effect when cement was replaced by LS up to 50% because least setting time was observed for control mix followed by 20%, 10%, 40%, 5% and 50% replacement of cement by LS. The dilution effect became more dominant when cement was replaced by LS by more than 50%. Therefore there was a progressive increase in the setting times with increase in the volume of LS in the paste.

2.2.7 Sugarcane Bagasse Ash (SBA)

Bagasse is the dry residue left after extraction of juice from sugarcane stalks. It is burnt to produce Sugarcane Bagasse Ash. It can be used as supplementary cementitious material (SCM) [21], [99]–[102].

Piedrahita et al. (2016) [103] studied the effects of SBA on mechanical and durability properties of mortars. They analysed the compressive strength (CS), Ultrasonic Pulse Velocity (UPV) test, Rapid Chloride Permeability Test (RCPT) and Electrical Resistivity (ER) test of the admixed cylindrical mortars. The density of OPC, fine calcareous aggregate and SBA was 3.06 g/cm^3 , 2.65 g/cm^3 and 2.1 g/cm^3 respectively. They collected SBA from a sugar factory and dried it in an oven at $105 \text{ }^\circ\text{C}$ for 24 h and then sieved it through a $75 \text{ }\mu\text{m}$ sieve. The cement by weight was replaced by SBA by 10 and 20%. The mean size of the OPC and SBA particles was $21.15 \text{ }\mu\text{m}$ and $53.91 \text{ }\mu\text{m}$, respectively. The particles of SBA were coarser than the OPC particles. However, the surface area of OPC particles ($1.94 \text{ m}^2/\text{g}$) was less than that of the SBA particles ($40.28 \text{ m}^2/\text{g}$). Even though the SBA particles were coarser, they still had higher surface area w.r.t OPC particles. This contradictory behaviour of SBA particles was because of their porous nature. The w/b and cementitious material to fine aggregate ratio were kept constant at 0.6 and 1:3.5 respectively. Superplasticizer was used to compensate for the loss in workability. The cylindrical mortars of 100 mm dia. and 200

mm height were cast and cured for 3, 7, 14, 28, 56, 90 and 180 days in a room with the temperature at 23 ± 2 °C and relative humidity (RH) at 95%. The authors classified SBA as class Class N pozzolan because the sum of SiO₂, Al₂O₃ and Fe₂O₃ content in SBA was 88.27% which is more than 70% as required by ASTM C618 [43]. The other studies also reported the sum to be in between 70-90% [99], [100], [104], [105]. The compressive strength was found to be decreasing with an increase in the percentage of SBA until 28 days of curing. At 56 days, the compressive strength of 10% SBA mortar became higher, but compressive strength of 20% SBA mortar remained lower than that of the control mix. At 90 days, compressive strength of 20% SBA mortar was higher than that of the control mix; however, it remained less than the compressive strength of 10% mortar. Another study also showed that the compressive strength of SBA concrete was higher at later days of curing [105]. However, some studies concluded that the compressive strength of mortar and concrete, when OPC was replaced by SBA by more than 10%, was lower than the control sample [100], [106]. It was because of the higher carbon content in the SBA used by them which greatly affects the compressive strength of cement mortar and concrete. Piedrahita et al. (2016) observed that UPV value of the mortar decreases until 90 days of curing when cement was partially replaced by SBA. However, at 180 days of curing, UPV value of 10% SBA mortar was higher, and that of 20% SBA mortar was lower than that of the control mortar. Generally, a high UPV value indicates a much denser matrix and higher compressive strength [107]. However, the efficiency of the UPV test decreases with increase in the time. Therefore, at later days of curing (56, 90 and 180 days), lower UPV values of SBA admixed mortars do not properly justify the increase in their compressive strength [108], [109]. Piedrahita et al. (2016) observed that there was an increase in the electrical resistivity (ER) of the mortars with an increase in the proportion of SBA at later days of curing (from 28 days

onwards). An increase in ER was only limited to later days of curing because at later days; calcium hydroxide converts into additional C-S-H gel thus densifying the cementitious matrix and reducing the interconnectivity between pores [110]–[113]. From RCPT, Piedrahita et al. (2016) found that the 10% SBA mortars were “highly” permeable to chloride ions at 28 and 56 days of curing and “moderately” permeable at 90 and 180 days of curing as per the ratings by ASTM C1202 [114]. While 20% SBA mortars were “moderately” permeable to chloride ions at 28 and 56 days of curing and “low” permeable at 90 and 180 days of curing. They concluded that with an increase in the percentage of SBA, the chloride ion permeability of the admixed mortar decreases w.r.t the control mortar as was found by another study as well [100]. It was due to the addition of SBA that changed the ionic concentration in the cementitious matrix [115].

2.2.8 Nanosilica (NS)

Nanoparticles of silicon dioxide are also known as Nanosilica (NS). NS has a similar chemical composition like microsilica (MS). Both improve cement properties tremendously by various mechanisms [116]. However, NS is known to impart better strength as compared to microsilica because of its higher fineness. NS has high silica content (> 99%), and very small mean particle size (< 50 nm) [117]. NS has high pozzolanicity and thus consumes calcium hydroxide at higher rate, to form additional C-S-H [118]. It generally influences the properties of cement by seeding effect [119].

Qing et al. (2007) [120] studied the consistency, setting times and compressive strength of admixed cement paste. They compared the effects of nanosilica and microsilica on the above-mentioned tests. The specific surface area of microsilica and nanosilica was 21.5 m²/g and 160 m²/g respectively, and their average particle size was 180 nm and 15nm, respectively. The ratio between cementitious material, water and

superplasticizer were kept at 1: 0.22: 0.025. The cubes of size (25 x 25 x 25 mm) were cast and cured for 1, 3, 28 and 60 days for measurement of compressive strength. The replacement percentages by weight of cement by NS and MS were 1, 2, 3, 5% and 2, 3, 5% respectively. The authors found that, with an increase in the percentage of NS, the water demand of the cement paste decreases while it remained almost the same with an increase in the proportion of MS in the cement paste. However, a study done by Tobon et al. (2018) [121], found that water demand increases with increase in the ratio of NS in the cement paste due to increase in the total surface area. The contrary finding was because Tobon et al. (2018) did not use superplasticizer to compensate for the loss in workability while Qing et al. (2007) kept the amount of superplasticizer constant for the all the paste. Qing et al. (2007) also observed that with an increase in the proportion of NS, the initial and final setting time of the cement paste decreases while it was opposite in the case of MS. It was because superplasticizer gets adsorbed on the surface of MS and cement particles and causes a delay in their hydration, thus leading to increased setting times [122]–[124]. Due to the decreasing water demand by the cement paste with NS, it was able to control the delaying action of superplasticizer [121]. The decrease in initial and final setting times of NS admixed paste was found in another study as well [117]. Qing et al. (2007) concluded that the NS admixed cement paste gave higher compressive strength as compared to MS admixed cement paste because of its higher pozzolanic activity.

Haruehansapong et al. (2014) [125] studied the effects of different particle sizes of nanosilica (NS) on the compressive strength of the admixed mortar and compared it with microsilica (MS). The average particles sizes of NS were 12, 20 and 40 nm, and the average particle size of MS particles was 100 nm. The cement and sand used was Type I OPC and standard river sand, respectively. The silica content in NS and MS was

88.3% and 99.9% respectively. The w/b and sand to cementitious material ratio were kept fixed to 0.65 and 2.75, respectively. The replacement percentages of cement by NS and MS in the mix were 3, 6, 9, and 12% by weight of cement. 50 x 50 x 50 mm mortar cubes were cast and cured in water for 1, 7 and 28 days. The authors found that incorporation of both NS and MS improves the compressive strength w.r.t. control mortar. However, the improvement in NS admixed mortar was significantly higher as compared to MS admixed mortar, similar to another study [126]. It was because the silica content in MS was lower and also its particles were coarser as compared to NS particles. The higher silica content of NS increased the pozzolanic activity in mortar while its smaller particle size increased the packing of the mortar [117], [127], [128]. The higher compressive strength was observed for mortar with NS particles of size 40 nm at all replacement percentage and days of curing w.r.t. to NS particles of finer size (12 and 20 nm). It was because of the coating of finer NS particles onto the surface of cement particles, thereby reducing the hydration reaction. It was also because smaller NS particles have the agglomeration tendency [129]–[131]. Other studies also confirmed the higher compressive strength for 40 nm NS w.r.t 10 nm NS [126], [132], [133]. Haruehansapong et al. (2014) also observed that the compressive strength of mortar increases with the increase in the percentage of MS and NS (of all sizes). However, the compressive strength of mortar at 12% NS and MS was lower than 9% NS and MS even though it remained higher than the compressive strength of control mortar. It was because, at 12% replacement, the optimum quantity of OPC in the mix decreases, thereby reducing the hydration of cement. They concluded that the optimum level of replacement by NS was 9% and the most suitable particle size was 40 nm. The authors compared the SEM micrographs of control mortar and 9%-40 nm NS mortar at 7 days of curing, as shown in Figure 2.3 (a) and (b) respectively. It is clear from Figure

2.3 (a) that microstructure of control mortar had a nest of C-S-H gel connected by needle-shaped $\text{Ca}(\text{OH})_2$. However, as can be seen in Figure 2.3 (b), the microstructure of 9%-40 nm NS mortar was more densified and homogeneous as compared to control mortar.

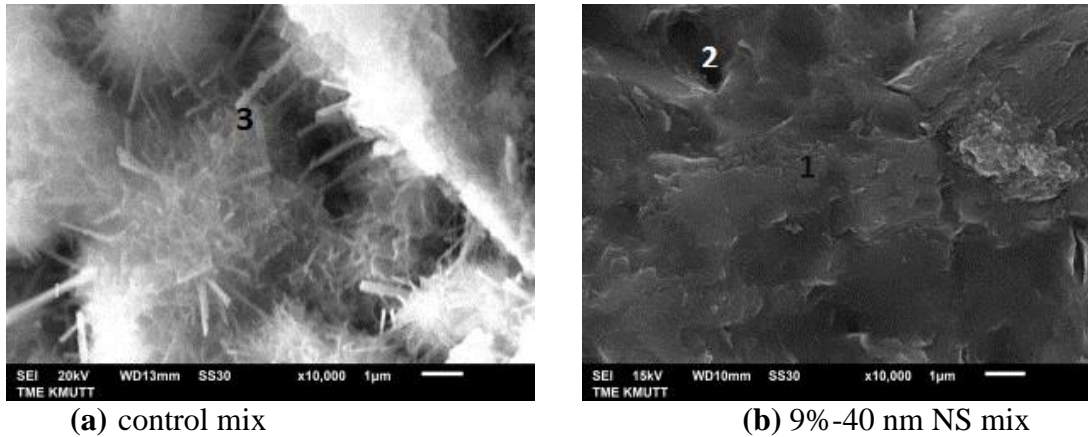


Figure 2.3 SEM images of specimen with (a) 100% OPC (b) 9%-40 nm NS (1 : C-S-H, 2 : pore, 3 : $\text{Ca}(\text{OH})_2$ crystal) [125]

2.2.9 Microsilica (MS)

Microsilica has higher silica content as compared to most of the mineral admixtures. Its particle size is finer than the conventional cement. Therefore it is considered as a highly reactive pozzolan which improves the properties of the cement paste and mortars considerably. However, it is one of the most expensive pozzolanic materials. It is used where there is great concern about the durability of the structure. Therefore most of the time, its usage is generally in combination with other pozzolanic materials like FA, GGBFS, MK etc. which are cheap as well as which provide sufficient durability to the structure [23], [134]–[136]. The usage of microsilica with other pozzolanic materials decreases the overall cost of the structure without compromising with durability.

Sezer (2012) [137] studied the effects of microsilica on the flow value, compressive strength and sulphate resistance of cement mortars (with or without limestone powder). The MS and LS replaced cement by weight in the following proportion: 5, 10, 15% and 5, 20, 35% respectively. The samples were cured for 2, 7, 28, 90 and 180 days for compressive strength (CS) test. For the sulphate resistance test, samples were cured until they attained the strength of 20 MPa and then were kept in two solutions: 5% sodium sulphate solution and 4.2% magnesium sulphate solution. The authors found that the flow value of mortar decreases with an increase in the amount of MS and increases with an increase in the amount of LS. It was because of the high surface area provided by the finer MS particles. The increase in the proportion of MS in the mixture decreases its workability at constant water content, thus increasing the water demand [138]. The increase in the flow value due to the mixing of LS was because of the variation in its particle size. The finer LS particles filled the wide pores in the cement paste and reduced the water requirement [139]. The flow value of mortar containing a combination of LS and MS at various proportions was lower than the LS mixture but higher than the MS mixture. Thus it was concluded that incorporating LS and MS together nullified each other's negative aspects and provided a better flow value. Sezer (2012) also found that the compressive strength of the mortars containing MS decreases up to 28 days of curing but at later days of curing (90 and 180 days), the compressive strength was higher w.r.t control mortar. MS increases the strength of the mortar by filling the pores and by forming additional C-S-H from Ca(OH)_2 formed due to hydration of cement. Since at curing age of up to 28 days, sufficient hydration of cement did not take place which stalls the formation of additional C-S-H, therefore, the compressive strength of MS admixed mortar decreases at early days of curing. However, many studies found that incorporation of MS led to an increase in the

compressive strength of mortar at all ages of curing [117], [120], [125]–[128]. The incorporation of LS led to a decrease in the compressive strength of mortar at all ages of curing due to the dilution effect. The combination of LS and MS led to further decrease in the compressive strength at early ages of curing however due to the pozzolanic activity of MS, the compressive strength was improved to a certain extent at later days of curing but remained lower than the compressive strength of control mortar. Sezer (2012) observed that the expansion of mortar due to immersion in sodium and magnesium sulphate solution decreases with the increase in the ratio of LS and MS. However, the reduction in the case of MS was much more significant as compared to LS. The increase in the amount of MS and LS decreases the amount of cement in the mixture. Therefore in LS admixed mortar, reduction in cement content led to decrease in the amount of C_3A thereby reducing the formation of ettringite and decrease in the amount of C_2S and C_3S thereby reducing the formation of gypsum which are usually formed due to sulphate attack upon the hydration products of cement. Whereas in the case of MS admixed mortar, its pozzolanic action reduces the $Ca(OH)_2$ content thereby reducing the formation of gypsum. Magnesium sulphate solution caused more damage to the admixed mortar as compared to the sodium sulphate solution because hydration products of magnesium are expansive in nature [140]–[142]. The relationship between compressive strength (CS , MPa) and limestone content (LS , %), microsilica content (MS , %), days of curing (T , days) was constituted by Sezer (2012) as mentioned in Equation 2.1 [137].

$$CS = -(0.6122 \times LS) - (0.0973 \times MS) + (0.2068 \times T) + 37.9776 \quad (2.1)$$

2.2.10 Rice Straw Ash (RSA)

Rice straw is an agricultural waste causing methane emission due to its decomposition and pollution due to field burning [143]. Rice straw ash is rich in silica content ($> 75\%$) and possesses pozzolanic properties for use as supplementary cementitious material [33], [34]. There is a scarcity of research on the characterization of RSA and their possible implementation. Few researchers have studied the use of RSA as a supplementary cementitious material in which the ash was burnt at high temperatures and was then pulverized for its usage as a SCM [31], [33], [34], [144].

El-Sayed and El-Samni (2006) [31] studied the effects of rice straw ash on the standard consistency and setting times of cement paste. Three different types of cement, namely OPC, Blast Furnace Slag Cement (BFSC) and Sulphate Resistant Cement (SRC) were used for the experiment. They incinerated the rice straw in the furnace at 550°C to minimize the unburnt carbon content, and the ash produced was subjected to grinding for 20,000 rotations in Los Angeles Abrasion Machine. The grounded ash was greyish in colour, and it was further sieved through $75\ \mu\text{m}$ sieve. The specific surface area of RSA before grinding was $1.846\ \text{m}^2/\text{g}$, and the mean particle size was $50\ \mu\text{m}$. They found that with the increase in the ratio of RSA (from 0-30% at an equal interval of 5%) in the paste, the water demand increases due to the comparatively high surface area of RSA particles. RSA affected the water demand of SRC the most, followed by OPC and BFSC. There was an increase in the initial and final setting times with the increase in the ratio of RSA. It was attributed to the inert behaviour of RSA at early ages. It was also due to the higher fineness value of RSA as compared to the cement. Similar explanations were given for the increase in the setting times of paste due to the inclusion of other SCMs [47], [48], [53], [85].

Munshi and Sharma (2018) [145] studied the effects of enhanced burning techniques on the usage of rice straw ash as a pozzolanic material. Firstly, rice straw was burnt in the open air, and the ash produced was further subjected to high temperatures in a muffle furnace at a temperature of 400 °C, 600 °C and 750 °C to remove all the organic compounds and the unburnt carbon residue. All the types of ashes were grounded for 30 minutes. The processing of RSA at elevated temperatures in the muffle furnace led to a change in its colour. The colour of RSA changed from dark black (uncontrolled burning) to light greyish (RSA at 750 °C). Munshi and Sharma (2018) also observed the variations in the particle size of RSA caused due to exposure to different temperatures in the muffle furnace. They concluded that with the increase in the temperature, there was a decrease in the mean particle size of RSA. The particle sizes of RSA (open-air burning), RSA at 400 °C, RSA at 600 °C and RSA at 750 °C were 7.5 µm, 1 µm, 0.8 µm and 0.75 µm respectively. They also observed that with the increase in temperature, the silica content in the RSA increases. Therefore, RSA processed at more than 400 °C, followed by grinding could be used as a supplementary cementitious material. The authors also studied the effect of RSA on the workability of the lime mortar. It was found that there was a decrease in the flow value when open-air burnt RSA was used because of the presence of unburnt carbon which has a high affinity towards water [47], [48]. The flow value was higher when the RSA, subjected to elevated temperatures was used. The compressive strength of RSA admixed lime mortar increases at later days of curing (28 and 56 days) due to the reaction between silica present in RSA and calcium present in lime. The reduction in compressive strength at 14 days of curing was due to inert behaviour of RSA. Higher improvement in the compressive strength was observed when RSA produced at a higher temperature

was used. The maximum compressive strength was when RSA produced at 750 °C was used.

2.3 EFFECTS ON MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE

2.3.1 Fly Ash

Yazici and Arel (2012) [146] studied the impact of fly ash (3 different particles sizes) on the compressive and split tensile strength of concrete. The specific surface area of the unprocessed FA (A) was 0.23 m²/g. It was grounded in the ball mill for 7200 and 14400 rotations. The resulting surface areas were 0.39 m²/g (B) and 0.52 m²/g (C), respectively. The surface area of the OPC used was 0.37 m²/g. Superplasticizer was also used, and the slump was maintained at 80-120 mm. The fine and coarse aggregates ratio and w/b ratio were kept constant at 0.55:0.45 and 0.5 respectively. The replacement percentages of cement by FA were 5%, 10% and 15%. The concrete samples were kept for curing in water for 7, 28, 56, 90, 120 and 180 days. It was observed that there was a decrease in the compressive strength with the increase in the ratio of FA (FA-A and FA-B) in the concrete at all days of curing. However, the compressive strength of concrete with FA-C (surface area = 0.52 m²/g) was higher than the control concrete at all days of curing. The compressive strength of concrete with FA-A (surface area = 0.23 m²/g) and FA-B (surface area = 0.39 m²/g) was much lower than the compressive strength of concrete with FA-C. It was due to the high fineness of the FA-C which was produced by grinding FA-A for longer durations. The highest compressive strength of concrete was found at 5% replacement of cement by FA-C. The test for split tensile strength gave similar results. The chemical composition of all the FA was same, the only difference being the particle sizes. Therefore it was concluded that if the FA is

processed to get the optimum surface area, it could be used as a cement replacement material without compromising with the strength of the concrete. A similar result was found in other studies as well, where the increase in the dosage of FA decreases the compressive strength but at optimum fineness, the compressive strength was more than the control mix [50], [147]–[149].

Barbhuiya and Kumala (2017) [150] studied the effects of FA and Ultra-Fine Fly Ash (UFFA) on the concrete subjected to immersion in 3% sulphuric acid (H_2SO_4) solution and 1.5% nitric acid (HNO_3) solution. The silica content and surface area of UFFA (73.4% and $2.51 \text{ m}^2/\text{g}$ respectively) were higher than that of the FA (51.8% and $0.34 \text{ m}^2/\text{g}$ respectively). The OPC was replaced by the combination of UFFA + FA, (10% + 20%), (10% + 30%), (10% + 40%) and (10% + 50%) designated as Mix 1, 2, 3 and 4 respectively. The admixed concrete samples were kept in the two acidic solutions for 7, 14, 28, 56 and 90 days after 28 days of curing. It was found that the loss of compressive strength was highest in control concrete (100% OPC) followed by Mix 1 at all ages of acidic immersion. The loss of compressive strength after immersion in both the acidic solutions decreased as the proportion of FA and UFFA in the mixture was increased. It was because incorporation of FA and UFFA particles in the mix increased the density of concrete matrix such that the ingress of sulphates and nitrates was not possible. As the amount of FA and UFFA was increased, there was a reduction in the amount of $\text{Ca}(\text{OH})_2$ due to their pozzolanic action which further reduced the effect of sulphuric and nitric acid on the concrete. Because $\text{Ca}(\text{OH})_2$ in the form of portlandite is most vulnerable to hydrolysis on account of its moderately high dissolvability in deionized water [151], [152]. It was also observed that loss of mass was higher in control concrete, and decreased with the increase in the content of mineral admixtures

under immersion in both the acidic solutions. The loss of compressive strength and mass was found to be more in sulphuric acid solution w.r.t. nitric acid solution.

Hussain et al. (2017) [153] studied the effects of incorporation of FA on concrete subjected to accelerated carbonation curing. The different w/b ratios adopted were 0.35, 0.5 and 0.65. The OPC was replaced by 30% FA only. After 28 days of curing in water, all the samples were placed in carbonation chamber for 7, 28, 60, 120, 180, 240, 300 and 365 days for accelerated carbonation curing (ACC). The temperature in the carbonation chamber was kept at 30-35 °C and relative humidity was maintained at 60-70%. It was observed that there was an increase in the compressive and flexural strength of the concrete with the increase in the duration of ACC because of the conversion of Ca(OH)_2 to CaCO_3 which occupies more volume and thus decreases the porosity and permeability. The highest compressive strength was observed in concrete containing 30% FA after ACC. Also, the increase in the depth of carbonation with the increase in the duration of ACC was perceived. The increase was higher for higher w/b ratios (0.5 and 0.65). The incorporation of FA in concrete led to increase in the carbonation depth w.r.t control concrete however the change was minimal. The carbonation rate was higher in FA admixed concrete with higher w/b ratios w.r.t. the control concrete.

Saha (2018) [154] studied the effects of fly ash on drying shrinkage, porosity, water sorptivity and chloride permeability of concrete. The OPC by weight was replaced by Class F fly ash by 10, 20, 30 and 40%. The w/b ratio and the amount of Class A superplasticizer (naphthalene based) were kept constant at 0.35 and 4 kg/m³ respectively. For measurement of drying shrinkage, sorptivity and chloride permeability of admixed concrete, 75 x 75 x 280 mm prisms were cast for testing at various days of

curing. The sorptivity test and RCPT were conducted at 28 days and 180 days of curing while drying shrinkage measurement was observed at 7, 28, 56, 90, 180 and 360 days of curing. It was found that the drying shrinkage decreases gradually with the increase in the ratio of FA in the concrete. The drying shrinkage is mostly associated with w/b ratio, the volume of paste and the hydration rate. As w/b and amount of paste were constant throughout the experiment, the reduction in the drying shrinkage was attributed mainly to the decrease in the hydration rate [155], [156]. Lime content associated with OPC decreases as the amount of FA in the concrete increases. The incorporation of FA reduced the volume of the permeable voids at 28 days of curing. At 180 days of curing, the volume of permeable voids was even less due to the hydration of cement and FA. It was because of the fineness of FA which causes densification of the concrete matrix. For the same reason, reduction in the sorptivity of the admixed concrete was observed at 28 days of curing w.r.t. control concrete. The rate of reduction in sorptivity was even higher at 180 days of curing. Another reason for the decrease in sorptivity of admixed concrete was the improvement of ITZ between aggregates and the paste due to the filler effect of the FA [157], [158]. The ingress of chloride ions into the admixed concrete was determined by RCPT. It was discovered that there was a reduction in the permeability of chloride ions at 28 days of curing and it decreased further after 180 days of curing with the increase in the percentage of FA. Similar results were observed in other studies as well suggesting that incorporation of FA improves the durability properties of admixed concrete [159]–[161].

2.3.2 Ground Granulated Blast Furnace Slag

Oner and Akyuz (2007) [162] studied the effects of various dosages of GGBFS on the compressive strength of concrete. The cement content was kept constant at 250

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kg/m³ for the control concrete however for all the admixed concrete containing various proportions of GGBFS; it was fixed to 175 kg/m³. The GGBFS was added to the admixed concrete in the percentage of 0%, 15%, 30%, 50%, 70%, 90% and 110% of the cement content of the control concrete i.e. 0, 37.5, 75, 125, 175, 225 and 275 kg/m³ respectively. The compressive strength of all the 8 samples was tested after curing for 7, 14, 28, 63, 119, 180 and 365 days. It was seen that all the admixed concrete showed higher compressive strength w.r.t. to control concrete at all ages of curing except the mix containing a combination of OPC (175 kg/m³) and GGBFS (37.5 kg/m³). The progressive increase in the strength at all ages of curing was up to 70% GGBFS only. At 90% and 110% GGBFS content, the strength reduced, however, remained more than the control concrete. It was also observed that the strength gain in all the mix was higher at later days of curing as compared to early days of curing because of unavailability of calcium hydroxide at early days which a slowed down the pozzolanic reaction by GGBFS. Therefore the concrete containing the highest amount of GGBFS content (275 kg/m³) showed the highest strength gain at 365 days of curing as compared to strength at 7 days of curing. Oner and Akyuz (2007) concluded that the optimum content of GGBFS for maximum strength was 55% of the total cementitious content.

Divsholi et al. (2014) [163] studied the effects of natural carbonation on GGBFS admixed concrete. The OPC was replaced by 10, 30 and 50% GGBFS and the samples of concrete were initially cured for 7, 14 and 21 days in water and then kept for 4 years for natural carbonation. Natural Carbonation is a long term process [164]. There was an increase in the rate of carbonation in the GGBFS admixed concrete due to the consumption of calcium hydroxide. It was observed that carbonation rate in concrete with 10% GGBFS was similar to the control concrete but increased with the percentage of GGBFS in concrete.

Mohan and Mini (2018) [165] studied the effects of ultra-fine GGBFS and microsilica (MS) on compressive strength, water absorption test, RCPT, sorptivity test and acid corrosion test of concrete. The OPC was partially replaced by 5, 10 and 15% ultra-fine GGBFS and MS. The w/b ratio was fixed at 0.34 and loss in workability was compensated by the usage of polycarboxylic ether superplasticizer. The 15 x 15 x 15 cm cube samples were cured in water for 7, 28, 56 and 90 days to determine their compressive strength (CS). It was observed that MS showed higher strength as compared to GGBFS at all replacement ratios, and it was attributed to the higher fineness of MS particles. Similar results were observed in another study as well, where concrete containing MS had higher compressive strength than the concrete containing GGBFS [166]. Due to their higher fineness, the hydration rate of MS was better than GGBFS. Comparatively, MS contribution to the strength at the early days of curing is much higher than the GGBFS [162]. The compressive strength of concrete with 5% GGBFS was lower than the control concrete, while it was opposite when 10% GGBFS was used. Therefore Mohan and Mini (2018) chose only 10% replacement of OPC by ultra-fine GGBFS for further investigation on their durability properties. For water absorption and acid test, 10 x 10 x 10 cm cubes were cast. The water absorption percentage was calculated after 0.5, 1, 24, 72, and 168 hours in water. For RCPT and water sorptivity test, cylindrical samples of 100 mm dia. and 200 mm height were cast and cured in water for 56 days. These samples were then cut in 3 parts of 50 mm each, and each piece was tested for chloride permeability and water sorptivity. For acid attack test, 10 x 10 x 10 cm cubes were cast and cured in water for 28 days. They were then immersed in 2 acidic solutions of 1% sulphuric acid and 1% hydrochloric acid for 90 days. The incorporation of MS and GGBFS in the concrete decreases the volume of pores due to which there was a reduction in water absorption, chloride permeability and

sorptivity value of the admixed concrete as found in other studies as well [166], [167]. However, MS admixed concrete had better durability properties due to their finer size and high silica content. In the case of acidic attack test, there was an improvement in terms of loss of mass and strength in the MS and GGBFS admixed concrete w.r.t. control concrete. The damage was more in control concrete under immersion in H_2SO_4 solution due to the presence of high amount of $Ca(OH)_2$. The deterioration of $Ca(OH)_2$ results in gypsum formation which is expansive in nature. The gypsum then reacts with tri-calcium aluminate (C_3A) in an aqueous environment to form a relatively more expansive ettringite [168]. In admixed concrete, $Ca(OH)_2$ was consumed due to pozzolanic action of MS and GGBFS. Therefore, there was improved resistance to sulphuric acid. Similarly, the loss was more in control concrete under immersion in HCl solution due to the action of the hydrochloric acid solution on calcium hydroxide, which results in the formation of salts of calcium chloride. In the presence of water, these soluble salts find the smooth movement to the outer parts of concretes. Under such a situation, continuous reactions increases the porosity of cement pastes [169].

2.3.3 Metakaolin

Kannan and Ganesan (2014) [170] compared the effects of MK and rice husk ash (RHA) on the compressive strength (CS), water absorption, sorptivity, chloride permeability and acidic resistance of the self-compacting concrete (SCC). The mean particles sizes of OPC, RHA and MK were $23.4\ \mu m$, $6.27\ \mu m$ and $3.79\ \mu m$ respectively. The OPC was replaced by both RHA and MK individually from 0% to 30% by weight at equal intervals of 5%. The combination of both was also used at percentages of 10, 20, 30 and 40% in concrete. Mix design was done for M30 grade concrete with constant w/b ratio and superplasticizer content (sulfonated naphthalene based) of 0.55 and 2%

respectively. The ratio between coarse aggregates and fine aggregates was fixed at 0.91. For compressive strength and acid resistance test, 100 mm concrete cubes were cast. For various tests related to permeability, 100 mm dia. and 50 mm height concrete cylinders were cast. All the concrete specimens were cured in water for 28 days. It was found that the compressive strength of the MK and RHA admixed SCC increases with an increase in the ratio of MK and RHA up to 20% and 15% respectively. At 25% and 30% replacement of cement by MK and 20% and 25% replacement of cement by RHA, reduction in the strength was observed; however, it was more than the compressive strength of control SCC. The strength at 30% replacement of cement by RHA was lower than the strength of control concrete. The incorporation of MK reduces the workability of the concrete due to its higher surface area and water demand. The lower workability in MK admixed concrete was the main factor behind the higher compressive strength w.r.t RHA admixed concrete. At 30% and 40% replacement of cement by a combination of MK + RHA, compressive strength was lower as compared to 10% and 20% replacement of cement by their combination; however, it was higher than the strength of control SCC. The result justified the benefits of using MK with RHA in SCC with a high replacement of OPC by 40% (20% MK + 20% RHA). The water absorption of MK admixed SCC was lower as compared to RHA admixed SCC and control SCC. The sorptivity value of concrete is associated with the ability of water to travel through concrete [171]. The sorptivity of the MK admixed SCC and RHA + MK admixed SCC was lower than the control SCC and RHA admixed SCC. It was also due to the fact that particles of MK were finer. In general, fine particles reduce the pore volume by filling pores and thereby improving the structure of concrete [172]. The chloride ion permeability in RHA and MK admixed SCC was determined by RCPT. Kannan and Ganesan (2014) gave ratings of “negligible”, “very low”, “low”,

“moderate” and “high” to all the tested SCC samples in accordance with ASTM C1202 [114] for their chloride ion permeability. It was found that the MK admixed SCC and RHA + MK admixed SCC showed better resistance to chloride ion penetration (“very low”) as compared to the control SCC and RHA admixed SCC. The higher resistance to chloride ion penetration was because of the formation of additional C-S-H gel by pozzolanic action of MK, which decreases the interconnectivity between pores [173], [174]. For acid resistance test, all the samples were immersed in 2 different acidic solutions of 5% sulphuric acidic solution (H_2SO_4) and 5% hydrochloric acidic solution (HCl) and the weight loss was observed every 7 days up to 84 days. Contrary to the improvement in other properties of MK admixed SCC, they were least resistant to sulphuric acid solution as compared to control SCC and RHA admixed SCC. It was due to high alumina content (43.75%) of MK, which upon attack by sulphuric acid led to the formation of ettringite [175]. The formation of ettringite, which is expansive in nature, disturbs the microstructure of the hardened cement paste thus leading to high mass loss. All the admixed specimens however, showed better results as compared to the control SCC on exposure to HCl solution. It was due to the consumption of $Ca(OH)_2$ by the pozzolanic action of RHA and MK. The mass loss in all the specimens exposed to HCl solution was lower than their exposure to H_2SO_4 solution. The SEM analysis of control concrete, concrete with 15% RHA, concrete with 20% MK and concrete with a combination of 15% MK + 15% RHA can be seen in Figure 2.4. The presence of pores and the formation of ettringite can be seen clearly in the SEM image of control concrete in Figure 2.4 (a). However, these were hardly visible in the admixed concrete due to the consumption of $Ca(OH)_2$ by pozzolanic action of RHA and MK as can be seen in Figure 2.4 (b), (c) and (d).

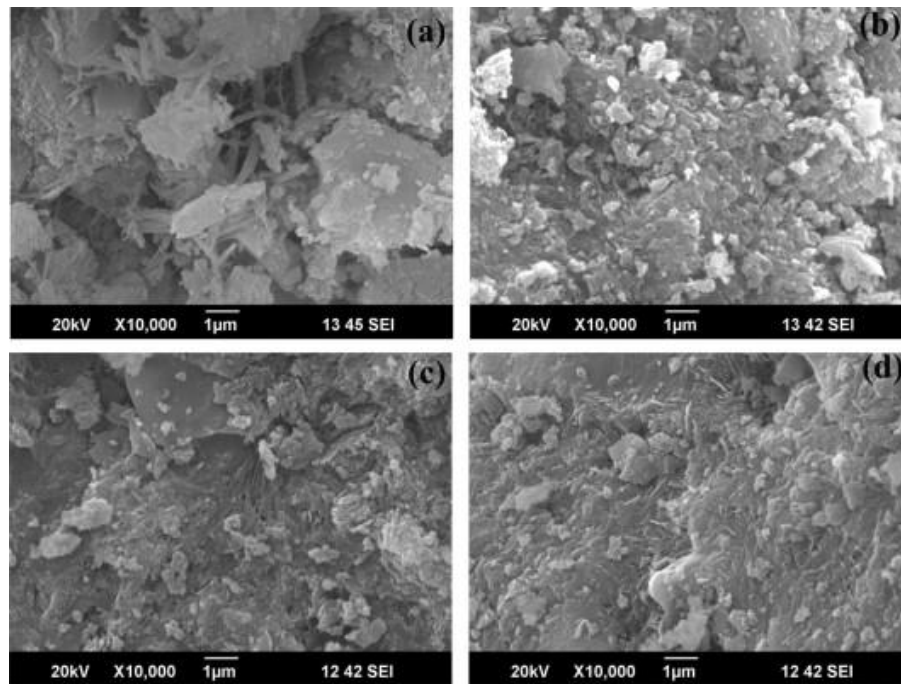


Figure 2.4 SEM images of specimen with (a) 100% OPC (b) 15% RHA (c) 20% MK (d) 15% RHA + 15% MK [170]

Nicolas et al. (2014) [176] studied the effects of flash-calcined metakaolin (FMK) on different types of concretes subjected to accelerated carbonation curing (ACC) namely immediate release concrete (iRC), self-compacting concrete (SCC), low performance concrete (LPC), high performance concrete (HPC), general-purpose concrete (GPC) and structural purpose concrete (SPC). FMK is a pozzolanic material produced when kaolinite is processed by flash calcination [177], [178]. The major difference between FMK and MK particles is their shape and size. The FMK particles are lamellar as well as spherical shaped with a diameter of approximately 10 μm . The FMK had silica and aluminium oxide content of 67.1% and 26.8% respectively. Different dosage of carboxylic ether based superplasticizer was adopted by the authors for different types of concretes. The partial replacement of OPC by weight was by 25% FMK in various concrete. For testing, 70 x 70 x 280 mm prism samples of concrete were cast. After curing in water for 28 days, these samples were transferred to the carbonation chamber for 28 days of ACC at 20 $^{\circ}\text{C}$ temperature, 65% RH and 50% CO_2

concentration. The carbonation depth was found to be higher for all types of concrete with 25% FMK as compared to the respective control concrete. This higher carbonation rate however was contradictory to the findings of few researchers [179], [180] while some researchers did observe an increase in the rate of carbonation of concrete with mineral admixtures like fly ash, limestone, pulverized fuel ash, etc. [153], [181], [182]. Nicolas et al. (2014) concluded that the depth of carbonation after 28 days of ACC was lower in concretes with higher 28 days compressive strength (curing in water).

2.3.4 Rice Husk Ash

Ramasamy (2012) [68] studied the effects of RHA on the mechanical and durability properties of different grades of concrete (M30 and M60). The replacement percentage of OPC by RHA was fixed at 5, 10, 15 and 20% by weight. The w/b ratios for M30 and M60 grade concrete were fixed at 0.43 and 0.35, respectively. The decrease in workability was compensated by the use of sulfonated naphthalene based superplasticizer (SP) in various ratios. The concrete cubes of size 100 x 100 x 100 mm were cast (with and without SP) and cured in water for various days until the time of testing of compressive strength (7, 28, 56, 90 and 180 days), saturated water absorption (60 days), RCPT (28 and 90 days) and acid resistance (28 days). It was observed that when SP was not used, the compressive strength of RHA admixed M60 grade concrete was lower than the control concrete at all ages of curing. It was because low w/b ratio (0.35) was adopted for M60 concrete which could have lowered the workability below the desired level and hindered the hydration of cement and pozzolanic action of RHA. However, the higher compressive strength was observed in M30 grade concrete with RHA up to 10% w.r.t. control concrete even when SP was not used. The compressive strength of RHA admixed M30 and M60 grade concrete was higher when SP was used

as compared to respective concretes without SP. It signifies the importance of superplasticizer when mineral admixtures of higher surface area are mixed with OPC at constant w/b ratio. The optimum level of RHA for both grades of concrete was found to be 10% by weight as per compressive strength test which was in agreement with the study done by Abalaka (2013) [183]. According to Abalaka (2013), the optimum level of RHA in concrete was found to be 5% for w/b ratio of 0.35, 0.4, 0.45 and 0.55 and 15% for w/b ratio of 0.5. However, a study done by Ganesan et al. (2008) [184] concluded that the optimum replacement level of cement by RHA was 30% at w/b ratio of 0.53. This high replacement level was possible due to the higher fineness of RHA adopted for a relatively lower grade of concrete (M25). Ramasamy (2012) also studied the water absorption of 60 days water cured concrete. The water absorption was found to be growing with increase in the ratio of RHA in both M30 as well as M60 grade concrete when SP was not used. Similar results were found by other studies as well [183], [184]. According to Abalaka (2013) [183], water absorption increases with the rise in the ratio of RHA in the concrete when w/b ratios of 0.35, 0.4, 0.45, 0.5 and 0.55 was adopted at all days of curing. Ganesan et al. (2008) [184] also observed the rise in water absorption with an increase in the ratio of RHA up to 35% in concrete at 28 days of curing. It was attributed to the hygroscopic nature of the RHA. However, at curing age of 90 days, water absorption was lower for concrete with 30% RHA w.r.t. control concrete. The significance of prolong curing can be observed by the fact that RHA concrete (30% RHA) cured for 90 days absorbed less water as compared to the same concrete cured for 28 days. It was because prolonged curing is known for reduction in the volume of permeable voids in the concrete. According to Ramasamy (2012), water absorption was lower for M30 and M60 grade concrete (when RHA up to 10%, 15% respectively and SP was admixed) as compared to the respective control concrete of

grade M30 and M60. A study done by Zareei et al. (2017) [185] found similar results when SP was used in RHA admixed concrete. However, the water absorption of concrete was lower than the control concrete when cement was replaced by RHA up to 30% in the study by Zareei et al. (2017) as compared to the 15% in the study by Ramasamy (2012). It was because RHA used by Zareei et al. (2017) was grounded to smaller particle size to increase its fineness value thus high replacement percentage was possible. Ramasamy (2012) also studied the resistance of RHA admixed concrete to chloride ion permeability by RCPT. The charge passed through the specimen was measured over a period of 6 hours. RCPT is based on the phenomenon that “higher the total charge passed; higher would be the penetration of chloride ions into the concrete sample”. It was observed that in M30/M60 grade concrete (with/without SP), there was a reduction in the total charge passed as the level of replacement of cement by RHA was increased. It was mainly because partial replacement of cement by RHA led to improved pore structure and optimum w/b ratio at the ITZ. The results of RCPT were conflicting with the results of water absorption test with an increase in RHA content of concrete. It was because of the inability of the chloride ions to penetrate into RHA admixed concrete because of finer pore diameter. Similar results of RCPT were found in other studies as well [184], [185]. The optimum level of RHA content in concrete which provided the highest resistance to chloride ion permeability was found to be 30%. The incorporation of 30% RHA decreases the chloride ion permeability by as high as 4 times [186] and by as much as 70% [184]. According to Ganesan et al. (2008) [184], the total charge passed in concrete is directly proportional to the amount of unburnt carbon present in the RHA. The less the amount of unburnt carbon is, higher will be the resistance to chloride ion permeability by RHA admixed concrete. Ramasamy (2012) used a 5% HCl solution to find out the effects of the acidic

environment on the RHA admixed concrete. The cubes were immersed in an acidic solution for 60 and 90 days after 28 days of curing in water. It was found that the resistance of RHA admixed concrete (M30 and M60) to HCl solution increases with increase in the RHA content in the concrete w.r.t. the control concrete. $\text{Ca}(\text{OH})_2$ in the hydrated cement paste is the first compound to be affected by an acidic environment. It converts into calcium salt when attacked by HCl solution. Due to the pozzolanic action of RHA, $\text{Ca}(\text{OH})_2$ was converted into C-S-H, thus decreasing the effects of acidic solution on concrete. When RHA was admixed in the concrete, the effect of HCl solution was more profound on M60 grade as compared to M30 grade. All the samples of RHA admixed concrete were more resistant to the acid attack when SP was used as compared to the respective concrete without SP.

2.3.5 Wollastonite

Kalla et al. (2014) [187] studied the properties like compressive strength, water absorption, carbonation and chloride diffusion of concrete with wollastonite. The concrete samples were prepared using three different w/b ratios (0.45, 0.5 and 0.55) and by replacing 53 grade OPC by 0-25% wollastonite at equal intervals of 5%. The amount of SP used was varied between 0.82 and 0.9% according to the workability of the mixture. The ratio of cement, fine aggregate, 10 mm and 20 mm nominal size aggregate by weight was maintained at 1, 1.61, 1.6 and 1.6 respectively. For compressive strength test, 100 mm cubes were cast and cured in water for 7, 28 and 90 days. It was observed that the compressive strength of the admixed concrete increases up to 10% replacement of OPC by wollastonite. The strength of concrete at replacement of cement by more than 10% wollastonite was lower than the control concrete. Also, at a particular replacement level, it was observed that compressive strength was higher at lower w/b

ratio (lowest strength at w/b of 0.55 and highest at w/b of 0.45). The increase in the compressive strength was due to the fibrous nature of wollastonite as found in other studies as well [188], [189]. On the contrary, a study by Zareei et al. (2019) [190] observed that compressive strength decreases by 3 to 7% w.r.t. control concrete with an increase in the ratio of wollastonite (0 to 50% at equal intervals of 10%). It was attributed to the lower amount of hydration products as cement was partially replaced by wollastonite. The reduction in strength due to lower amount of hydration products could not be compensated by filling and pozzolanic effect of wollastonite particles. Another reason could be different w/b ratios adopted in both the studies as wollastonite used had similar properties. Kalla et al. (2014) maintained w/b ratio at 0.45 (CS was highest at w/b = 0.45) while w/b ratio in a study by Zareei et al. (2019) was only 0.38. It can be concluded from the comparison of both these studies that the sufficient w/b ratio should always be maintained while using SCMs in concrete to compensate for the loss of workability. For the water absorption test by Kalla et al. (2014), 150 mm cubes were cast and cured for 28 days in water. After curing, the samples were put under constant water pressure (0.50 MPa) on the face perpendicular to the casting face for 72 hours. Immediately after 72 hours, the samples were split from the middle into two parts, and the depth up to which the water penetrated was measured. As expected, the water absorption was found to be decreasing with increasing amount of wollastonite in concrete. It was because the incorporation of wollastonite led to the dense packing of the concrete causing water tightness and reduction in the total volume of pores. Similar results were observed in other studies as well [84], [190], [191]. Also, the concrete with lowest w/b ratio (0.45) absorbed the least amount of water as compared to admixed concrete samples with higher w/b ratios (0.50 and 0.55). For carbonation test, 100 mm cubes were cast and cured in water for 28 days. After curing, the cubes were cut into

four equal parts of size 100 mm x 50 mm x 50 mm and were put in the oven at 70 °C for 14 days. After coating the longitudinal side of the specimens with epoxy paint, samples were placed in the carbonation chamber for 14, 21, 28, 35, 42, 49 and 90 days with RH at 50-65%, the temperature at 27 ± 2 °C and CO₂ concentration at $5 \pm 2\%$. The carbonation depth was found to be decreasing with increasing wollastonite percentage up to 10% in the concrete. It was expected because due to incorporation of wollastonite, the concrete is densified to the extent that ingress of CO₂ through pores into the concrete becomes difficult. The reaction between CO₂ and Ca(OH)₂ is stronger as compared to the CO₂ and C-S-H gel. The addition of wollastonite led to consumption of Ca(OH)₂ by its pozzolanic action therefore, the carbonation depth was lower for wollastonite admixed concrete. A high amount of water fills the pores of the concrete and obstructs the ingress of CO₂ [192]. The authors also studied the chloride ion migration resistance of concrete cured for 28 days in water by the steady-state method. The higher resistance to chloride ion permeability was observed in samples with low w/b ratio (0.45) as compared to samples with high w/b ratio of 0.5 and 0.55. Also, the resistance to chloride ion diffusion increased with increase in the proportion of wollastonite up to 10% in the mix as compared to the control concrete at all w/b ratios. However, the replacement of cement by wollastonite by more than 10% had an adverse impact, and thus the resistance was found to be lower than the control concrete. Therefore the authors suggested the replacement of cement by 10-15% wollastonite in the concrete at w/b ratio of 0.45.

Zareei et al. (2019) [190] studied the effects of acidic immersion on wollastonite admixed concrete. The mix design of concrete was for M25 grade. The OPC was partially replaced by wollastonite in the percentages of 0-50% by weight at equal intervals of 10%. The w/b ratio and polycarboxylic ether based superplasticizer content

were maintained at 0.38 and 2.5% respectively by weight of cementitious materials. 150 mm cubes were cast and cured in water for 28 days. After curing, cubes were immersed in the 5% H₂SO₄ solution for another 28 days. For comparison between strength loss before and after acidic immersion, another set of concrete cubes were cast and cured in water for 56 days. The authors observed that the mass loss due to acidic immersion did not show a distinct behaviour with an increasing proportion of wollastonite in the concrete. The percentage difference between the mass of the samples before and after acidic immersion was found to be less than 1% for all the samples with the highest being 0.75% for concrete with 50% wollastonite. Similarly, the lowest loss of compressive strength (4%) was observed for concrete with 10% wollastonite followed by concrete with 50% (5%), 40% (7%), 30% (7.5%) and 20% (9%) wollastonite. The loss of compressive strength was because of ingress of H₂SO₄ solution into the concrete through pores and voids, which disturbs the concrete matrix and breaks the bond between different concrete components.

2.3.6 Limestone Powder

Al-Tamimi and Sonebi (2003) [193] compared the effects of the hydrochloric acid solution and sulphuric acid solution on normal concrete and SCC with 47% LS. The w/b ratio for normal concrete and SCC was 0.46 and 0.36 respectively, and the cement content for the same was 490 and 280 kg/m³. A copolymer-based HRWR was used in SCC to compensate for the larger surface area of 47% LS. Cylindrical samples of concrete of 45 mm dia. and 90 mm height were cast and cured for 28 days in water. After curing, samples were put in 2 acidic solutions: 1% H₂SO₄ and 1% HCl for 18 weeks and the loss of mass was measured after 1, 2, 3, 4, 6, 8, 10 and 18 weeks of immersion. It was found that the total mass loss in normal concrete after 18 weeks

immersion in H_2SO_4 solution was 21% as compared to 9% in SCC. It was due to the incorporation of LS powder in SCC. On the contrary, under HCl solution immersion, the total mass loss in normal concrete was 7% as compared to 10% in SCC. The process behind the acid attack is that the sulphates from H_2SO_4 solution react with hydrated C-S-H gel to form gypsum, which in turn reacts with C_3A to form ettringite and monosulphoaluminate. In case of HCl attack, the chloride reacts with hydrated C-S-H gel to form CaCl_2 which in turn reacts with C_3A to form ettringite and chloroaluminate. Overall, the HCl solution was found to be more harmful to limestone admixed concrete as compared to H_2SO_4 solution.

Lollini et al. (2014) [194] studied the effects of limestone powder on the compressive strength, sorptivity, carbonation resistance and resistance to chloride ion penetration of concrete. The OPC was replaced by LS in two proportions: 15 and 30%. The median particle size of both OPC and LS was 7.5 μm . However, the maximum particle size of OPC and LS was 30 μm and 100 μm , respectively. Three w/b ratios were adopted (0.42, 0.46 and 0.61). The dosage of cementitious materials in concrete was maintained between 250 to 400 kg/m^3 . Crushed limestone aggregates (max. size = 12.5 mm) and acrylic-based superplasticizer were used. After 24 hours of casting, demoulded samples were cured at 20 $^\circ\text{C}$ and 95% RH until the time of testing. For compressive strength (CS) test, 100 mm cube samples were cured for 1, 7, 28, 90 and 180 days. It was discovered that the compressive strength of the concrete increases with decrease in w/b ratio. The compressive strength of LS admixed concrete was lower w.r.t. control concrete with same w/b ratio and age of curing. However, the study done by Li and Kwan (2015) [195] found that at a constant w/b ratio and age of curing (7 and 28 days), the compressive strength of LS admixed concrete was higher as compared to control concrete. Similar results of compressive strength were observed in another

study, as well [196]. The increase in the strength was mainly due to the incorporation of finer LS particles which may have gone about as centre for precipitation of C-S-H gel. Another reason could be that the increase in the amount of LS and decrease in w/b ratio may have led to a reduction in bleeding of the concrete samples thus improving the ITZ around the surface of aggregates [197]. Lollini et al. (2014) also found out the sorptivity value of the cylindrical concrete specimens of 100 mm dia. and 50 mm height after 28 days of curing. It was observed that sorptivity value decreases with a drop in the w/b ratio and the binder content. However, the sorptivity value was found to be increasing with the rise in the replacement percentage of OPC by LS. Gesoglu et al. (2012) [196] observed that the incorporation of LS led to decrease in the sorptivity value of the concrete. It was mainly attributed to the improved pore structure of LS admixed concrete such that there was a decrease in the ingress of water through the pores of the gel matrix [198]. For evaluating the resistance to carbonation, 100 mm cubes were cast and cured for 1, 7 and 28 days by Lollini et al. (2014). These cured samples were then put in the carbonation chamber for ACC (20 °C temperature, 65% RH and 2% CO₂ concentration) for 28 days (1 and 7 days water cured samples) and 30 days (28 days water cured samples). The decrease in w/b ratio led to a reduction in the carbonation coefficient at a constant binder content. In general, it was observed that the increase in LS percentage led to an increase in the resistance to carbonation by accelerating the hydration reaction at early days of curing. The carbonation coefficient was found to be similar for concretes with similar strength. For observing the resistance to chloride ion penetration by RCPT, the concrete samples were cured for 28 days by the authors. The decrease in chloride diffusion coefficient was observed with decrease in w/b ratio at a particular replacement level of cement by LS. Similar results were obtained in the study by Li and Kwan (2015) [195]. It was attributed to smaller pore size at lower w/b ratio.

According to Lollini et al. (2014), chloride diffusion coefficient increases with increase in the ratio of LS in concrete while opposite was observed by Li and Kwan (2015) and Gesoglu et al. (2012). This harmful effect of LS on resistance of concrete to chloride ion penetration was because of C_3A present in LS admixed concrete which has a lower chloride ion binding capacity in comparison with C_3A present in control concrete.

2.3.7 Sugarcane Bagasse Ash

Bahurudeen et al. (2015) [199] perceived the effects of SBA on mechanical and durability properties of concrete. The raw SBA consisted of 2 types of particles: completely burnt particles (fine, rich in silica) and unburnt particles (fibrous, rich in unburnt carbon). The unburnt particles in SBA were removed by sieving through 300 μm sieve. They were then subjected to grinding to the fineness of cement (approximately 300 m^2/kg). The process adopted by the authors for preparation of SBA for its usage as an SCM can be seen in Figure 2.5. The processed SBA replaced OPC up to 25% in an equal interval of 5%. Polycarboxylic ether-based HRWR was used (dosage of 0.5% by weight of OPC). The total binder content and w/b ratio were kept constant at 360 kg/m^3 and 0.45, respectively. For compressive strength test, 150 mm cubes were cast and retained in the curing room for 3, 28 and 56 days. It was found that the compressive strength of admixed concrete (up to 10% replacement of OPC by SBA) was higher than the control concrete at all days of curing. Even though there was a reduction in the compressive strength at 15 and 20% replacement level, it was still higher than the compressive strength of control concrete. Similar results were found in another study, as well [200]. The compressive strength of control concrete and concrete with 25% SBA were identical. Beyond 25% replacement of cement by SBA, the compressive strength was lower w.r.t control concrete due to the dilution effect caused

by a decrease in the ratio of cement in the concrete. It was concluded that the same grade of concrete could be produced either by having 100% OPC or by replacing 25% OPC with SBA. This result was similar to the compressive strength of the concrete with 100% recycled aggregates in which up to 20% replacement of cement by SBA increased the compressive strength of admixed RAC [201]. For determining the resistance to chloride ion penetration through RCPT by Bahurudeen et al. (2015), cylindrical specimens of 100 mm dia. and 500 mm height were cast and cured for 28 and 56 days. These concrete samples were then subjected to various techniques of preconditioning until the time of testing as per ASTM C1202 [114]. It was perceived that the inclusion of SBA in the concrete increases its resistance to chloride-ion penetration at 28 days as well as at 56 days of curing. Similar results were obtained for SBA admixed concrete [200] as well as SBA admixed concrete with 100% recycled aggregates [201]. Finer SBA particles reduce the dimension, distribution and structure of pores. Due to the higher fineness of SBA, larger pores are divided into many smaller pores, thus increasing the nucleation sites for precipitation of C-S-H (formed due to pozzolanic action of SBA). For determining the water sorptivity value, 150 mm cubes were cast and cured for 56 days. After curing, the samples were conditioned and set up as per ASTM C1585 [202]. Lower sorptivity value of the concrete with 5% SBA was observed as compared to the control concrete. However, the sorptivity value was higher for concrete with 15% and 25% SBA w.r.t the control concrete. This contrary behaviour of SBA admixed concrete as compared to the general notion (inclusion of SCMs decreases the sorptivity value due to the filling of pores through pozzolanic action) was because of surface features of the admixed concrete. The surface characteristics of the concrete influence its sorptivity value more as compared to its permeability [203], [204]. For water penetration depth test, 150 mm cubes were cast and cured for 28 and

56 days. It was found that with the increase in the proportion of SBA in the concrete, there was reduction in the depth of water penetration in concrete.

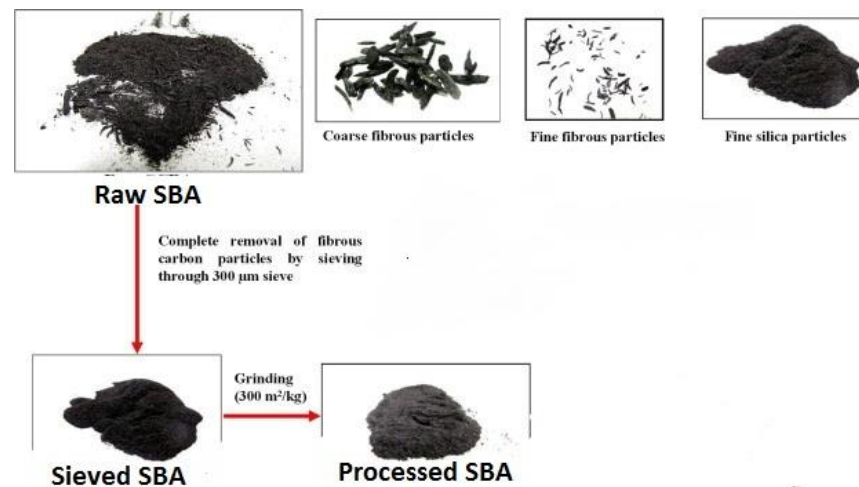


Figure 2.5 Processing of SBA for its usage as an SCM [199]

Moretti et al. (2016) [205] studied the use of SBA as a filler in concrete. The effect of replacing the 30% normal quartz sand with SBA sand on the carbonation depth of concrete (accelerated carbonation curing for 56 and 112 days) was analysed. SBA sand is produced during burning of sugarcane bagasse in boilers at high temperatures and is also known as bottom ash. It was observed by the authors that the carbonation depth was higher in concrete with 30% SBA sand w.r.t control concrete after 56 days of ACC. However, it was similar for both the concrete after 112 days of ACC. The increase in the carbonation depth was due to lower alkalinity of the SBA sand, which in turn reduces the overall alkalinity of the concrete, thereby accelerating the carbonation process [206].

Arif et al. (2017) [207] studied the use of SBA as a sand replacement in concrete. The effect of replacing the normal quartz sand (up to 20% in equal intervals of 5%) with SBA sand on the concrete subjected to the acidic environment was analysed. The concrete samples were cured in water for 28 days before being subjected to 1%

H₂SO₄ solution for 28 days and 145 days. It was found that the incorporation of 15% and 20% SBA sand decreased the compressive strength of concrete on being exposed to the acidic solution for 28 days. However, the compressive strength of 5% and 10% SBA sand concrete after 28 days of acidic exposure was higher than the compressive strength of respective concretes after 0 days of exposure. The improvement in acid resistance of concrete with 15% and 20% SBA sand was because of lower permeability due to the filling of pores by SBA sand particles [208], [209].

2.3.8 Nanosilica

Isfahani et al. (2016) [116] studied the effects of NS (0.5, 1 and 1.5% by weight of cement) on mechanical and durability properties of concrete with different w/b ratios (0.5, 0.55 and 0.6). The mean size of the NS particles was 20 nm. The different dosage of superplasticizer for concretes with different w/b ratios were fixed at 1.8 to 5.5 kg/m³, 2.4 kg/m³ and 1.5 kg/m³ respectively. For compressive strength, 100 mm cubes were cast and moist cured for 7 and 28 days. Higher compressive strength was observed for concrete with NS w.r.t. control concrete at 7 days of curing. The increase in the strength was less pronounced at 28 days of curing as compared to 7 days because NS accelerates the hydration of cement leading to formation of larger amounts of Ca(OH)₂ at the early age of curing. The pozzolanic action by NS leads to the consumption of Ca(OH)₂ and formation of additional C-S-H gel thereby increasing the strength of the concrete at early days of curing. A similar result was also found in study by Ghafari et al. (2014) [210]. The NS particles have a surface that is highly reactive, which increases the hydration rate of the C₃S phase [119], [211]. It confirms that the pozzolanic action by NS happens at early days of curing [126], [212], [213]. The enhancement of strength at 28 days of curing was mainly due to the filler effect of NS particles [214]. Also, the

strength enhancement due to NS was higher when w/b ratio of 0.65 was adopted, followed by 0.55 and 0.45. For water sorptivity and carbonation resistance test, slabs with dimensions 500 x 395 x 60 mm were cast and cured for 28 days. After 28 days of curing, cylindrical specimens of 100 mm dia. were cored from the slabs and tested. No change in water sorptivity value was observed by Isfahani et al. (2016) for NS admixed concrete (1% and 1.5%) as compared to the control concrete at w/b ratio of 0.65. However, a slight increase was observed at w/b ratio of 0.5. A considerable decrease in the water sorptivity value was observed at w/b ratio of 0.55. The decrease was due to infilling of larger pores by finer NS particles. It was because of formation secondary C-S-H gel which divided the larger pores into smaller pores thereby improving the overall pore structure of concrete and decreasing the connectivity between pores. Ghafari et al. (2014) [210] and Du et al. (2014) [215] also observed the similar effects of NS on sorptivity value of concrete. Improvement in resistance to chloride penetration as compared to the control concrete was observed for 0.5%, 1% and 1.5% NS admixed concrete at w/b ratios of 0.55, 0.55 and 0.5 respectively. The ingress of chloride ions was lower because of reduction in the pore sizes of the admixed concrete [214]. The resistance to chloride penetration of NS concrete (0.5% and 1.5% NS) at w/b ratio of 0.65 was similar to that of the control concrete. However, the same was found to be more than the control concrete at 1% NS content. For carbonation resistance test, cylindrical samples (after pre-conditioning) were put in the carbonation chamber set at 4% carbon dioxide concentration, 20 °C temperature and 50-60% RH for 45 and 135 days. The carbonation depth was measured by the phenolphthalein indicator. It was found that the NS concrete showed lower resistance to carbonation as compared to the control concrete at w/b ratio of 0.65. Meanwhile, at w/b ratio of 0.5, the resistance was similar to that of the control concrete. However, at w/b ratio of 0.55, addition of NS

considerably improved the resistance to carbonation. It was due to the stabilizing effect of NS particles on the calcium ions of C-S-H gel [151]. It was concluded by Isfahani et al. (2016) that no reliable pattern was observed for the adequacy of NS on durability properties of concrete with different w/b ratios.

2.3.9 Microsilica

Jalal et al. (2012) [216] compared the effects of microsilica (MS) and nanosilica (NS) on the mechanical and durability properties of high performance self-compacting concrete (HPSCC). The OPC in concrete was replaced by MS, NS and their composite by weight in the ratio of 10%, 2% and 10 + 2% respectively. Three different proportion of binder content (400, 450 and 500 kg/m³) was used, and w/b ratio was kept constant at 0.38. A polycarboxylic based superplasticizer was also used in the ratio varying between 1.06 and 1.08. The specific surface area of OPC, MS and NS were 0.326, 2.11 and 165 ± 17 m²/g respectively. For compressive strength test, 150 mm cubes were cast and were cured in water until the time of testing. The compressive strength of concrete with NS, MS and combination of both was higher w.r.t control concrete as found in other studies as well [217]–[220]. The improvement in compressive strength of concrete by incorporation of NS was more as compared to the MS. Meanwhile, the improvement in compressive strength was more pronounced at higher binder content. The rapid formation of Ca(OH)₂ takes place because of acceleration in hydration reaction by MS and NS particles. Due to pozzolanic action of MS and NS, Ca(OH)₂ (formed on the surface of aggregates) is transformed into C-S-H gel, thus improving pore structure as well as the structure of ITZ. It was the main reason behind the increase in the compressive strength of the NS and MS admixed concrete. For the water absorption test and water sorptivity test, 100 mm cubes were cast and cured in water until the time of

testing. After curing, the samples were kept inside the oven at 45 °C for 14 days until the constant weight was achieved. For calculating the water absorption, the samples were completely submerged in water, and the change in weight was calculated after 30 min, 1, 24, 72 and 168 hours. It was found that incorporation of MS and NS decreases the water absorption of the concrete as compared to the control concrete by 31, 26, 34% and 35, 28, 32% respectively for total binder content of 400, 450 and 500 kg/m³ after 30 min. The improvement in water absorption was found to be more in 2% NS concrete as compared to 10% MS concrete at total binder content of 400 and 450 kg/m³ while 10% MS concrete performed better at 500 kg/m³ total binder content. It was because the replacement of cement by 10% MS decreases the amount of cement in concrete with lower binder content; thus, the dilution effect was dominant. However, at higher binder content (500 kg/m³), filler and pozzolanic effect of MS was more dominant as compared to the dilution effect. Similar results were observed in another study, as well [217]. For calculating the sorptivity value, the samples were kept on porcelain rods under water in a manner that only 5 mm of the sample was immersed. Also, all the surfaces were coated with epoxy resin (except the surface exposed to water) to allow for unidirectional flow of water from the bottom surface only for 3, 6, 24 and 72 hours. Unlike water absorption test, MS and NS admixed concrete had similar height of water absorption through capillary action. The increase in the height of capillary water absorbed was observed at early times (3 hours) for both MS and NS concrete w.r.t. control concrete. It was due to the fact they were dried in an oven beforehand. However, at longer times, the particles of MS and NS were found to be effective in decreasing the height of capillary water absorbed. For determining the chloride ion penetration depth after a curing period of 90 days, 150 mm concrete cubes were immersed in 3% NaCl solution for another 90 days. After 90 days immersion period in

NaCl solution, the samples were kept in the oven for another day for drying. The pulverized samples were obtained from the cubes at the height of 0-5, 5-10, 10-15, 15-20 and 20-30 mm from the surface and were tested further for their chloride content as per ASTM C114 [221]. It was found that admixing of both MS and NS reduces the ingress of chloride ions into the concrete. However, 10% MS was found to be more effective as compared to 2% NS. It was observed that the concrete with a total binder content of 500 kg/m³ with NS or MS had the highest resistance to chloride-ion penetration as compared to the other binder content.

Liu et al. (2017) [218] studied the effects of the acidic environment on microsilica admixed concrete. The OPC was replaced by MS in the percentage of 5, 10 and 15% by weight. The w/b ratio was kept constant at 0.4 and polycarboxylate based SP was used in varying proportions. 100 mm cubes were cast and cured for 28 days at 22 °C temperature and 95% RH. After curing, these samples were immersed in 2 acidic solutions: 5% H₂SO₄ solution and 5% acetic acid (CH₃COOH) solution for a period of 7, 14 and 28 days. The effects of the acidic environment on various concrete were studied by comparing the loss of compressive strength and loss of mass before and after the acidic immersion. There was considerable loss of compressive strength due to the immersion of concrete in both the acidic solutions, which further increased with the increase in the duration of immersion. However, the lower loss of compressive strength was observed due to the incorporation of 5% MS in the concrete w.r.t. the control concrete. However, the loss of compressive strength was found to be increasing with an increase in the MS content with maximum loss in 15% MS. Even the maximum loss of compressive strength in the concrete with MS was found to be lower than the control concrete. A similar trend of loss of compressive strength was observed in both the acidic solutions but the acetic acid solution was more detrimental to concrete as

compared to the sulphuric acid solution. In terms of loss of mass, the resistance of concrete to sulphuric acid solution improved with the increase in the amount of MS. The loss of mass and compressive strength of concrete in H_2SO_4 solution was mainly due to the formation of gypsum and ettringite, which are expansive in nature. In the acetic acid solution, the main by-product is $Ca(CH_3COO)_2$, which is much more soluble in water as compared to gypsum. It causes the hydration products to leach out, which in turn leads to the larger size of pores and collapse of the ITZ.

Massana et al. (2018) [217] compared the effects of microsilica (MS) and nanosilica (NS) on the carbonation of high performance self-compacting concrete (HPSCC). The usage of MS and NS was not as a cement replacement material but as additional cementitious material in the dosage of 2.5, 5 and 7.5% by weight of cement. The w/b ratio and the cement content were fixed at 0.36 and 450 kg/m^3 , respectively. The cylindrical concrete samples of 100 mm dia. and 200 mm height were cast and cured for 28 days in a curing chamber with $RH > 95\%$. After curing, the samples were transferred to the carbonation chamber for another 200 days with temperature, RH and CO_2 concentration fixed at $20 \pm 2 \text{ }^\circ\text{C}$, $75 \pm 5\%$ and $4.7 \pm 2.5\%$ respectively. Such was the positive impact of NS and MS on the pore structure and interconnectivity between the capillary pores of HPSCC that none of the concrete showed carbonation (Figure 2.6). Similar observations were made by Mohammed et al. (2014) [222] after accelerated carbonation curing of MS admixed HPSCC.

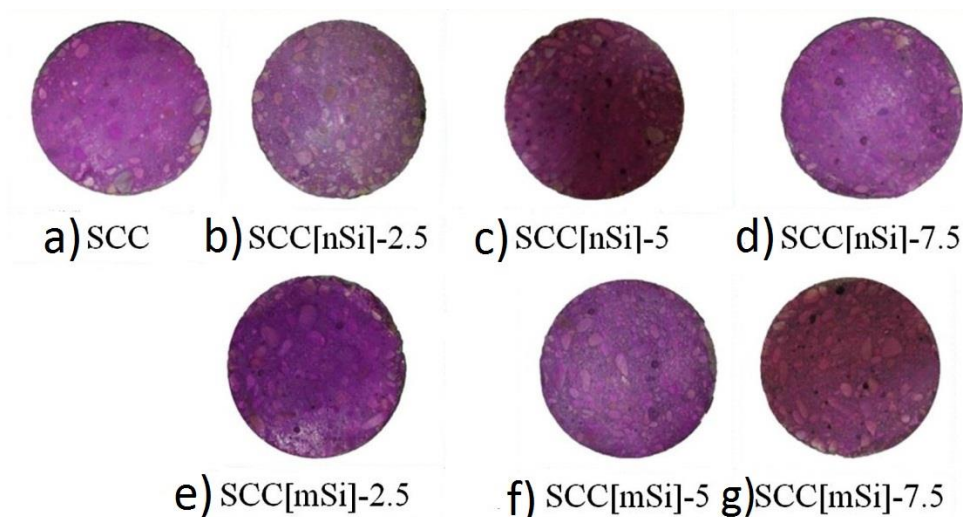


Figure 2.6 Carbonation of concrete (after 200 days) with (a) 100% OPC (b) 2.5% NS (c) 5% NS (d) 7.5% NS (e) 2.5% MS (f) 5% MS (g) 7.5% MS [217]

2.3.10 Rice Straw Ash

Munshi et al. (2019) [223] analysed the usage of 5% rice straw ash (RSA) in concrete for the construction of single-storey building having 3 rooms of size 4 x 5 m each. Rice straw was burnt in the open environment. The ash was then pulverized until 95% of it was able to pass through 90 μm sieve. The w/b ratio was kept constant at 0.6, and the ratio between binder, sand and coarse aggregate (CA) was 1: 1.5: 3. 150 mm cubes were cast and cured in water for 7, 14, 28 days. It was observed that the compressive strength of concrete increases with the incorporation of 5% RSA w.r.t. control concrete at all ages of curing. The increase in compressive strength was mainly attributed to the finer size and high silica content of RSA particles. However, the decrease in compressive strength due to the admixing of RSA was observed in the study by Singh et al. (2019) [224]. After 28 days of construction of the building, non-destructive tests like Rebound hammer test and UPV test were performed on the walls and beams of the building. In both the tests, similar values were observed for RSA admixed concrete and control concrete. Therefore the authors concluded that 5% RSA admixed concrete could be used for the construction of buildings of small size.

2.4 CHAPTER SUMMARY

The literature review depicted that the incorporation of various SCMs improves the physical, mechanical and durability properties of cement paste, mortar and concrete. The ratio of improvement generally depends on numerous factors like silica content, particle size and shape, pozzolanic action etc. The impact of the addition of different SCMs on the properties of cement paste/mortar and cement concrete as detailed by other researchers has been compiled in Table 2.1.

Most of the mineral admixtures improved the mechanical and durability properties of mortar and concrete when compared with the control concrete. The improvement in the properties of concrete at later age of curing was more profound w.r.t early age of curing in some these mineral admixtures. It was due to their inert behaviour. The particles of these types of mineral admixtures were found to be coarser than the others even though they had a higher specific surface area (which is generally associated with the finer particles). It shows the porous nature of these particles. These types of particles tend to absorb some amount of water in their pores while mixing. During later days, when the amount of water decreases in the hydrated cement paste, the water absorbed by the pores is released back for the continuation of hydration and pozzolanic reaction thereby improving the properties of the concrete at later ages. In short, it can be said that the packing effect by particles of inert SCMs is more effective on properties of concrete at an early age while pozzolanic action of SCMs is more effective at later days. The main factors which generally govern the effects of mineral admixtures on the properties of mortar or concrete are (1) acceleration of cement hydration (2) filler effect (3) dilution effect and (4) pozzolanic action.

The fineness of particle size of the SCM plays a significant role in the mechanical and durability properties of mortar/concrete. These SCMs increase the hydration of cement by their nucleation site effect. Due to their finer particle size, they divide larger pores into smaller pores, thus providing additional nucleation sites for precipitation of hydration products. It increases the density of the pore structure and decreases the permeability of the mortar/concrete. The packing density of the mortar/concrete is also improved by the filler effect of various SCMs. Their particles fill in the gaps between the comparatively coarser cement particles. These finer particles also decrease the w/b ratio at the ITZ around aggregate and bring it at par with the rest of the hardened cement paste.

Many researchers reported progressive improvement in various properties with an increase in the ratio of mineral admixture in concrete. However, after the optimum level of replacement of cement by SCMs, the mechanical and durability properties of the admixed mortar/concrete started degrading with further replacement due to their dilution effect. The substitution of cement is also called a dilution effect. When there is a rise in the amount of cement replacement by various SCMs, C_3A content (which is associated with the cement content) and the formation of $Ca(OH)_2$ decreases. The reduction in the $Ca(OH)_2$ content effects the pozzolanic action of mineral admixtures.

In hydration of cement, C_3S and C_2S react with water to form hydration products: C-S-H and $Ca(OH)_2$. C-S-H is responsible for increasing the strength and consecutively decreasing the permeability of concrete. $Ca(OH)_2$ is highly soluble in water; therefore, the contact between the two leads to an increase in the porosity of concrete. When SCMs are used with the cement, the consumption of $Ca(OH)_2$ takes place by their pozzolanic action (reaction between SiO_2 and calcium hydroxide) leading

to the formation of secondary C-S-H gel. The secondary C-S-H gel leads to the formation of a denser microstructure of concrete.

It was found in the literature review that RSA may have similar or different consequences on the properties of mortar/concrete when compared with the different SCMs. Few authors studied the effects of RSA on the compressive strength of mortar and concrete. However, the effect of RSA on durability properties of concrete was not assessed by researchers. Therefore the effects of RSA on various properties of cement paste, mortar and concrete were considered in the present investigation.

Table 2.1 Effect of various SCMs on cement paste, mortar and concrete (contd.)

SCMs	Properties Studied	References	Tendency w.r.t. Control	Additional Remarks	
Fly Ash (FA)	Paste	Normal Consistency	[47]	Increase ^a	a) High amount of unburnt carbon b) Initial setting time was equal to control paste while final setting time decreases for 5% replacement only c) Higher strength as compared to control mortar for only 1 day of curing of UFFA & “Class N” FA admixed mortar & performance of UFFA was better than Class N FA d) Higher strength only when FA of Blaine’s fineness = 0.52 m ² /g was used e) Higher strength only when UFFA of Blaine’s fineness = 2.51 m ² /g was used f) (10% UFFA + 20/30/40/50% FA) admixed concretes→28 days curing→3% H ₂ SO ₄ as well as 1.5% HNO ₃ immersion for 7, 14, 28, 56, 90 days g) H ₂ SO ₄ immersion – lower CS loss of (10% UFFA + 20% FA) for 56 & 90 days, (10% UFFA + 30% FA) for 28, 56 & 90 days, (10% UFFA + 40%/50% FA) for 90 days & lower mass loss of every sample h) HNO ₃ immersion – lower CS loss of (10% UFFA + 20%/30% FA) for 28, 56 & 90 days & lower mass loss of every sample i) Higher CS loss of other samples after immersion in both acidic solutions j) 28 days curing→ up to 365 days ACC→ compressive strength as well as carbonation depth k) Lower sorptivity value only for FA admixed concrete (40%) at 28 days of curing
			[45], [48]	Decrease	
		Setting Time	[47], [45] ^b , [48], [49]	Increase	
	Mortar	Compressive Strength	[48], [50]	Decrease	
		Compressive Strength	[47], [45], [49], [50], [44] ^c	Decrease	
	Modulus of Toughness & Chloride Migration	[44]			
	Concrete	Compressive Strength	[146] ^d , [160] ^e , [159]	Decrease	
		Acidic Immersion	[150] ^f	Decrease ^{g, h, i}	
		Carbonation	[153]	Increase ^j	
		Porosity	[154]	Decrease	
		Water Sorptivity	[160] ^k , [159] ^k , [198]	Increase	
		[154]	Decrease		
Chloride Permeability	[160], [159], [154], [161]	Decrease			
Ground Granulated Blast Furnace Slag (GGBFS)	Paste	Normal Consistency	[53]	Increase ^a	
			[54]	Decrease	
		Setting Time	[53], [52], [54],	Increase	
	Mortar	Compressive Strength	[53]	Decrease	
	Concrete	Compressive Strength	[51], [162], [163], [165] ^b , [167] ^c	Increase	
			[165], [55] ^d , [166] ^e	Decrease	
		Acidic Immersion	[165] ^f , [167] ^g	Decrease	
		Carbonation	[163]	Increase ^h	
		Water Absorption	[165]	Decrease	
		Water Sorptivity	[165], [166] ⁱ		
Chloride Permeability	[163], [165], [166], [167]				
Metakaolin (MK)	Paste	Compressive Strength	[62]	Increase	
		Porosity & Water Absorption	[62]	Decrease	
	Mortar	Compressive Strength	[61] ^a	Increase	
		Carbonation	[181] ^b		
	Concrete	Compressive Strength	[57], [58], [59], [60] ^c , [111], [170], [173], [176] ^d	Increase	
		Acidic Immersion	[170] ^e	Decrease ^f	
				Increase ^g	
		Carbonation	[176] ^h	Increase	
		Porosity	[57], [58], [176]	Decrease	
		Water Absorption	[57], [111], [170], [173]		
Water Sorptivity	[58], [111], [170], [173]				
Chloride Permeability	[59], [111], [170], [173], [176]				

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Table 2.1 Effect of various SCMs on cement paste, mortar and concrete (contd.)

SCMs	Properties Studied	References	Tendency w.r.t. Control	Additional Remarks	
Rice Husk Ash (RHA)	Paste	Normal Consistency & Setting Time	[71], [184] ^a	Increase	a) Final setting time decreases b) Lower strength when replacement of cement by RHA was more than 30%
	Mortar	Compressive Strength	[79], [184] ^b , [186]	Increase	c) Lower strength because of coarser RHA particles d) Lower strength for Uruguay RHA (20% replacement) & USA RHA (10, 20% replacement) at 7, 28 days of curing (w/b = 0.32, 0.40)
		Electrical Resistivity & UPV Test	[79]		
		Water Absorption	[79], [186]	Decrease	e) At w/b = 0.50, lower strength for 7, 28, 91 days cured Uruguay RHA (10% replacement) concrete and for 7 days cured USA RHA (10, 20% replacement) concrete
		Chloride Permeability	[79]		
	Concrete	Compressive Strength	[64] ^c , [73]	Decrease	f) Lower strength for 7 days cured concretes (RHA mean particle size = 95 μm)
			[65] ^{d,e} , [66], [67] ^{f,g} , [68] ^h , [69] ⁱ , [70] ^j , [72], [75], [76] ⁱ , [80] ^k , [81], [82], [183] ^{l,m} , [184] ^b , [185]		Increase
		Flexural & Split Tensile Strength	[66], [183] ^l , [184], [185]	Increase	
		Acidic Immersion	[68] ⁿ	Decrease	k) Lower strength when unprocessed (natural) RHA was used
		Water Absorption	[67] ^o , [70], [73] ^p , [80], [184] ^q , [185]	Decrease	l) Lower strength when ≥ 10% RHA was used at w/b = 0.45 m) Lower strength when ≥ 15% RHA (w/b = 0.55) & ≥ 20% RHA (w/b = 0.45) was used
			[68] ^r , [72] ^s , [183]		Increase
		Water Sorptivity	[67] ^o , [70], [72], [183] ^t , [184]	Decrease	o) Higher water absorption/sorptivity value for admixed concretes (RHA mean particle size = 95 μm) at 7, 28 days of curing
Porosity		[68] ^r	Increase	p) Higher water absorption when replacement % of cement by RHA > 20%	
Chloride Permeability	[68], [70], [72], [82], [184], [185]	Decrease	q) Higher water absorption for all the concretes cured for 28 days		
			r) Lower water absorption/porosity for M30 & M60 grade RHA (10% & 15% respectively) concrete (with SP)		
Wollastonite	Paste	Normal Consistency	[22], [85]	Increase	a) Higher strength when wollastonite was used as a sand replacement material
		Setting Time	[22]		b) Higher strength for samples at only 2 days of curing when wollastonite was used as a cement replacement material
	Mortar	Compressive Strength	[22], [85] ^{a,b} , [86]	Decrease	c) Higher strength only when replacement of cement by 12% wollastonite (by volume)
		Flexural Strength	[85] ^a		d) Lower strength at 20 & 25% replacement of cement by wollastonite
		Drying Shrinkage	[85]		e) Higher strength only when wollastonite was used with 50% natural coarse aggregate replacement by ceramic waste aggregate and lower strength when wollastonite was used with 100% natural coarse aggregate
	Concrete	Compressive Strength	[87] ^c , [187] ^d , [188], [190] ^e , [191] ^f	Increase	f) Lower strength/water absorption for 20% (w/b = 0.55) & 25% (w/b = 0.45, 0.55) replacement of cement by wollastonite
			[187] ^d , [188], [190], [191] ^f		
		Acidic Immersion	[190] ^g	Decrease	g) 28 days curing → 5% H ₂ SO ₄ immersion for 28 days → mass & compressive strength loss
		Carbonation	[187] ^{h,i} , [191] ^{h,i}		h) 28 days curing → 90 days ACC → carbonation depth
		Water Absorption	[84], [187], [188], [190], [191] ^f		i) Higher carbonation depth/chloride permeability in concrete with 20 & 25% replacement of cement by wollastonite
		Porosity	[187] ^j , [191] ^k		j) Higher porosity for concrete with 20 & 25% replacement of cement by wollastonite at w/b = 0.50
	Chloride Permeability	[84], [187] ⁱ , [191] ⁱ		k) Higher porosity for concrete with 15, 20 & 25% replacement of cement by wollastonite	

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Table 2.1 Effect of various SCMs on cement paste, mortar and concrete (contd.)

SCMs	Properties Studied	References	Tendency w.r.t. Control	Additional Remarks	
Limestone Powder (LS)	Paste	Normal Consistency	[93]	Increase	a) Higher water demand when cement having low C ₃ S content and fineness value of 2%, was used b) Lower calcium hydroxide content at 28 days of curing of cement paste with 15% LS c) Higher strength at all ages of curing only when high early strength cement was used. When general use cement was used, similar strength (w.r.t. control mortar) was observed at 12 and 16 hours of curing while the strength was lower after 7 days curing d) Lower strength at later days (≥ 28 days) of curing e) Lower strength at 90 days of curing of concrete with 5% LS f) 28 days curing \rightarrow 1% H ₂ SO ₄ as well as 1% HCl immersion for 18 weeks \rightarrow mass loss g) 1, 7, 28 days curing \rightarrow 28, 30 days ACC \rightarrow carbonation coefficient h) In all concrete samples (control or admixed), carbonation coefficient was higher with increase in curing time
			[94] ^a , [95]	Decrease	
		Heat of Hydration	[93]	Increase	
		Ca(OH) ₂ Content	[93] ^b		
	Mortar	Compressive Strength	[90], [93], [94], [95]	Decrease	
			[96]	Increase	
	Concrete	Compressive Strength	[93] ^c , [94] ^d	Increase	
			[194]	Decrease	
			[197], [196] ^e , [195], [198]	Increase	
		Split Tensile Strength	[196], [195]	Increase	
		Acidic Immersion	[193] ^f	Decrease	
		Carbonation	[194] ^{g, h}	Increase	
	Water Sorptivity	[194], [196], [195], [198]	Decrease		
		[194]	Increase		
	Chloride Permeability	[196], [195]	Decrease		
Sugarcane Bagasse Ash (SBA)	Paste	Normal Consistency & Setting Time	[100]	Increase	a) Lower strength when replacement of cement by SBA > 20% b) Lower strength for all the concretes at 3, 7, 14, 28 days of curing c) Lower strength when SBA was used as a sand replacement material (100% replacement) d) Higher strength for samples after 14, 28 days of curing [when grounded SBA (240 minutes) was used] e) Higher value for mortars with 10% SBA after 180 days of curing f) Lower value for mortars with 10% SBA after 14 days of curing g) Lower strength when replacement of cement by SBA > 20% at 14, 28, 90 days of curing however 7 days strength was higher than control even at 30% replacement of cement by SBA h) Lower strength for concrete with 25% SBA at 7 days of curing & with 35, 45% SBA at all days of curing i) Lower strength for concrete with 15, 20% SBA at 7, 28, 90 days of curing while at 180 days, the strength was similar to control concrete j) Lower strength for concrete with 25% SBA at all days of curing k) Lower strength for concrete with 30% SBA at 7 days of curing l) Lower strength was because of 100% usage of Reclaimed Asphalt Pavement (RAP) aggregate m) Lower strength was because of 100% usage of Recycled Coarse Aggregate (RCA) n) Higher strength of all the concrete after 91 days of curing o) 28 days curing \rightarrow 1% H ₂ SO ₄ immersion for 28, 145 days \rightarrow compressive strength loss & mass loss p) Higher CS loss for concretes with 5, 10% SBA exposed for 145 days to acidic solution q) 28 days curing \rightarrow 56, 112 days ACC \rightarrow carbonation depth r) Higher water absorption for all the concrete after 28 days of curing & for concrete with 30% SBA after 90 days of curing s) Higher water absorption for concrete with 20, 30% SBA at all days of curing t) Higher sorptivity value for concrete with 15, 25% SBA at all days of curing u) Higher sorptivity value for concrete with 50% SBA at all days of curing
	Mortar	Compressive Strength	[100] ^a , [103] ^b , [206] ^c	Increase	
			[104] ^d	Decrease	
		UPV Test	[103] ^e	Decrease	
		Chloride Permeability	[103]		
	Electrical Resistivity	[103] ^f	Increase		
	Concrete	Compressive Strength	[100] ^{a, g} , [102] ^h , [105], [106] ⁱ , [199] ^j , [200] ^k , [207]	Increase	
			[21] ^l , [201] ^m , [205] ⁿ	Decrease	
		Split Tensile Strength	[100] ^a , [102] ^h , [206]	Increase	
			[21] ^l	Decrease	
		Flexural Strength	[21] ^l	Decrease	
		Acidic Immersion	[207] ^{o, p}		
		Carbonation	[205] ^q	Increase	
		Water Absorption	[100] ^r , [21], [105], [199], [200] ^s , [205], [206]	Decrease	
Water Sorptivity	[100], [199] ^t , [201] ^u				
Chloride Permeability	[100], [106], [199], [200], [201]				

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Table 2.1 Effect of various SCMs on cement paste, mortar and concrete

SCMs	Properties Studied	References	Tendency w.r.t. Control	Additional Remarks	
Nanosilica (NS)	Paste	Normal Consistency	[120]	Decrease	a) Higher setting time when cement was replaced by 3% NS (without SP) & by 10% NS (with SP) b) Lower strength of mortar with 5% NS at 84 days of curing c) Lower strength of mortar with 1 & 3% NS at 3, 7, 28, 56 days of curing d) Lower strength of all the concrete at 1 & 3 days of curing e) Lower strength of concrete with 3% NS at all days of curing f) 28 days curing→45, 135 days ACC→ carbonation coefficient g) Higher carbonation coefficient of concrete with 1 & 1.5% NS at w/b = 0.65 h) Higher sorptivity value of concrete with 0.5 & 1.5% NS at w/b = 0.5 & with 1.5% NS at w/b = 0.65 i) Higher sorptivity value for concrete with 1% NS at w/b = 0.5 & 0.65
			[121], [211]	Increase	
		Setting Time	[117], [120], [121] ^a , [211], [212], [213]	Decrease	
		Compressive Strength	[120], [213]	Increase	
	Mortar	Compressive Strength	[118] ^b , [121] ^c , [125], [126], [132], [133], [211]	Increase	
	Concrete	Compressive Strength	[116], [127], [151], [210], [214] ^d , [215], [216], [217]	Increase	
		Flexural Strength	[127] ^e , [128], [132], [151]		
		Split Tensile Strength	[214], [216]		
		Carbonation	[116] ^{f, g}	Decrease	
		Water Absorption	[210], [215], [216]		
Water Sorptivity		[116] ^h , [210], [215], [216], [217]			
Chloride Permeability	[116] ⁱ , [214], [215], [216]				
Microsilica (MS)	Paste	Normal Consistency	[120]	Increase	
		Setting Time	[120], [212] ^a		
		Compressive Strength	[120] ^b , [136]		
	Mortar	Compressive Strength	[125], [126], [133], [136], [137] ^c ,	Increase	
		Flow Value	[137]	Decrease	
		Sulphate Expansion	[137] ^d		
		Porosity	[138]		
	Concrete	Compressive Strength	[134], [135], [136], [138], [216], [217] ^e , [218]	Increase	
		Split Tensile Strength	[134], [216] ^f , [219]		
		Flexural Strength	[136]	Decrease	
		Acidic Immersion	[218] ^g		
		Carbonation	[217] ^{e, h}	No change	
			[222] ⁱ	Decrease	
Water Absorption		[216]	Decrease		
Water Sorptivity	[216], [217] ^e				
Chloride Permeability	[134], [216]				
Rice Straw Ash (RSA)	Paste	Normal Consistency	[34], [31]	Increase	
		Setting Time	[144], [31], [224]		
	Mortar	Compressive Strength	[34] ^a , [144] ^a , [145], [223] ^b	Increase	
		Flexural Strength	[34] ^a		
		Rebound Hammer Test	[223]	Decrease	
		UPV Test	[223]		
		Workability	[34] ^c , [145] ^d		
		Water Permeability	[34] ^e		
	Concrete	Compressive Strength	[223]	Increase	
		Rebound Hammer & UPV Test	[223]	Decrease	