CHAPTER 6 STUDY ON DURABILITY PROPERTIES OF CONCRETE

6.1 GENERAL

Concrete durability is a critical aspect of its performance and longevity. The durability of concrete is related to its resistance to various environmental factors such as water permeability, carbonation, and acid attack. Concrete is a porous material that can allow water to penetrate through it and reach the steel reinforcement, which can cause corrosion. Corrosion of steel reinforcement can lead to cracking and spalling of concrete, reducing its structural integrity.

Carbonation is another major factor that can affect concrete durability. Carbon dioxide in the air can react with the alkaline components in the concrete and reduce its pH, which can accelerate the corrosion of steel reinforcement. Acid attack is another common problem that can affect concrete durability. Acids from various sources, such as industrial processes, can penetrate the concrete and cause chemical reactions that weaken the structure of the concrete.

In addition to the above factors, the durability of concrete can also be affected by the quality of the concrete mix, the curing process, and the presence of mineral admixtures and/or chemical admixtures. The use of mineral admixtures, such as GGBS, MS and FA, can enhance the durability of concrete by reducing water permeability and increasing its resistance to chemical attacks. Chemical admixtures, such as superplasticizers, can improve the workability and flowability of the fresh concrete mixture, leading to a more homogenous and compacted concrete structure, which can also improve its durability.

Overall, ensuring the durability of concrete is essential for its longevity and the safety of structures built with it. By considering factors such as water permeability, carbonation, and acid attacks, and by using appropriate admixtures, it is possible to improve the durability of concrete and extend the lifespan of structures built with it.

6.2 WATER PERMEABILITY

Primarily, concrete durability is measured in terms of its resistance to water permeability. In the past, the water absorption capacity of concrete has been measured in many ways, such as water sorptivity test (water absorption by capillary action), saturated water absorption test (water absorption by complete immersion), etc. In this study, the coefficient of permeability ('k') of concrete (given in Table 6.1 and shown in Figure 6.1 & Figure 6.2) was determined as per the procedure laid out in specification IS 3085 [257].

6.2.1 Effect of w/b

Concrete permeability is an important property that affects the durability and service life of concrete structures. The permeability of concrete is influenced by several factors, including the water to binder ratio (w/b). The effect of w/b ratio on concrete permeability was investigated by conducting permeability tests on different concrete mixtures with varying w/b ratios. The results showed that as the w/b ratio increased, the permeability of concrete increased as well.

For instance, when comparing the permeability coefficient of C40 concrete at 28 days with that of C45, C50, and C55 concrete, it was found that the permeability coefficient increased by approximately 15.7% for C45, 32% for C50, and 51.3% for C55. Similarly, for the CF group, the permeability coefficient increased by 14% for CF45, 28.9% for CF50, and 45% for CF55 compared to CF40. Furthermore, the permeability coefficient of concrete samples in the CB, CM, SC, SCF, SCB, and SCM groups also showed a similar trend of increasing with an increase in w/b ratio. The increase in permeability coefficient ranged from 18% to 56% for CB45 to CB55, 18% to 59% for CM45 to CM55, 13% to 45% for SC45 to SC55, 14% to 50% for SCF45 to SCF55, 19% to 64% for SCB45 to SCB55, and 14% to 48% for SCM45 to SCM55 as given in Table 6.1 and shown in Figure 6.1 and Figure 6.2.

Table 6.1 Coefficient of permeability of different concrete mix at 28 and 90 days curing

W/B	Concrete mix	Coefficient of permeability 10^{-8} cm/s		Concrete mix	Coefficient of permeability 10^{-8} cm/s	
		28 Days	90 days		28 Days	90 days
0.4	C40	11.21	7.98	SC40	7.02	5.35
0.45	C45	12.97	11.22	SC45	7.97	7.06
0.5	C50	14.8	12.98	SC50	8.9	8.02
0.55	C55	16.96	14.86	SC55	10.18	9.15
0.4	CF40	13.89	7.23	SCF40	7.85	5.88
0.45	CF45	15.83	10.8	SCF45	9.01	7.88
0.5	CF50	17.9	12.6	SCF50	10.25	9.02
0.55	CF55	20.14	14.48	SCF55	11.75	10.32
0.4	CB40	14.23	9.8	SCB40	8	6.02
0.45	CB45	16.85	14.02	SCB45	9.5	8.5
0.5	CB50	19.3	16.35	SCB50	11.05	10.02
0.55	CB55	22.13	18.88	SCB55	13.05	11.5
0.4	CM40	9.5	6.4	SCM40	6.7	4.74
0.45	CM45	11.21	9.03	SCM45	7.7	6.52
0.5	CM50	13.15	10.46	SCM50	8.62	7.47
0.55	CM55	15.09	12.06	SCM55	9.88	8.54

The effect of w/b ratio on concrete permeability was further investigated by conducting permeability tests at 90 days. The results showed that the trend observed at 28 days was consistent with that at 90 days. As the w/b ratio increased, the permeability of concrete increased as well.

For example, the permeability coefficient of C40 concrete at 90 days was 7.98 cm/s *10-8, while that of C45, C50, and C55 concrete was 11.22 *10^{-8} cm/s, 12.98 *10^{-8} cm/s, and 14.86 *10^{-8} cm/s, respectively. This represented an increase of approximately 41%, 63%, and 86% for C45, C50, and C55, respectively, compared to C40 as given in Table 6.1 and shown in Figure 6.1.

Similarly, for the CF group, the permeability coefficient of CF40 concrete at 90 days was 7.23 $*10^{-8}$ cm/s, while that of CF45, CF50, and CF55 concrete was 10.8$*10^{-8}$ cm/s, 12.6 $*10^{-8}$ cm/s, and 14.48$*10^{-8}$ cm/s, respectively. This represented an increase of approximately 49%, 74%, and 101% for CF45, CF50, and CF55, respectively, compared to CF40 as given in Table 6.1 and shown in Figure 6.1.

The permeability coefficient of concrete samples in the CB, CM, SC, SCF, SCB, and SCM groups also showed a similar trend of increasing with an increase in w/b ratio at 90 days. The increase in permeability coefficient ranged from 43% to 93% for CB45 to CB55, 41% to 89% for CM45 to CM55, 32% to 71% for SC45 to SC55, 34% to 76% for SCF45 to SCF55, 41% to 91% for SCB45 to SCB55, and 38% to 81% for SCM45 to SCM55 as given in Table 6.1 and shown in Figure 6.1 and Figure 6.2.

The cause behind the increase in permeability with an increase in w/b ratio is the increased porosity of the concrete. The water to binder ratio determines the amount of water used in the mixture, which affects the space between the aggregate particles. A higher w/b ratio leads to a greater amount of water in the mixture, which fills the gaps between the aggregate particles and creates more voids in the hardened concrete. These voids increase the permeability of the concrete and allow water to penetrate more easily. Therefore, lower w/b ratios are recommended to reduce permeability and improve the durability of concrete structures.

In conclusion, the results of the study indicate that the w/b ratio has a significant effect on the permeability of concrete, and the use of lower w/b ratios can help reduce permeability and improve the durability of concrete structures over time.

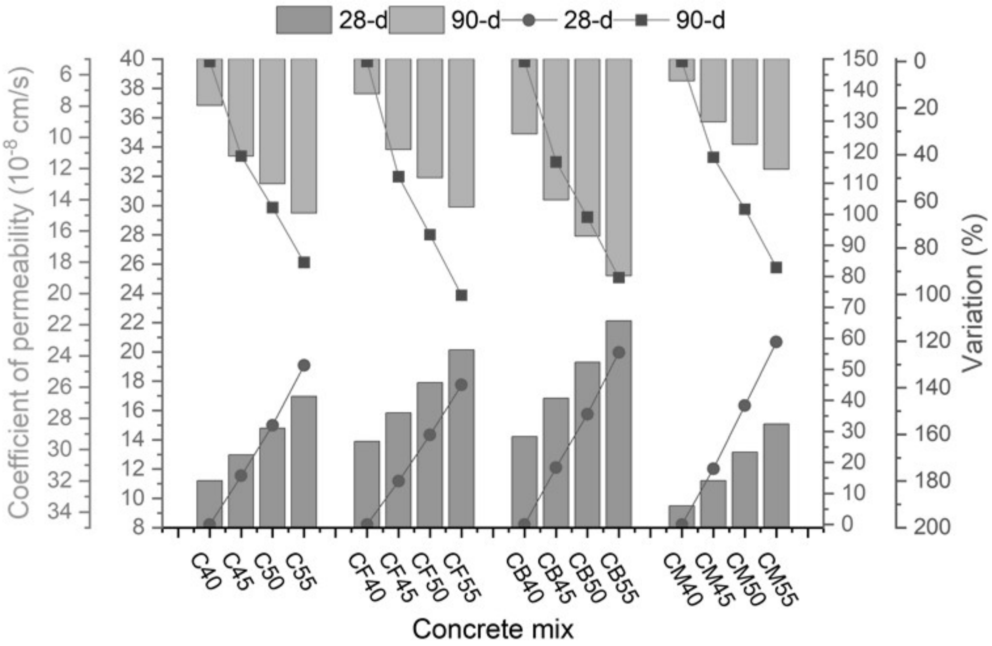

Figure 6.1 Coefficient of permeability of concrete mix without SP and % variation w.r.t 0.4 w/b

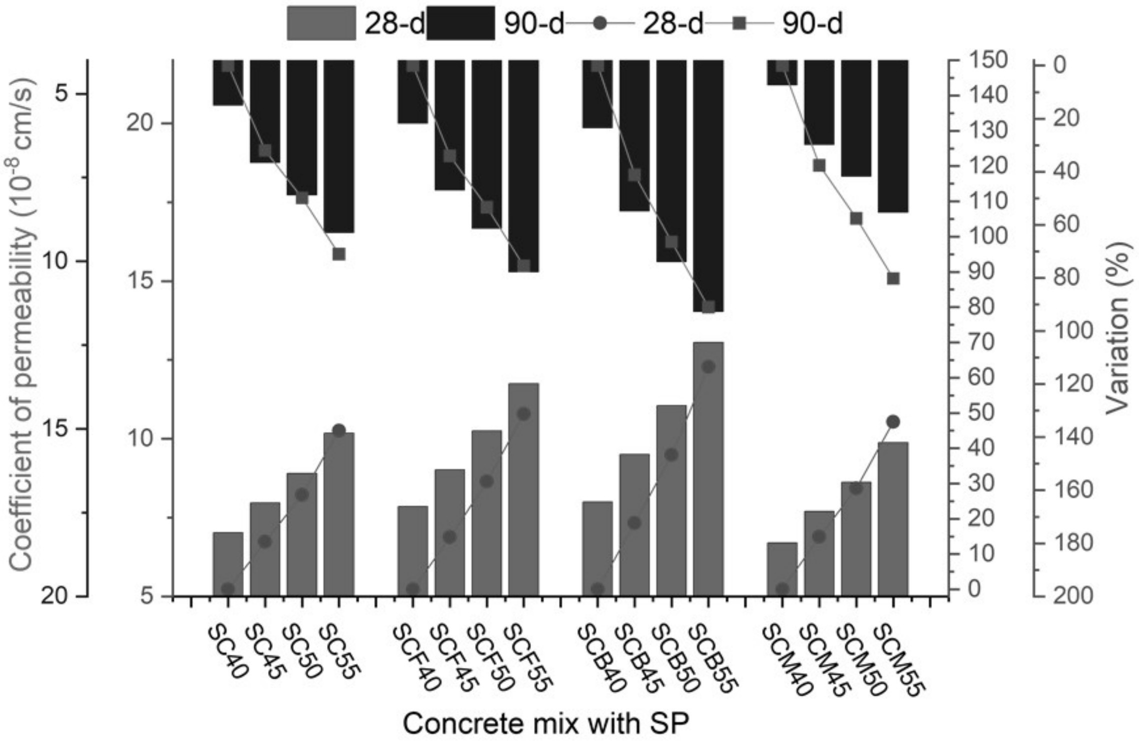

Figure 6.2 Coefficient of permeability of concrete mix with SP and % variation w.r.t 0.4 w/b

6.2.2 Effect of Mineral Admixture

The addition of mineral admixtures such as fly ash (FA), ground granulated blast furnace slag (GGBS), and micro silica (MS) to concrete can have a significant effect on its permeability. In this study, we evaluated the coefficient of permeability of concrete samples with different mineral admixtures at various water-binder ratios (w/b) and ages (28 days and 90 days).

At 28 days, the results showed that the coefficient of permeability of FA admixed concrete was higher than the control group (C group) for all w/b ratios. The increase in permeability ranged from 19% for w/b of 0.55 to 24% for w/b of 0.4. Similarly, GGBS admixed concrete also exhibited higher permeability than the C group for all w/b ratios, with an increase in permeability ranging from 30.5% for w/b of 0.55 to 26.9% for w/b of 0.4. On the other hand, the addition of micro silica (MS) resulted in a lower coefficient of permeability for the CM group than the C group, with a reduction in permeability ranging from 15.3% for w/b of 0.4 to 11% for w/b of 0.55. Similar trend was observed for SP samples as given in Table 6.1.

Now, let's compare the C group to the CF, CB, and CM groups at their respective w/b ratios for the 90-day test. At a w/b ratio of 0.4, the permeability coefficient of CB40 was 22.8% higher than that of C40, while the permeability coefficients of CF40 and CM40 were 9.4% and 19.8% lower than that of C40 respectively. At a w/b ratio of 0.45, the permeability coefficients of CF45 and CM45 were 3.7% and 19.5% lower than that of C45, while the permeability coefficient of CB45 was 25% higher than that of C45. At a w/b ratio of 0.5, the permeability coefficients of CF50 and CM50 were 2.9% and 19.4% lower than that of C50, while the permeability coefficient of CB50 was 26% higher than that of C50. At a w/b ratio of 0.55, the permeability coefficients of CF55 and CM55 were

2.6% and 18.3% lower than that of C55, while the permeability coefficient of CB55 was 27.1% higher than that of C55 as given in Table 6.1.

Lastly, let's compare the SC group to the SCF, SCB, and SCM groups at their respective w/b ratios for the 90-day test. At a w/b ratio of 0.4, 0.45, 0.50, and 0.55 the permeability coefficient of SCM was 11.4%, 7.6%, 6.9%, and 6.7% lower than that of SC group respectively, while the permeability coefficients of SCB and SCF were higher than that of SC. At a w/b ratio of 0.40, 0.45, 0.50, and 0.55 the permeability coefficients of SCF were 11.8%, 13%, 15.2%, and 15.4% higher than that of SC at their respective w/b. At a w/b ratio of 0.40, 0.45, 0.50, and 0.55, the permeability coefficients of SCB, were 12.5%, 20.4%, 24.9%, and 25.7% higher than that of SC at their respective w/b as given in Table 6.1.

In conclusion, the addition of mineral admixtures to concrete can have a significant effect on its permeability. FA and GGBS admixtures generally increased the coefficient of permeability of concrete, while MS and superplasticizer admixtures generally decreased it. The effect of the admixtures on permeability varied depending on the water-binder ratio and age of the concrete. For example, at 28 days, the permeability of concrete with FA and GGBS admixtures was higher than that of the control group, while the permeability of concrete with MS and superplasticizer admixtures was lower.

6.2.3 Effect of SP

The addition of SP to concrete can have a significant effect on its permeability. In this study, we evaluated the coefficient of permeability of concrete samples with SP at various water-binder ratios (w/b) and ages (28 days and 90 days) and compared it with different admixtures.

At 28 days, the results showed that the coefficient of permeability of SP admixed concrete was lower than the control group (C group) for all w/b ratios. The reduction in permeability ranged from 38% for w/b of 0.40 to 40% for w/b of 0.55 as shown in Figure 6.3.

Now, let's compare the C group to the SC group at their respective w/b ratios for the 90-day test. At a w/b ratio of 0.4, 0.45, 0.5, and 0.55, the permeability coefficient of SC was 32.96%, 37.08%, 38.21%, and 38.43% lower than that of C group, respectively as shown in Figure 6.3.

Similar to C group, let's compare the CB group to the SCB group at their respective w/b ratios for the 90-day test. At a w/b ratio of 0.4, 0.45, 0.5, and 0.55, the permeability coefficient of SCB was 38.57%, 39.37%, 38.72%, and 39.09% lower than that of CB group, respectively as shown in Figure 6.4.

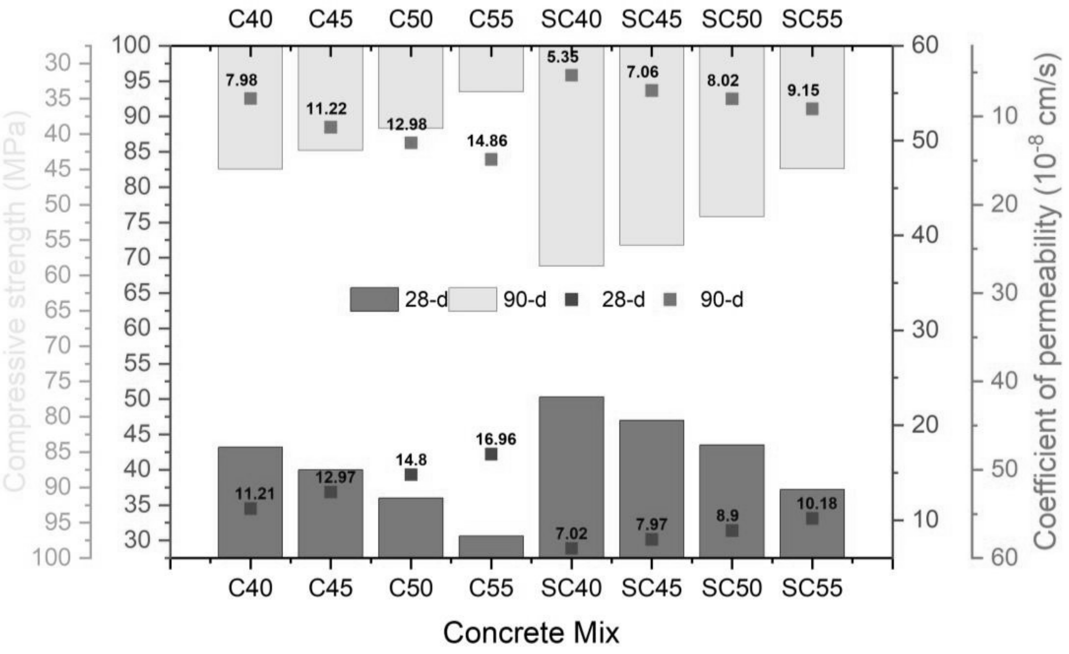

Figure 6.3 CS vs coefficient of permeability at 28 & 90 d curing of Control conrete with and without SP

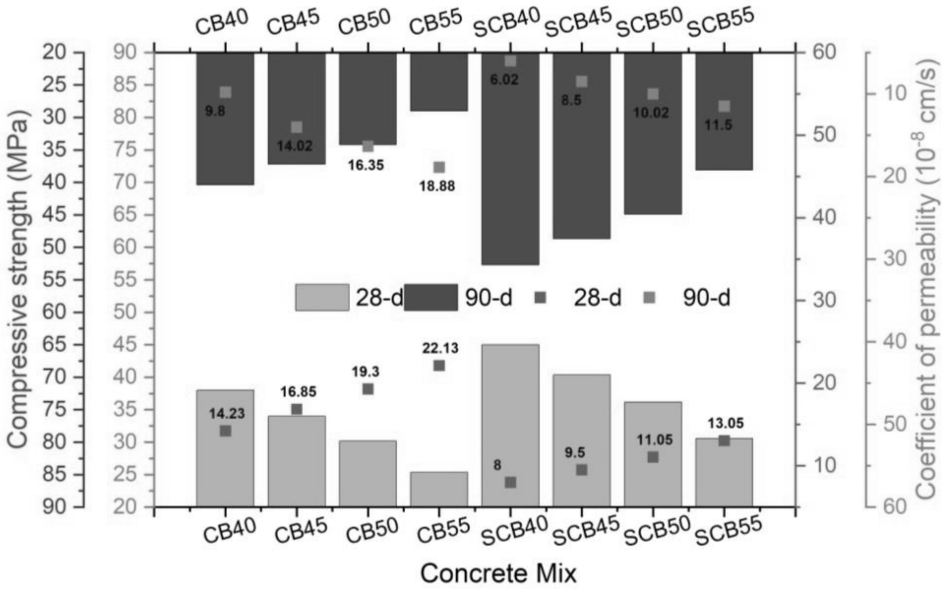

Figure 6.4 CS vs coefficient of permeability at 28 & 90d curing of GGBS admixed concrete with and without SP

Furthermore, we compared the CF group to the SCF group and CM group to the SCM group at their respective w/b ratios for the 90-day test. At a w/b ratio of 0.4, the permeability coefficient of SCF was 18.67% lower than that of CF, while the permeability coefficient of SCM was 25.94% lower than that of CM. At a w/b ratio of 0.45, the permeability coefficient of SCF was 27.04% lower than that of CF, while the permeability coefficient of SCM was 27.8% lower than that of CM. At a w/b ratio of 0.5, the permeability coefficient of SCF was 28.41% lower than that of CF, while the permeability coefficient of SCM was 28.60% lower than that of CM. At a w/b ratio of 0.55, the permeability coefficient of SCF was 28.73% lower than that of CF, while the permeability coefficient of SCM was 29.19% lower than that of CM as shown in Figure 6.5 and Figure 6.6. Overall, the addition of SP to concrete can significantly reduce its permeability. When compared to different admixtures, the effectiveness of SP in reducing permeability varies depending on the w/b ratio and the specific admixture used.

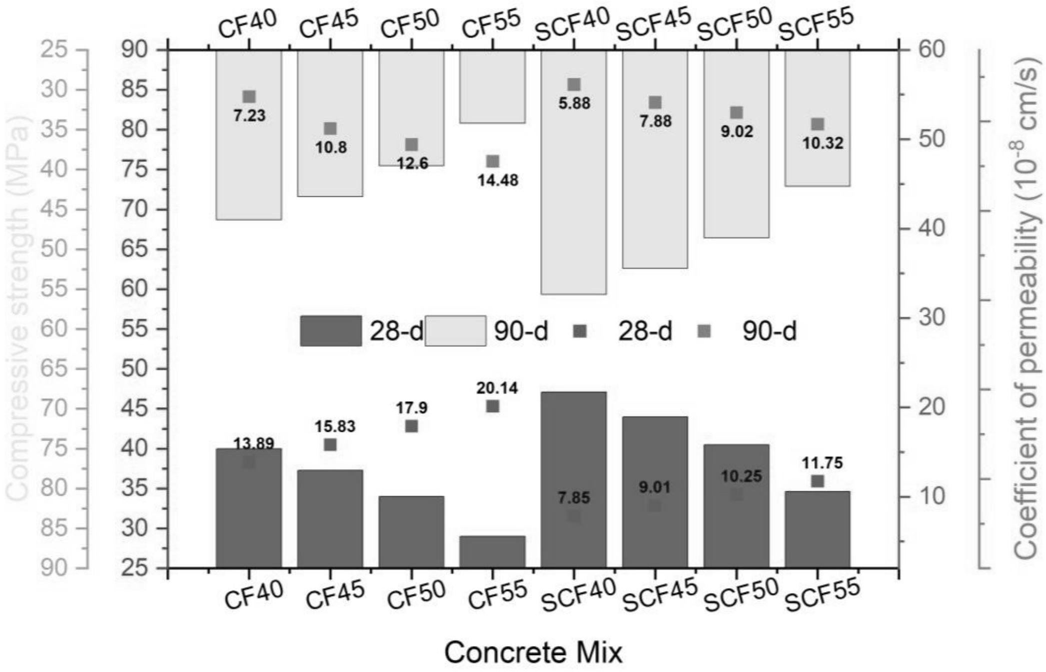

Figure 6.5 CS vs coefficient of permeability at 28 d & 90d curing of FA admixed concrete with and without SP.

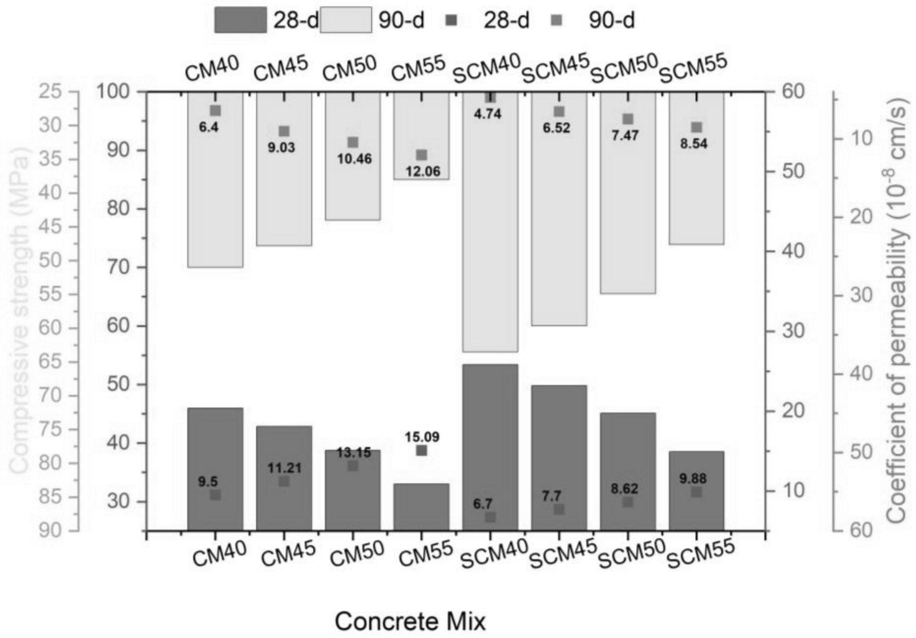

Figure 6.6 CS vs coefficient of permeability at 28 & 90d curing of MS admixed conrete with and without SP.

6.2.4 Combined Effect of SP and mineral admixture

To investigate the combined effect of SP and mineral admixtures on concrete permeability, we compared the C group to the SCF, SCB, and SCM groups at their respective w/b ratios for the 28 days and 90-days test.

At 28 days and a w/b ratio of 0.4, the permeability coefficient of SCF40 was 30% lower than that of C40, while the permeability coefficients of SCB40 and SCM40 were 28.6% and 40.2% lower than that of C40 respectively as shown in Figure 6.7 . At a w/b ratio of 0.45, the permeability coefficients of SCF45 and SCM45 were 30.5% and 40.6% lower than that of C45, while the permeability coefficient of SCB45 was 26.8% lower than that of C45 as shown in Figure 6.8. At a w/b ratio of 0.5, the permeability coefficients of SCF50, SCB50, and SCM50 were 30.7%, 25.3%, and 41.8% lower than that of C50 as shown in Figure 6.9. At a w/b ratio of 0.55, the permeability coefficients of SCF55, SCB55, and SCM55 were 30.7%, 23.1%, and 41.7% lower than that of C55 as shown in Figure 6.10.

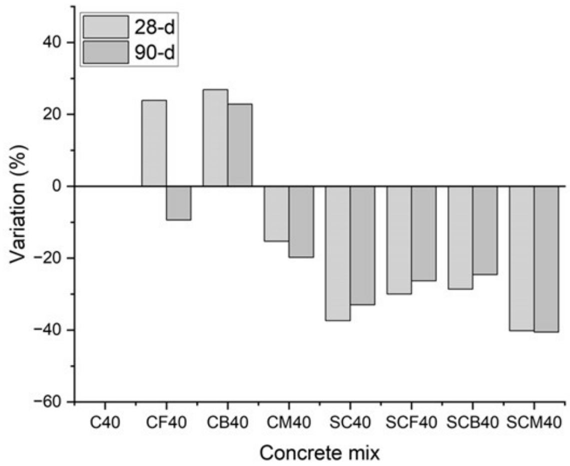

Figure 6.7 % variation in permeability coefficient of concrete mix at 0.4 w/b w.r.t C40 control concrete

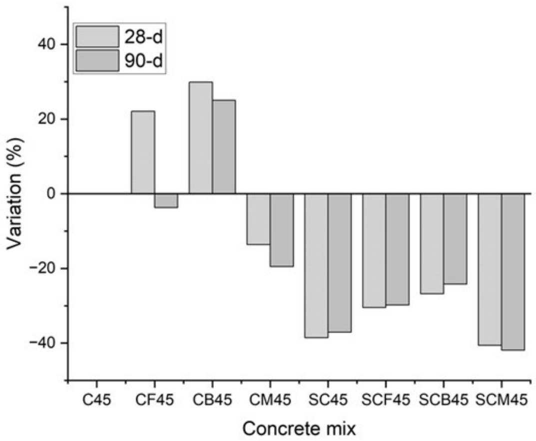

Figure 6.8 % variation in permeability coefficient of concrete mix at 0.45 w/b w.r.t C45 control concrete

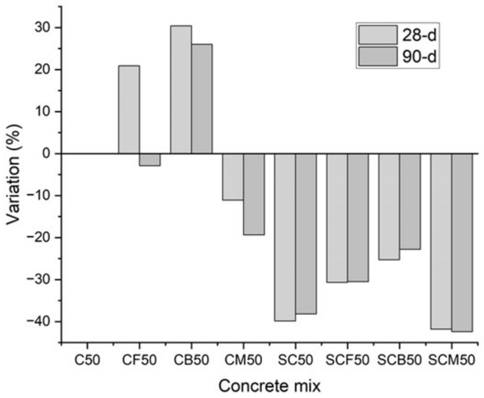

Figure 6.9 % variation in permeability coefficient of concrete mix at 0.5 w/b w.r.t C50 control concrete

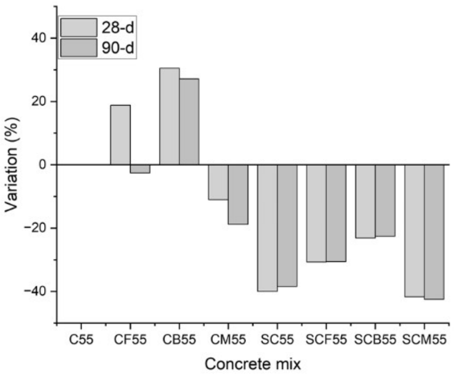

Figure 6.10 % variation in permeability coefficient of concrete mix at 0.55 w/b w.r.t. C55 control concrete

On other hand at 90 days and a w/b ratio of 0.4, the permeability coefficient of SCF40 was 26.3% lower than that of C40, while the permeability coefficients of SCB40 and SCM40 were 24.6% and 40.6% lower than that of C40 respectively as shown in Figure 6.7. At a w/b ratio of 0.45, the permeability coefficients of SCF45 and SCM45 were 29.8% and 41.9% lower than that of C45, while the permeability coefficient of SCB45 was 24.2% lower than that of C45 as shown in Figure 6.8 . At a w/b ratio of 0.5, the permeability coefficients of SCF50, SCB50, and SCM50 were 30.5%, 22.8%, and 42.4% lower than that of C50 respectively as shown in Figure 6.9 . At a w/b ratio of 0.55, the permeability coefficients of SCF55, SCB55, and SCM55 were 30.6%, 22.6%, and 42.5% lower than that of C55 respectively as shown in Figure 6.10.

Overall, the addition of SP to concrete mixtures with mineral admixtures can have a significant effect on the permeability of concrete, with the SCF, SCB and SCM groups showing consistently lower permeability coefficients than the C group at the whole w/b ratio.

The addition of superplasticizer (SP) and mineral admixtures such as fly ash (FA), ground granulated blast furnace slag (GGBS), and micro silica (MS) can reduce concrete permeability. This can be due to several reasons such as increased workability, pozzolanic reactions, reduced water-to-cement ratio, and microstructure modification.

The addition of SP and mineral admixtures can increase the workability of concrete without increasing the water content. This results in a denser and more compact structure, which reduces the permeability. Mineral admixtures such as FA, GGBS and MS are pozzolanic materials that react with the calcium hydroxide in cement to form additional calcium silicate hydrate (C-S-H) gel. This additional gel fills the voids and reduces the permeability of the concrete.

The addition of chemical admixtures can reduce the water-to-cement ratio, resulting in a stronger and more durable concrete. This reduced water content also reduces the permeability of the concrete. Additionally, mineral admixtures can modify the microstructure of concrete by reducing the size of pores and improving the interconnectivity of pores. This results in a denser and less permeable concrete.

In conclusion, the combined effect of SP and mineral admixtures reduces the permeability of concrete by improving its workability, reducing water-to-cement ratio, and producing favorable microstructures.

6.3 EFFECTS OF ACCELERATED CARBONATION CURING

Carbonation is a natural process that occurs in concrete over time. It is the reaction of carbon dioxide from the atmosphere with the calcium hydroxide in concrete to form calcium carbonate. This reaction results in a decrease in the alkalinity of concrete, which can lead to the corrosion of steel reinforcement and a reduction in the durability of concrete.

Accelerated carbon curing (ACC) is a process that involves exposing concrete to high levels of carbon dioxide in a controlled environment to speed up the carbonation process.

This can be done by placing concrete in a chamber where carbon dioxide is injected at a high pressure, or by spraying a carbon dioxide solution onto the surface of the concrete.

6.3.1 Compressive Strength

The compressive strength is an important parameter for assessing the durability and quality of concrete. In the given data, we have eight groups of concrete mix designs, namely C, CF, CB, CM, SC, SCF, SCB, and SCM. Each group has four samples with different w/b ratios (0.4, 0.45, 0.5, and 0.55). Compressive strength of concrete at 56 days of water curing (WC) as well as 56 days of combined curing (28 days of WC + 28 days of AAC) are given in Table 6.2 and shown in Figure 6.11, Figure 6.12. The percentage increase in the compressive strength of concrete due to 56 days combined curing w.r.t respective strength at 56 days of WC are given in Table 6.2.

The results show that for the C group, the percentage increase in compressive strength from WC to ACC is 7.19% for C40, 6.75% for C45, 5.15% for C50, and 4.85% for C55. For the CF group, the percentage increase in compressive strength from WC to ACC is 11.69% for CF40, 10.57% for CF45, 9.51% for CF50, and 7.40% for CF55. For the CB group, the percentage increase in compressive strength from WC to ACC is 13.29% for CB40, 11.50% for CB45, 10.92% for CB50, and 9.15% for CB55. For the CM group, the percentage increase in compressive strength from WC to ACC is 7.49% for CM40, 6.92% for CM45, 6.05% for CM50, and 5.41% for CM55. For the SC group, the percentage increase in compressive strength from WC to ACC is 3.85% for SC40, 3.35% for SC45, 2.87% for SC50, and 2.34% for SC55. For the SCF group, the percentage increase in compressive strength from WC to ACC is 8.82% for SCF40, 7.17% for SCF45, 6.75% for SCF50, and 4.65% for SCF55. For the SCB group, the percentage increase in compressive strength from WC to ACC is 11.11% for SCB40, 10.69% for SCB45, 9.20% for SCB50, and 7.40% for SCB55. Finally, for the SCM group, the percentage increase in compressive strength from WC to ACC is 4.87% for SCM40, 3.61% for SCM45, 3.13% for SCM50 and 2.16% for SCM55 as given in Table 6.2.

The increase in compressive strength after ACC (Accelerated Carbonation Curing) is due to the formation of calcium carbonate crystals ($CaCO_3$) in the pores of the concrete matrix. When CO_2 gas reacts with calcium hydroxide ($Ca (OH)_2$) present in the concrete matrix, it forms calcium carbonate crystals, which fills the pore space and makes the concrete denser and stronger as seen in Figure 6.13 to Figure 6.16. This process is similar to the natural carbonation process that occurs over the long-term life of concrete structures, but ACC speeds up the process by introducing a high concentration of CO_2 gas in a controlled environment. Therefore, the samples cured with ACC exhibit a higher compressive strength compared to those cured under normal curing conditions.

Table 6.2 Compressvive strength of concrete at 56 days of wc and 56 days of combined curing and at its carbonation depth and % increase in compressive strength

Water-binder ratio	Concrete mix	Compressive strength (MPa)		Carbonation depth (mm)	% increase in strength	Concrete mix	Compressive strength (MPa)		Carbonation depth (mm)	% increase in strength
		56-d WC	28-d WC+ 28-d ACC				56-d WC	28-d WC+ 28-d ACC		
0.4	C40	47.95	51.40	6	7.19	SC40	58.93	61.20	4	3.85
0.45	C45	44.31	47.30	9.5	6.75	SC45	54.96	56.80	7.2	3.35
0.5	C50	40.42	42.50	11.8	5.15	SC50	50.94	52.40	9.8	2.87
0.55	C55	34.05	35.70	13.7	4.85	SC55	43.09	44.10	12	2.34
0.4	CF40	46.20	51.60	8	11.69	SCF40	55.00	59.85	5.2	8.82
0.45	CF45	45.51	50.32	11.5	10.57	SCF45	51.34	55.02	8.6	7.17
0.5	CF50	42.69	46.75	13.6	9.51	SCF50	47.85	51.08	11.5	6.75
0.55	CF55	36.33	39.02	15.5	7.40	SCF55	40.61	42.50	13.5	4.65
0.4	CB40	44.31	50.20	9	13.29	SCB40	53.28	59.20	5.8	11.11
0.45	CB45	38.62	43.06	14	11.50	SCB45	48.06	53.20	9.3	10.69
0.5	CB50	34.71	38.50	16.7	10.92	SCB50	43.50	47.50	11.7	9.20
0.55	CB55	28.86	31.50	19.2	9.15	SCB55	36.33	39.02	13.6	7.40
0.4	CM40	53.03	57.00	4.5	7.49	SCM40	63.70	66.80	3	4.87
0.45	CM45	49.12	52.52	7.2	6.92	SCM45	59.07	61.20	5.5	3.61
0.5	CM50	44.32	47.00	9.4	6.05	SCM50	53.35	55.02	8.2	3.13
0.55	CM55	38.42	40.50	12	5.41	SCM55	46.20	47.20	10.5	2.16

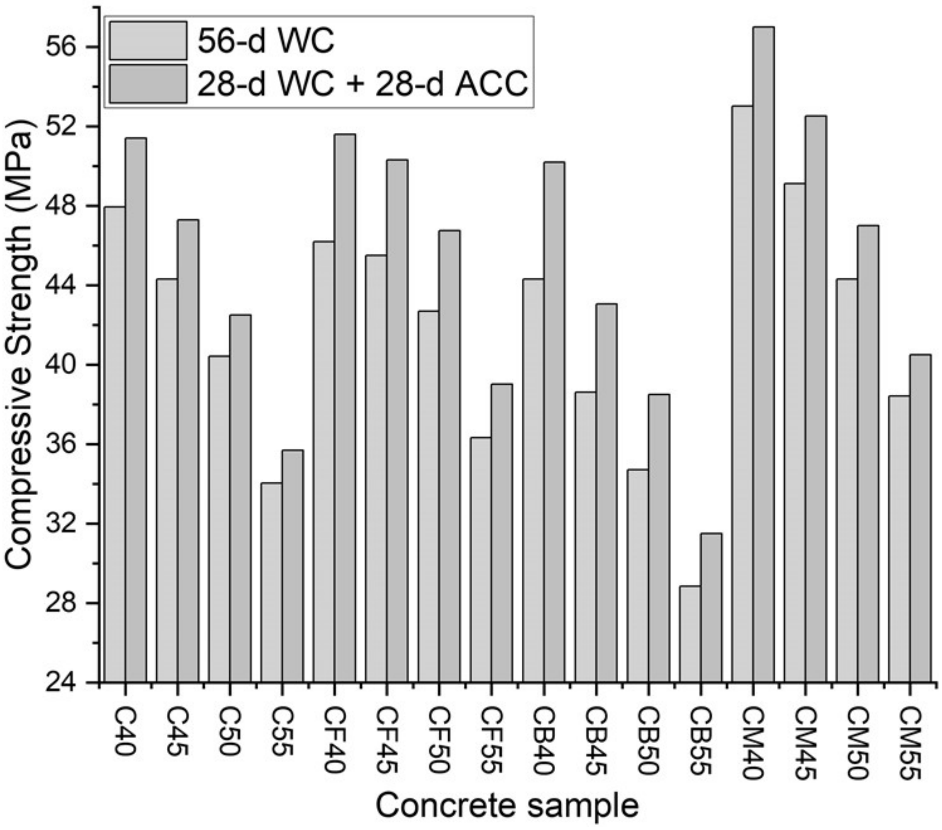

Figure 6.11 Compressive strength of concrete without SP

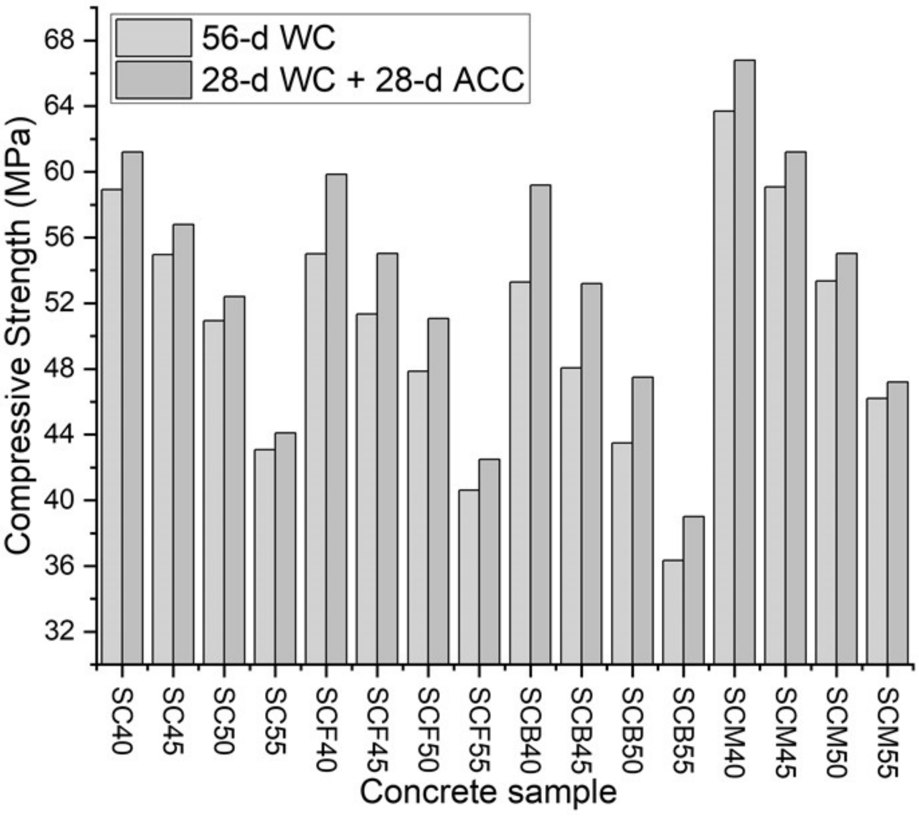

Figure 6.12 Compressive strength of concrete with SP

6.3.2 Carbonation Depth

6.3.2.1 Effect of w/b

The effect of the water-to-binder ratio on carbonation depth was observed by comparing the X40 sample to the other samples with higher water-to-binder ratios, namely X45, X50, and X55. X is a symbol which can we replaced by C, CF, CB, CM, SC, SCF, SCB, and SCM. The results showed that increasing the water-to-binder ratio led to an increase in carbonation depth as given in Table 6.2.

For the C40 to C55 group, as the w/b ratio increases, the carbonation depth also increases. Comparing C40 to C45, there is an increase of 3.5 mm in carbonation depth, which is an increase of 58.33% compared to C40. Similarly, comparing C40 to C50 and C55, there is an increase of 5.8 mm and 7.7 mm in carbonation depth, respectively. This indicates that as the w/b ratio increases, the concrete becomes more permeable to CO_2, leading to an increase in carbonation depth.

For the CF40 to CF55 group, there is a similar trend where increasing the w/b ratio leads to an increase in carbonation depth. Comparing CF40 to CF45, there is an increase of 3.5 mm in carbonation depth, which is an increase of 43.75% compared to CF40. Similarly, comparing CF40 to CF50 and CF55, there is an increase of 5.6 mm and 7.5 mm in carbonation depth, respectively. This again shows that increasing the w/b ratio leads to a more permeable concrete, resulting in a deeper carbonation depth.

In the CB40 to CB55 group, the trend of increasing carbonation depth with increasing w/b ratio is also observed. Comparing CB40 to CB45, there is an increase of 5.0 mm in carbonation depth, which is an increase of 55.56% compared to CB40. Similarly, comparing CB40 to CB50 and CB55, there is an increase of 7.7 mm and 10.8 mm in carbonation depth, respectively. This suggests that the w/b ratio has a significant effect on the carbonation depth of concrete.

For the CM40 to CM55 group, a similar trend is observed where increasing the w/b ratio leads to an increase in carbonation depth. Comparing CM40 to CM45, there is an increase of 2.7 mm in carbonation depth, which is an increase of 60% compared to CM40. Similarly, comparing CM40 to CM50 and CM55, there is an increase of 4.9 mm and 7.5 mm in carbonation depth, respectively. This indicates that the w/b ratio is an important factor to consider in the design of durable concrete structures.

In the SC40 to SC55 group, the trend of increasing carbonation depth with increasing w/b ratio is again observed. Comparing SC40 to SC45, there is an increase of 3.2 mm in carbonation depth, which is an increase of 80% compared to SC40. Similarly, comparing SC40 to SC50 and SC55, there is an increase of 5.8 mm and 8 mm in carbonation depth, respectively. This again highlights the importance of w/b ratio in the durability of concrete structures.

Finally, for the SCF40 to SCF55 and SCM40 to SCM55 groups, the same trend is observed, where increasing the w/b ratio leads to an increase in carbonation depth. Comparing SCF40 to SCF45, there is an increase of 3.4 mm in carbonation depth, which is an increase of 66% compared to SCF40. Similarly, comparing SCF40 to SCF50 and SCF55, there is an increase of 6.3 mm and 8.3 mm in carbonation depth, respectively. Similarly, in the SCM40 to SCM55 group, comparing SCM40 to SCM45, there is an increase of 2.5 mm in carbonation depth, which is an increase of 83% compared to SCM40. Similarly, comparing SCM40 to SCM50 and SCM55, there is an increase of 5.2 mm and 7.5 mm in carbonation depth, respectively.

For instance, the SEM images suggest that as shown in Figure 6.13and Figure 6.14 the lower w/b concrete may have a denser microstructure, which could be due to improved particle packing or reduced porosity. This denser microstructure could be contributing to the observed decrease in microcracking and carbonation, as it may limit the movement of water and other reactive species through the material. In contrast, the higher w/b concrete may be more susceptible to microcracking due to greater drying shrinkage or thermal expansion/contraction, which could be causing the observed differences.

Another possible explanation for the differences seen in the SEM images (Figure 6.14) is that the higher w/b concrete may be more porous, which could allow for greater diffusion of carbon dioxide into the material, leading to increased carbonation. This could also contribute to the observed microcracking, as the expansion of calcium carbonate crystals during carbonation could cause mechanical stresses that lead to cracking.

The increase in carbonation depth with an increase in w/b ratio can be attributed to the higher porosity and permeability of the concrete matrix at higher w/b ratios. As the w/b ratio increases, the amount of water used in the mix increases, leading to more capillary pores in the hardened concrete matrix. These pores provide more pathways for CO_2 to diffuse into the concrete, resulting in a greater extent of carbonation.

Moreover, the increased water content in higher w/b ratio mixes leads to a greater loss of calcium hydroxide (CH) through leaching. CH is a product of the hydration of cement and is an essential component for the concrete's alkalinity. A reduction in CH content reduces the pH buffering capacity of the concrete, making it more vulnerable to carbonation.

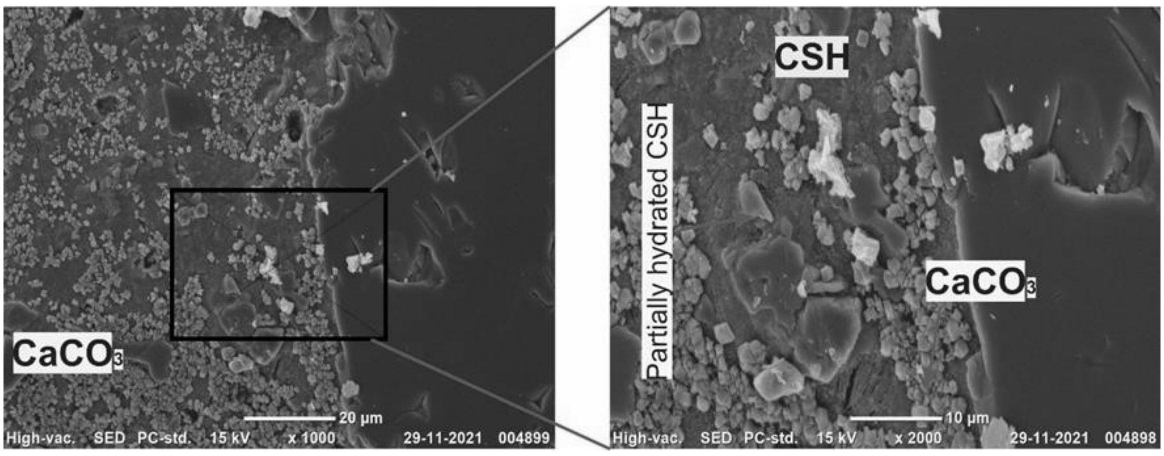

Figure 6.13 SEM micrographs of concrete of mix SC40 after 56 days of combined curing

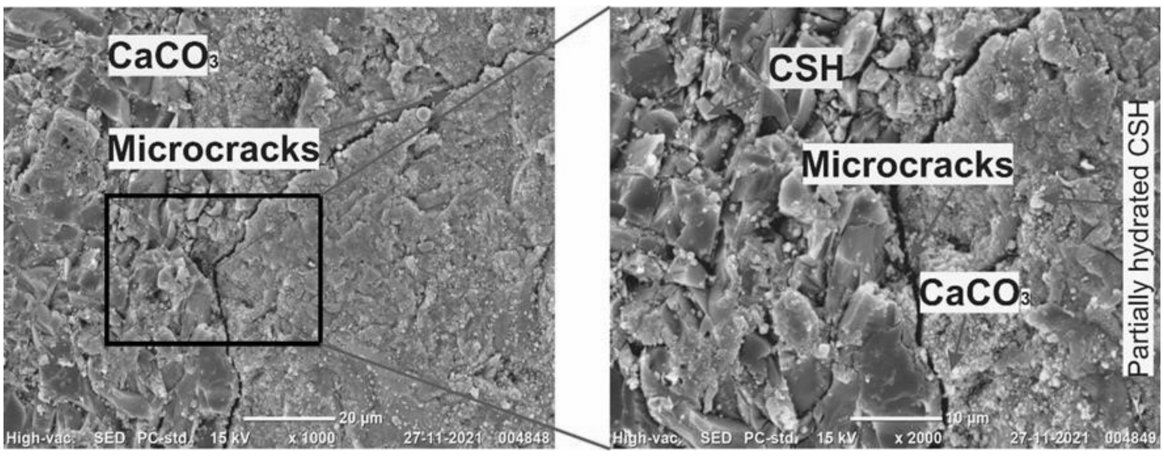

Figure 6.14 SEM micrographs of concrete of mix SC50 after 56 days of combined curing

Furthermore, the reduced compressive strength of higher w/b ratio mixes can also contribute to greater carbonation depth. Lower strength concrete is generally more porous and permeable, allowing CO_2 to diffuse into the concrete more easily and penetrate deeper into the matrix.

In summary, the increase in carbonation depth with an increase in w/b ratio can be attributed to the increased porosity, permeability, reduced CH content, and lower strength of the concrete.

6.3.2.2 Effect of Mineral Admixture

At w/b ratio of 0.40, the carbonation depth of the C group was 6 mm, which increased to 8 mm with the addition of fly ash in the CF group. This indicates that the carbonation resistance of CF40 was 33.3% lower than C40. The addition of GGBS in the CB group increased the carbonation depth to 9 mm, which is higher than that of the C group, indicating a 50% decrease in carbonation resistance. On the other hand, the addition of MS in the CM group reduced the carbonation depth to 4.5 mm, which is lower than that of the C group, indicating a 25% increase in carbonation resistance.

At w/b ratio of 0.45, the carbonation depth of the C group was 9.5 mm, which increased to 11.5 mm with the addition of FA in the CF group. This indicates that the carbonation resistance of CF45 was 21.05% lower than C45. The addition of GGBS in the CB group increased the carbonation depth to 14 mm, which is significantly higher than that of the C group, indicating a 29.17% decrease in carbonation resistance. On the other hand, the addition of MS in the CM group reduced the carbonation depth to 7.2 mm, which is lower than that of the C group, indicating a 24.21% increase in carbonation resistance.

At w/b ratio of 0.50, the carbonation depth of the C group was 11.8 mm, which increased to 13.6 mm with the addition of fly ash in the CF group. This indicates that the carbonation resistance of CF50 was 15.25% lower than C50. The addition of GGBS in the CB group increased the carbonation depth to 16.7 mm, which is 41.53% higher than that of the C group, indicating a decrease in carbonation resistance. On the other hand, the addition of MS in the CM group reduced the carbonation depth to 9.4 mm, which is lower than that of the C group, indicating a 20.34% increase in carbonation resistance.

At w/b ratio of 0.55, the carbonation depth of the C group was 13.7 mm, which increased to 15.5 mm with the addition of FA in the CF group. This indicates that the carbonation resistance of CF55 was 13.14% lower than C55. The addition of GGBS in the CB group increased the carbonation depth to 19.2 mm, which is 40.15% higher than that of the C group, indicating a decrease in carbonation resistance. On the other hand, the addition of MS in the CM group reduced the carbonation depth to 12 mm, which is lower than that of the C group, indicating a 12.41% increase in carbonation resistance.

For the SC group, at w/b ratio of 0.40, the carbonation depth was 4 mm, which increased to 5.2 mm with the addition of FA in the SCF group. This indicates that the carbonation resistance of SCF40 was 30% lower than SC40. The addition of GGBS in the SCB group increased the carbonation depth to 5.8 mm, which is higher than that of the SC group, indicating a 45% decrease in carbonation resistance. On the other hand, the addition of MS in the SCM group reduced the carbonation depth to 3 mm, which is 25% lower than that of the SC group, indicating an increase in carbonation resistance.

At w/b of 0.45, the carbonation depth for the SC group increased to 7.2 mm. The addition of FA in the SCF group increased the carbonation depth to 8.6 mm, which is higher than that of the SC group, indicating a 19.44% decrease in carbonation resistance. The addition of GGBS in the SCB group increased the carbonation depth to 9.3 mm, which is higher than that of the SC group, indicating a 29.17% decrease in carbonation resistance. The addition of MS in the SCM group reduced the carbonation depth to 5.5 mm, which is lower than that of the SC group, indicating an increase in carbonation resistance.

At w/b ratio of 0.50, the carbonation depth for the SC group increased to 9.8 mm. The addition of FA in the SCF group increased the carbonation depth to 11.5 mm, which is higher than that of the SC group, indicating a decrease in carbonation resistance. The addition of GGBS in the SCB group increased the carbonation depth to 11.7 mm, which is higher than that of the SC group, indicating a decrease in carbonation resistance. The addition of MS in the SCM group reduced the carbonation depth to 8.2 mm, which is lower than that of the SC group, indicating an increase in carbonation resistance.

At w/b ratio of 0.55, the carbonation depth for the SC group increased to 12 mm. The addition of FA in the SCF group increased the carbonation depth to 13.5 mm, which is higher than that of the SC group, indicating a decrease in carbonation resistance. The addition of GGBS in the SCB group increased the carbonation depth to 13.6 mm, which is higher than that of the SC group, indicating a decrease in carbonation resistance. The addition of MS in the SCM group reduced the carbonation depth to 10.5 mm, which is lower than that of the SC group, indicating an increase in carbonation resistance.

For instance, the SEM images Figure 6.15and Figure 6.16 suggest that the addition of FA as a partial replacement for OPC can lead to changes in the microstructure and chemical composition of concrete. Compared to the C50 sample, the FA50 sample showed more micro cracks and a higher concentration of $CaCO_3$ particles after accelerated carbonation curing.

One possible explanation for these differences is the finer particle size of the FA particles in the FA50 sample, which could have resulted in a denser packing of particles and greater internal stresses. This, in turn, could have contributed to the formation of more microcracks after accelerated carbonation curing. Additionally, the reaction of fly ash with $Ca(OH)_2$ in the presence of CO_2 can lead to the formation of additional $CaCO_3$ particles, which would explain the higher concentration of $CaCO_3$ particles in the FA50 sample after accelerated carbonation curing.

In summary, the addition of mineral admixtures showed varying effects on the carbonation resistance. The addition of FA and GGBS decreased the carbonation resistance of the samples, while the addition of MS increased the carbonation resistance.

The extent of the effect of the mineral admixture on carbonation depth depended on the type of admixture and the w/b ratio as given in Table 6.2 and shown in Figure 6.17 and Figure 6.18.

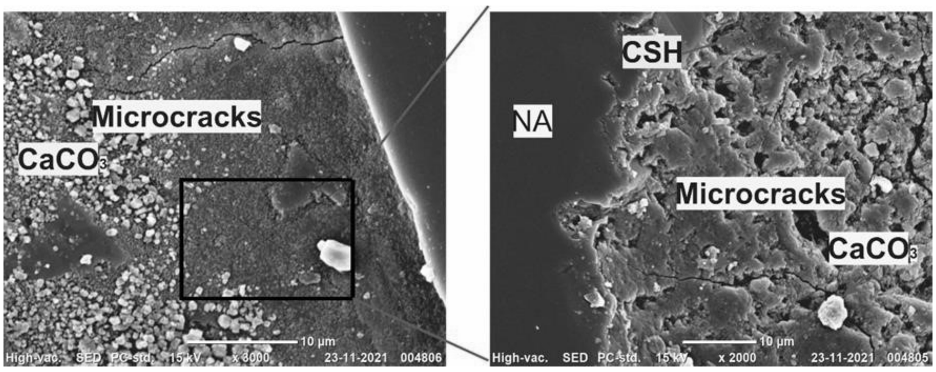

Figure 6.15 SEM micrographs of concrete of mix C50 after 56 days of combined curing

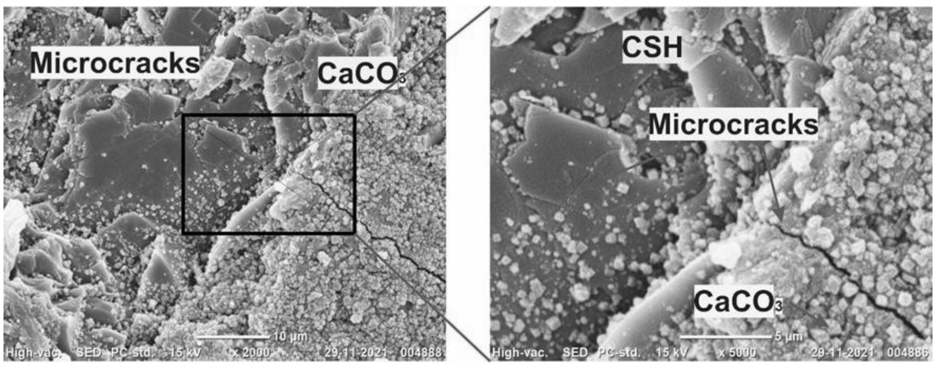

Figure 6.16 SEM micrographs of concrete of mix FA 50 after 56 days of combined curing

The addition of FA and GGBS in concrete can reduce the carbonation resistance because these mineral admixtures are pozzolanic in nature and react with calcium hydroxide ($Ca(OH)_2$) produced during the hydration of cement. This reaction results in the formation of additional calcium silicate hydrate (C-S-H) gel, which fills the pores in the concrete, making it more compact and less permeable. However, this also reduces the amount of $Ca(OH)_2$ available for reaction with CO_2 during carbonation, leading to an increase in the carbonation depth.

On the other hand, MS is a highly reactive pozzolanic material that has a very small particle size and high surface area. When added to concrete, it reacts with the $Ca(OH)_2$ to form more C-S-H gel, which densifies the concrete and makes it less permeable. This reduces the ingress of CO_2, leading to a decrease in the carbonation depth and an increase in carbonation resistance. Additionally, the high reactivity of MS also leads to the formation of calcium silicate hydrate with a smaller particle size, resulting in a more compact microstructure, which further enhances the carbonation resistance.

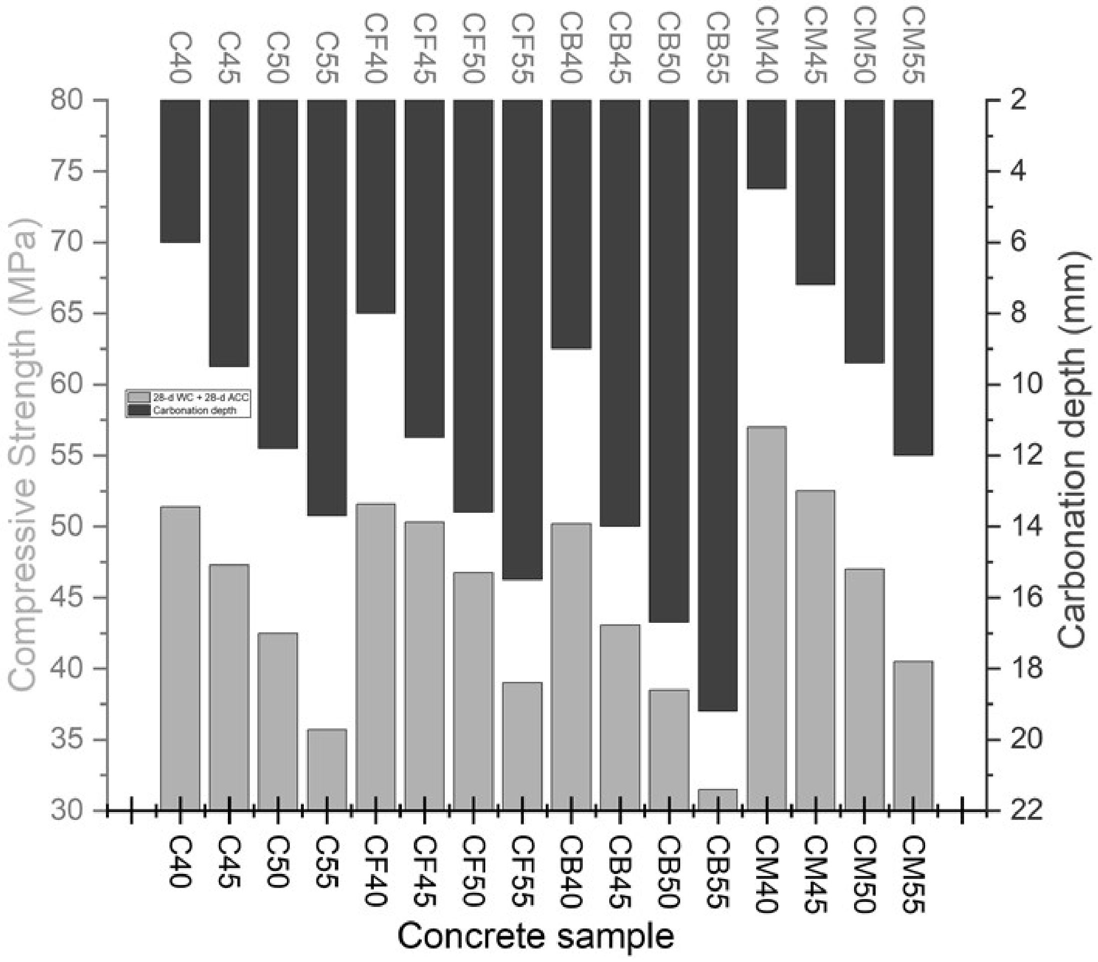

Figure 6.17 Carbonated compressive strength vs carbonation depth of various concrete samples without SP

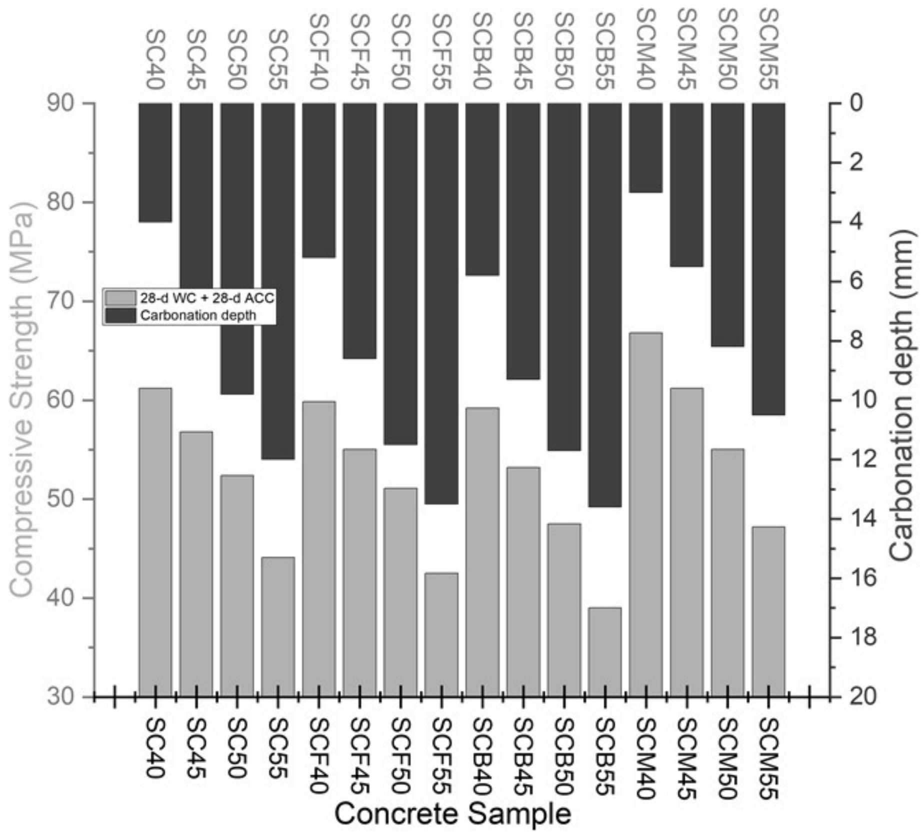

Figure 6.18 Carbonated compressive strength vs carbonation depth of various concrete samples with SP

6.3.2.3 Effect of SP

The results show that the addition of SP had a significant effect on the carbonation depth of the specimens. In the C group, at a w/b ratio of 0.40, the carbonation depth was 6 mm, which decreased to 4 mm with the addition of SP in the SC group, indicating a 33.33% increase in carbonation resistance. Similarly, at w/b ratios of 0.45, 0.50, and 0.55, the addition of SP in the SC group reduced the carbonation depth 24.21%, 16.95%, and 12.41% respectively compared to the C group, indicating an increase in carbonation resistance. As given in Table 6.2 and shown in Figure 6.21.

For the CF group, the addition of SP in the SCF group also reduced the carbonation depth compared to the CF group at all w/b ratios. At w/b ratios of 0.40, 0.45, 0.50, and 0.55, the addition of SP in the SCF group reduced the carbonation depth 35%, 25.22%, 15.44%

and 12.41% respectively compared to the CF group, indicating an increase in carbonation resistance. As given in Table 6.2 and shown in Figure 6.22. This indicates an improvement in the carbonation resistance of the SCF group with the addition of SP.

For the CB group, the addition of SP in the SCB group reduced the carbonation depth compared to the CB group at all w/b ratios. At w/b ratios of 0.40, 0.45, 0.50, and 0.55, the addition of SP in the SCB group reduced the carbonation depth 35.56%, 23.57%, 29.94% and 29.17% respectively as given in Table 6.2 and shown in Figure 6.23 compared to the CB group, indicating an increase in carbonation resistance.

For the CM group, the addition of SP in the SCM group reduced the carbonation depth compared to the CM group at all w/b ratios. At w/b ratios of 0.40, 0.45, 0.50, and 0.55, the addition of SP in the SCM group reduced the carbonation depth 35.33%, 23.61%, 12.77% and 12.5% respectively as given in Table 6.2 and shown in Figure 6.24 compared to the CM group, indicating an increase in carbonation resistance.

The addition of SPs to concrete not only improves its workability but also improves its durability properties such as carbonation resistance. The improved carbonation resistance can be attributed to the formation of a denser and more compact microstructure of the concrete.

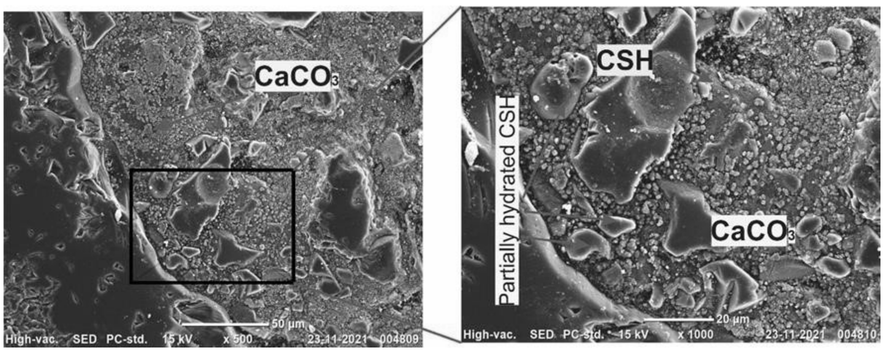

Figure 6.19 SEM micrographs of concrete of mix CM40 after 56 days of combined curing

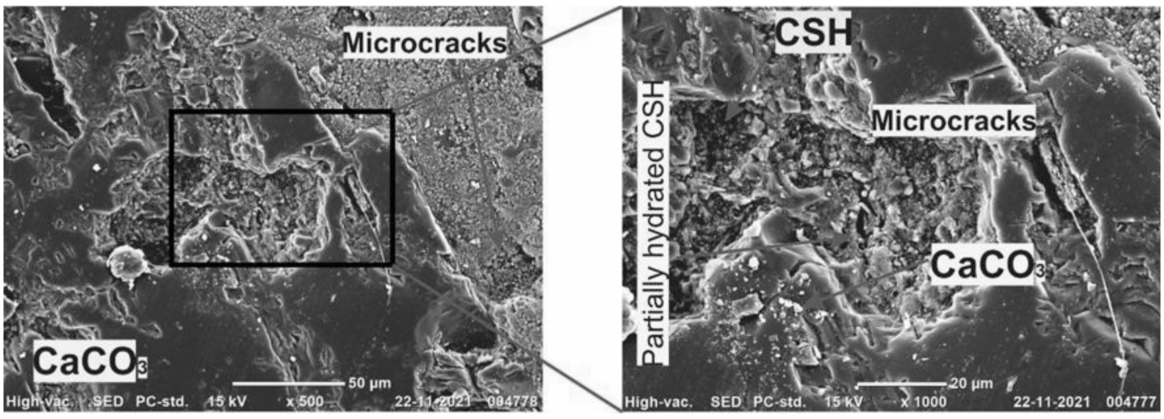

Figure 6.20 SEM micrographs of concrete of mix SCM40 after 56 days of combined curing

For instance, the SEM images Figure 6.19 and Figure 6.20 suggest that the addition of SP to the mix can reduce the degree of carbonation and the formation of micro cracks in the material.

One possible explanation for these observations is that the SP reduces the water demand of the concrete mix, resulting in a more compacted microstructure with fewer voids. This, in turn, can reduce the diffusion of CO_2 into the material and slow down the carbonation process. Additionally, the SP can help to reduce the formation of micro cracks by improving the workability of the mix and reducing the risk of segregation and bleeding.

In contrast, the CM40 sample without SP showed a higher degree of carbonation and more micro cracks. This could be due to the lower workability of the mix without the SP, which can lead to higher porosity and increased diffusion of CO_2 into the material. Additionally, the lack of SP may have led to higher levels of segregation and bleeding, which could have contributed to the formation of micro cracks in the material.

The SPs can reduce the water-to-cement ratio, resulting in a lower porosity of the concrete, which in turn reduces the rate of carbonation. The entrained air voids in concrete can act as channels for the ingress of carbon dioxide, but the use of SPs can minimize these voids, making it difficult for carbon dioxide to penetrate the concrete [43].

Furthermore, the adsorption of SP molecules on the surface of cement particles creates a negative charge on the cement particles, resulting in greater repulsion forces between them. This repulsion force enhances the dispersion of cement particles, resulting in a more uniform distribution and reduced agglomeration, which contributes to a denser and more compact microstructure. This denser microstructure can impede the ingress of carbon dioxide, resulting in improved carbonation resistance [44].

Therefore, the use of SPs in concrete can improve the carbonation resistance by reducing the water-to-cement ratio, minimizing the entrained air voids, and improving the microstructure of the concrete. Overall, the results indicate that the addition of SP improves the carbonation resistance of concrete specimens, regardless of the type of mineral admixture used.

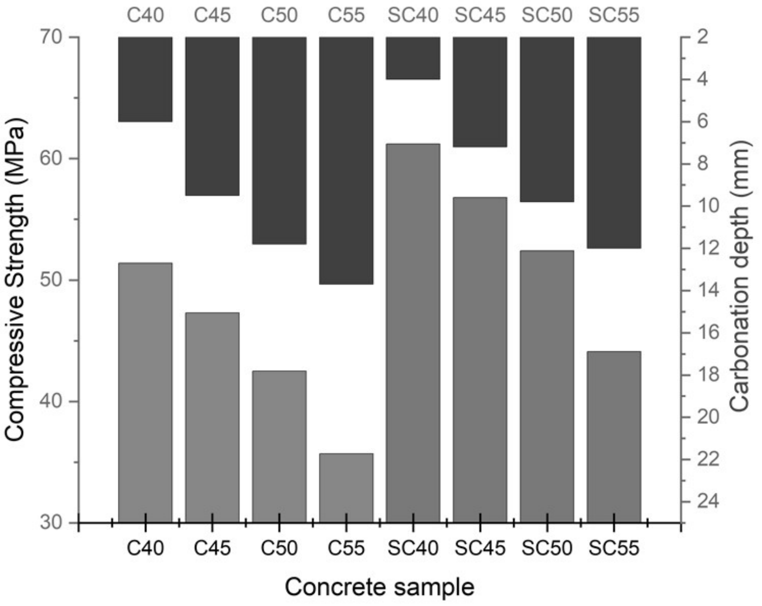

Figure 6.21 Carbonated CS vs carbonation depth of control concerte with and without SP

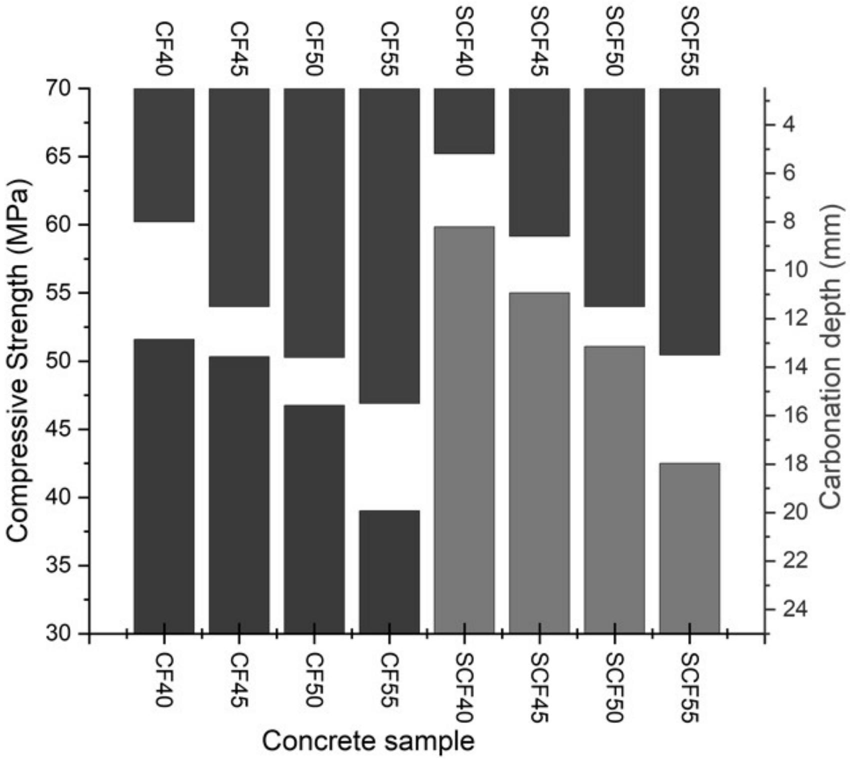

Figure 6.22 Carbonated CS vs carbonation depth of FA admixed concrete with and without SP

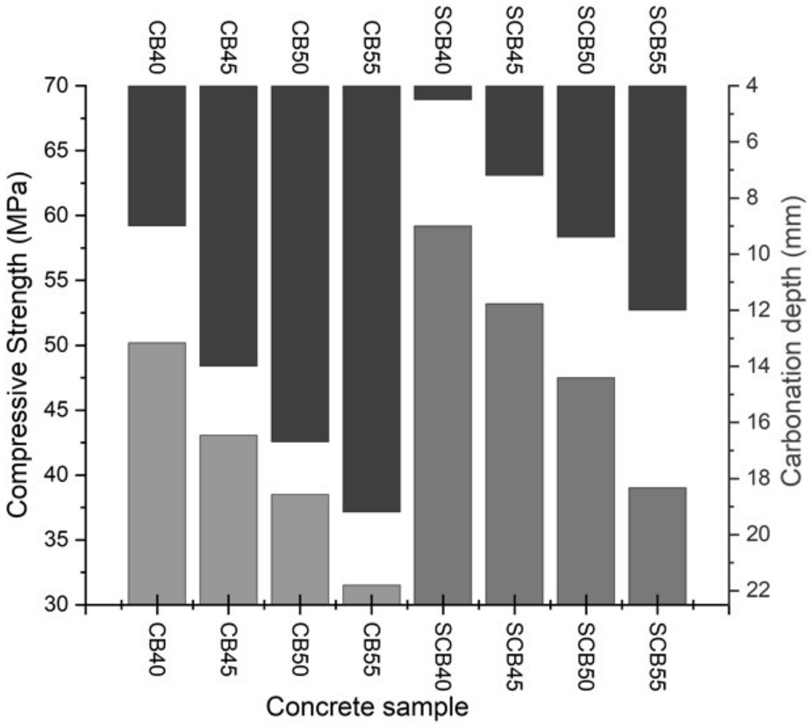

Figure 6.23 Carbonated CS vs carbonation depth of GGBS admixed concrete with and without SP

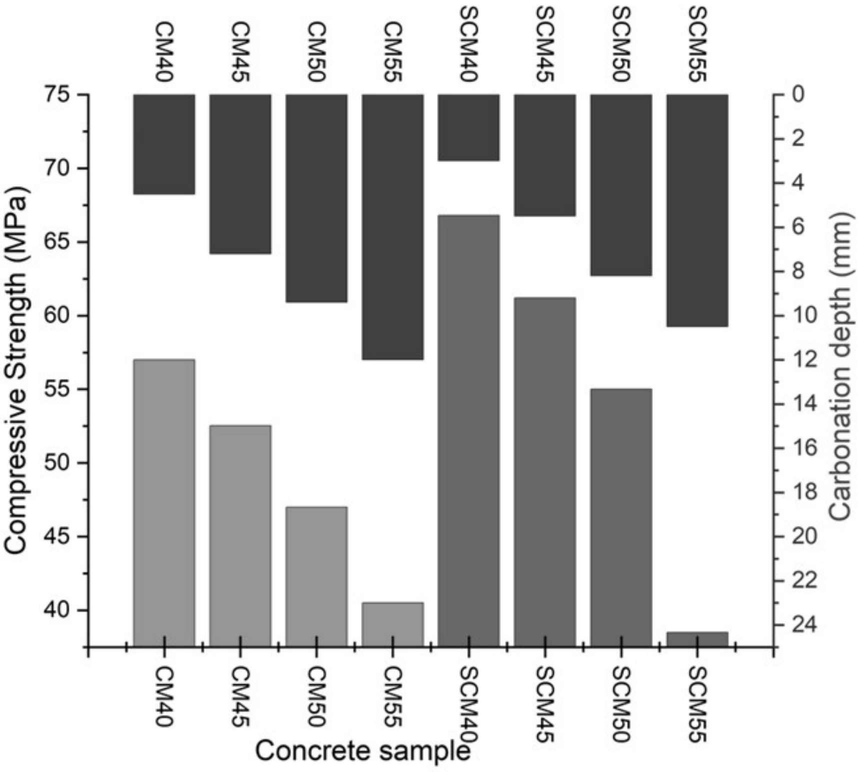

Figure 6.24 Carbonated CS vs carbonation depth of MS admixed concrete with and without SP

6.3.2.4 Combined Effect of Mineral Admixture and Superplasticizer

The results of the study demonstrate that the addition of mineral admixtures and SP can have a positive effect on the carbonation resistance of concrete. Across all w/b ratios tested, the carbonation depth of the control concrete was higher than that of the concrete with mineral admixtures and SP as given in Table 6.2 and shown in Figure 6.28. This suggests that the use of these additives can improve the durability of concrete in carbonating environments.

When considering the individual mineral admixtures, it was found that SCM showed the highest improvement in carbonation resistance, with an improvement of 50%, 42.11%, 30.51%, and 23.36% at the w/b ratio of 0.40, 0.45, 0.50, and 0.55 respectively compared to control concrete (C). This was followed by SCF and SCB, which both showed smaller improvements compared to SCM. It was found that SCB showed least improvement in carbonation resistance, with an improvement of 3.33%, 2.11%, 0.85%, and 0.73% at the w/b ratio of 0.40, 0.45, 0.50, and 0.55 respectively compared to control concrete (C). It was found that SCF showed medium carbonation resistance, with an improvement of 13.33%, 9.47%, 2.54%, and 1.46% at the w/b ratio of 0.40, 0.45, 0.50, and 0.55 respectively compared to control concrete (C) as given in Table 6.2 and shown in Figure 6.28 SCMs, such as FA, MS, and GGBS, contain reactive silica and alumina, which can react with calcium hydroxide and produce additional calcium silicate hydrate (C-S-H) gel. This additional C-S-H gel can fill in the pores in the concrete, reducing permeability and increasing resistance to carbonation. Additionally, the pozzolanic reaction that occurs with SCMs can consume some of the calcium hydroxide in the concrete, reducing the amount available for reaction with carbon dioxide.

For instance, comparing the OPC-based C40 sample to the SCM40, SCF40, and SCB40 samples, we observe that the use of mineral admixtures and SP leads to a denser and more compact microstructure, as evidenced by the lower carbonation depth and fewer microcracks observed in the SEM images Figure 6.20, Figure 6.25, Figure 6.26, and Figure 6.27.

The use of MS with SP (such as SCM40) leads to the lowest carbonation depth and the fewest microcracks observed in the SEM image Figure 6.20. This is due to the fact that microsilica particles fill in the gaps between cement particles and hydrates, resulting in a more compact microstructure with fewer voids and less permeability to CO_2.

The addition of SP with FA (such as SCF40) further enhances the workability of the concrete and reduces the water demand, resulting in a more densely packed microstructure with fewer voids Figure 6.26. The use of GGBS with SP (such as SCB40) also contributes to a denser microstructure by filling in the pores and reducing the permeability of the concrete Figure 6.27.

SPs, such as polycarboxylate-based superplasticizers, can improve carbonation resistance by improving the dispersion of the cement particles, reducing the number of voids in the concrete and increasing the overall density. This reduces the rate of penetration of carbon dioxide into the concrete, reducing the rate of carbonation.

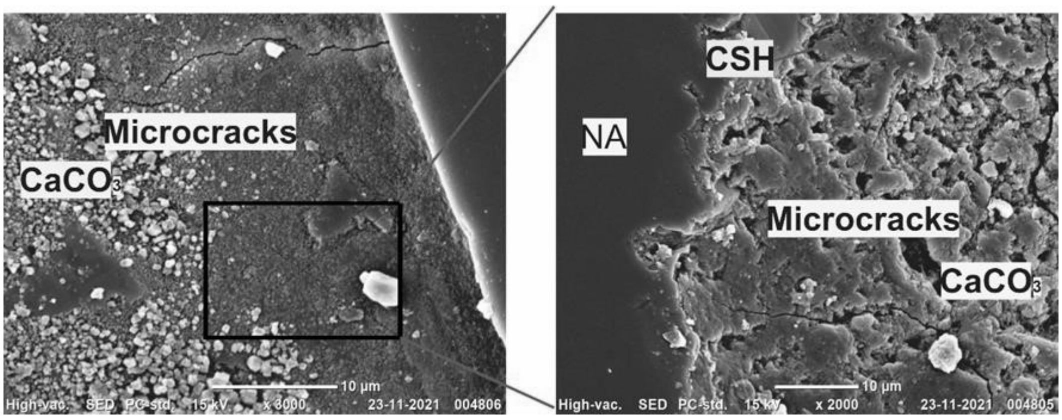

Figure 6.25 SEM micrographs of concrete of mix C40 after 56 days of combined curing

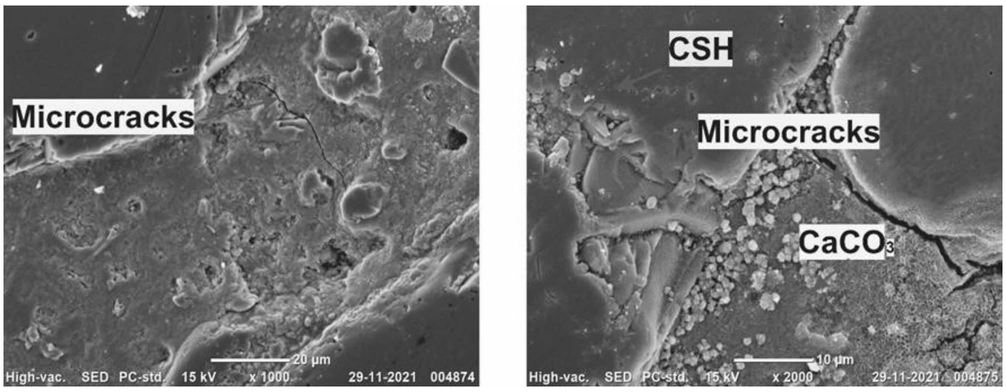

Figure 6.26 SEM micrographs of concrete of mix SCF40 after 56 days of combined curing

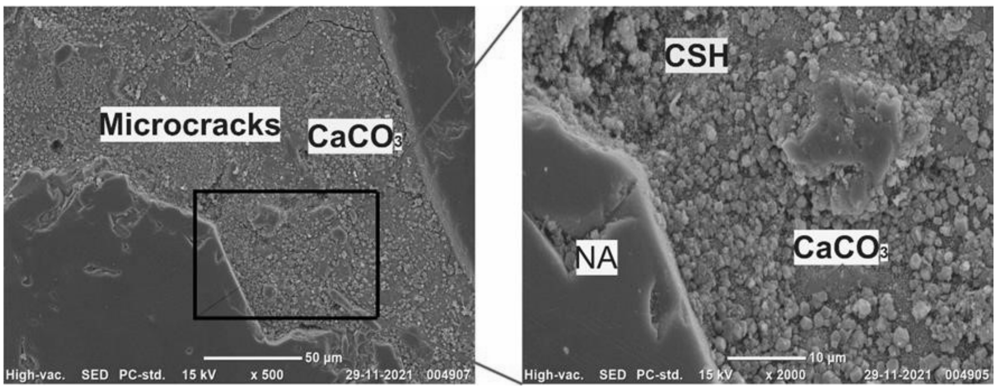

Figure 6.27SEM micrographs of concrete of mix SCB40 after 56 days of combined curing

The combination of SCMs and SP can have a synergistic effect on carbonation resistance. The additional C-S-H gel formed by the pozzolanic reaction of SCMs can be further improved by the dispersing action of the SP, creating a denser and more impermeable microstructure. The combination can also reduce the amount of calcium hydroxide available for reaction with carbon dioxide, further reducing the carbonation rate.

In addition to these chemical and physical changes, there may also be microstructural changes that contribute to improved carbonation resistance. For example, the formation of additional C-S-H gel can create a denser microstructure, while the reduction in calcium hydroxide can reduce the number of voids in the concrete as seen in Figure 6.25 to Figure 6.27. These changes can increase the overall density of the concrete and reduce its permeability, leading to improved carbonation resistance.

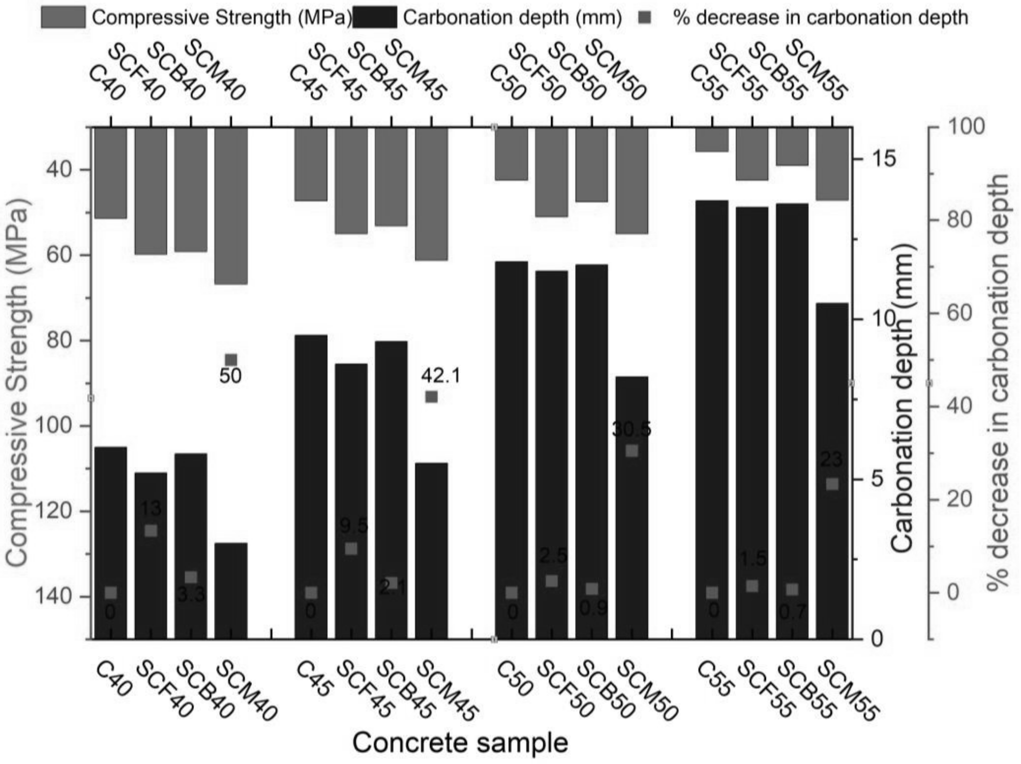

Figure 6.28 Combined effect of MA and SP on CS, carbonation depth and % decrease in carbonation depth w.r.t conctrol concrete at their respective w/b

6.4 EFFECTS OF ACIDIC ENVIRONMENT

Concrete is often exposed to acidic environments in various applications such as wastewater treatment facilities, chemical processing plants, acid rain, and acidic soil conditions. When concrete is exposed to an acidic environment, it undergoes a process called acid attack or acid corrosion, which can lead to significant damage to its properties and structural integrity [280].

Acid attack occurs when the acidic solution reacts with the calcium hydroxide ($Ca(OH)_2$) in the cement paste, resulting in the formation of calcium salts that dissolve and create voids within the concrete [281]. As a result, the concrete loses its strength and durability, leading to structural damage and even collapse.

The severity of acid attack depends on various factors such as the concentration of acid, the exposure time, the temperature, and the type of concrete mix used. Therefore, it is important to consider the effects of acidic environments on concrete and develop appropriate strategies to mitigate these effects[145], [282], [283].

In this study, 0.75% H_2SO_4 and 0.75% HNO_3 were considered along with air bubbles in the curing tank, and a 90-day curing period was used to study the effect of weight loss and strength loss. It is worth noting that the curing water was replaced weekly during the experiment to ensure consistency in the testing conditions.

The addition of air bubbles in the curing tank was done to simulate the effect of acid rain, where water droplets come in contact with the atmospheric air and can dissolve pollutants such as SO_2 and NOx, resulting in acidic rainwater. By considering the effect of air bubbles, we can better understand the effect of acidic environments on concrete in real-world scenarios.

6.4.1 Loss of Mass

The loss of mass due to immersion of concrete in acidic solution is given in

Table 6.3. The graph between different concrete mix and their loss of mass (%) is shown in Figure 6.29

6.4.1.1 Effect of w/b

The mass loss of concrete due to immersion in acid was found to increase with increasing water-to-binder (w/b) ratio for all types of concrete mixes tested. Comparing the mass loss of concrete samples at 0.45, 0.50, and 0.55 w/b ratios to that at 0.40 w/b ratio, it was observed that an increase in w/b ratio resulted in a higher mass loss in all groups, namely C, CF, CB, CM, SC, SCF, SCB, and SCM.

For plain concrete (C), the mass loss increased from 2.82% at 0.40 w/b ratio to 3.12%, 3.40%, and 3.65% at 0.45, 0.50, and 0.55 w/b ratios, respectively. The addition of 30% FA (CF) and 10% MS (CM) slightly reduced the mass loss compared to plain concrete, but the trend of increasing mass loss with increasing w/b ratio was still observed.

The addition of 50% GGBS (CB) showed a significant reduction in mass loss compared to plain concrete, with a mass loss of 2.59%, 2.82%, 3.06%, and 3.22% at 0.40, 0.45, 0.50, and 0.55 w/b ratios, respectively. Superplasticizer (SC) also showed a slight reduction in mass loss compared to plain concrete, with a mass loss of 2.30%, 2.55%, 2.91%, and 3.18% at 0.40, 0.45, 0.50, and 0.55 w/b ratios, respectively as shown in Figure 6.29.

The combination of FA with superplasticizer (SCF) and MS with superplasticizer (SCB) showed a significant reduction in mass loss compared to plain concrete and plain concrete with superplasticizer, with a mass loss ranging from 2.11% to 2.89% and 2.08% to 2.79% at 0.40 to 0.55 w/b ratios, respectively Figure 6.29.

The addition of GGBS and superplasticizer (SCB) showed the lowest mass loss among all the groups, with a mass loss of 2.04%, 2.24%, 2.52%, and 2.67% at 0.40, 0.45, 0.50, and 0.55 w/b ratios respectively Figure 6.29.

As the w/b ratio increases, the porosity of the concrete also increases. This increased porosity allows the acid solution to penetrate deeper into the concrete matrix, leading to more extensive degradation of the cement paste and the aggregates. This is because the acid reacts with the calcium-based minerals in the cement paste, resulting in the formation of calcium salts which are soluble in water. As a result, the hardened concrete becomes weaker and more prone to mass loss, especially at higher w/b ratios where there is more space for the acid solution to penetrate. Additionally, the increased porosity at higher w/b ratios can also facilitate the migration of harmful ions into the concrete, further accelerating the deterioration process.

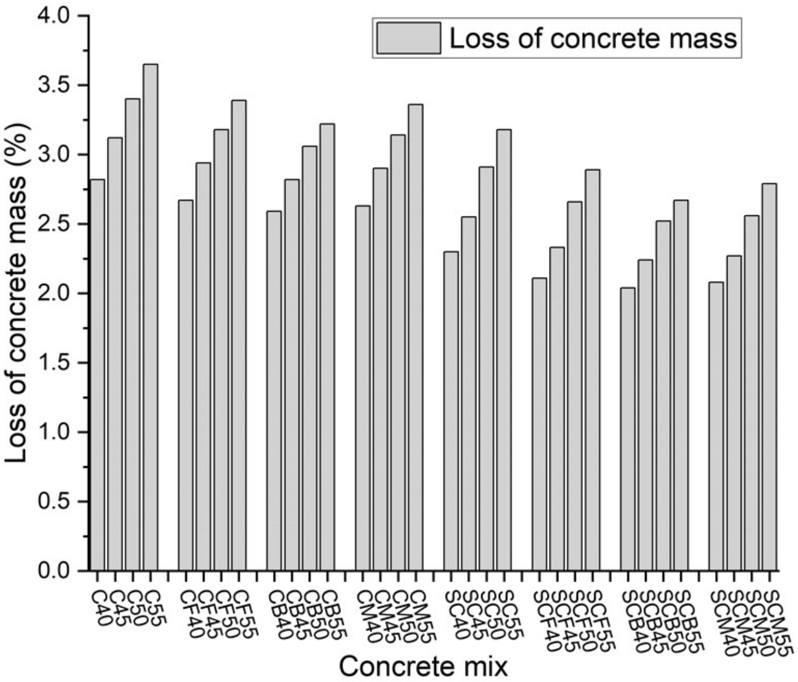

Figure 6.29 Percentage loss of mass in concrete

6.4.1.2 Effect of Mineral Admixture

The mass loss of concrete due to acid attack depends on the type and amount of mineral admixtures used in the concrete mix. The use of mineral admixtures such as FA, GGBS, and MS can significantly improve the durability of concrete against acid attack.

Compared to plain concrete (C), the addition of 30% FA (CF), 50% GGBS (CB) or 10% MS (CM) has shown to reduce the mass loss of concrete at all w/b ratios. At 0.4 w/b ratio, the mass loss of CF40, CB40, and CM40 was reduced by 6.71%, 19.75%, and 14.75% respectively, compared to C40. Similarly, at 0.55 w/b ratio, the mass loss of CF55, CB55, and CM55 was reduced by 12.77%, 27.45%, and 22.8%, respectively, compared to C55 Compared to plain concrete with SP (SC), the addition of 30% FA with SP (SCF), 50% GGBS with SP (SCB), or 10% MS with SP (SCM) has shown to reduce the mass loss of concrete at all w/b ratios. At 0.4 w/b ratio, the mass loss of SCF40, SCB40, and SCM40 was reduced by 12.1%, 23.35%, and 16.63% respectively, compared to SC40. Similarly, at 0.55 w/b ratio, the mass loss of SCF55, SCB55, and SCM55 was reduced by 13.14%, 26.08%, and 19.51%, respectively, compared to SC55 given in Table 6.3

When comparing the effect of mineral admixtures on the mass loss of concrete at their respective w/b ratios, it can be observed that the addition of GGBS is more effective in reducing the mass loss compared to FA and MS at all w/b.

The addition of mineral admixtures such as FA, GGBS, and MS a can significantly reduce the mass loss of concrete in acidic environments. This is due to the fact that these admixtures are pozzolanic in nature, meaning they react with the calcium hydroxide produced during cement hydration to form additional cementitious material.

GGBS concrete often exhibits superior acid resistance compared to concrete admixed with FA and MS. This enhanced acid resistance can be attributed to several factors.

GGBS is a byproduct of the iron and steel industry, rich in silica and alumina, which contributes to its pozzolanic reactivity. When incorporated into concrete, GGBS reacts with calcium hydroxide generated during cement hydration, forming additional cementitious material. This results in a denser microstructure with reduced permeability, limiting the penetration of acidic agents into the concrete matrix.

Moreover, GGBS generally has a higher replacement percentage than FA and MS, implying a greater substitution of cement clinker in the mix. This higher replacement not only enhances the utilization of industrial byproducts but also alters the overall composition of the concrete, influencing its chemical and physical characteristics. Additionally, GGBS contains compounds like calcium aluminate silicate hydrate, which contribute to improved durability in aggressive environments.

The formation of additional cementitious material leads to a denser microstructure, reducing the permeability of concrete and thus limiting the penetration of acid. Additionally, the reaction of these pozzolanic materials with the calcium hydroxide can also lead to the formation of calcium silicate hydrate (C-S-H) gel, which can fill any voids or cracks within the concrete and further enhance its durability.

Table 6.3 Loss of mass(%) and loss of strength(%) under 90 days immersion in acid solution

w/b	Sample	Compressive strength (MPa)		% Loss of mass of concrete (LOM)	% Loss of strength (LOS)	% Loss of mass of steel (LOMs)
		118-d WC	28-d WC+90-d Acid curing			
0.4	C40	49.68	43.28	2.82	-12.88	0.15
0.45	C45	46.71	39.25	3.12	-15.97	0.2
0.5	C50	43.63	35.28	3.4	-19.14	0.24
0.55	C55	37.80	29.48	3.65	-22.01	0.3
0.4	CF40	53.15	46.5	2.67	-12.51	0.14
0.45	CF45	49.87	42.23	2.94	-15.33	0.18
0.5	CF50	45.68	37.32	3.18	-18.31	0.22
0.55	CF55	39.48	31	3.39	-21.49	0.26
0.4	CB40	44.80	39.5	2.59	-11.83	0.12

0.45	CB45	41.75	36.2	2.82	-13.3	0.16
0.5	CB50	38.90	33.21	3.06	-14.63	0.19
0.55	CB55	33.12	27.5	3.22	-16.98	0.22
0.4	CM40	57.56	50.6	2.63	-12.1	0.13
0.45	CM45	54.06	46	2.9	-14.92	0.17
0.5	CM50	50.44	42.5	3.14	-15.73	0.2
0.55	CM55	43.52	35.6	3.36	-18.21	0.23
0.4	SC40	64.48	57.6	2.3	-10.66	0.13
0.45	SC45	61.02	53.52	2.55	-12.29	0.17
0.5	SC50	57.13	49	2.91	-14.23	0.21
0.55	SC55	49.90	41.2	3.18	-17.43	0.26
0.4	SCF40	61.67	54.2	2.11	-12.11	0.11
0.45	SCF45	58.10	49.6	2.33	-14.64	0.15
0.5	SCF50	54.32	45.3	2.66	-16.61	0.18
0.55	SCF55	47.09	38.2	2.89	-18.88	0.22
0.4	SCB40	58.75	53.2	2.04	-9.45	0.1
0.45	SCB45	55.08	48.5	2.24	-11.95	0.13
0.5	SCB50	50.65	43.5	2.52	-14.12	0.16
0.55	SCB55	43.42	36.2	2.67	-16.62	0.19
0.4	SCM40	70.42	63.2	2.08	-10.25	0.11
0.45	SCM45	65.88	58.3	2.27	-11.51	0.14
0.5	SCM50	61.24	52.9	2.56	-13.61	0.17
0.55	SCM55	53.03	45	2.79	-15.14	0.21

6.4.1.3 Effect of SP

The addition of superplasticizer (SP) had a significant effect on the mass loss of concrete specimens. Overall, the use of SP reduced the mass loss of concrete specimens, especially at higher w/b ratios.

Comparing plain concrete (C) to concrete with SP (SC), it can be observed that at all w/b ratios, the use of SP resulted in a significant reduction in mass loss. For instance, at 0.4 w/b ratio, the mass loss was reduced from 2.82% in C40 to 2.30% in SC40, indicating a reduction of 18.51%.

Similarly, for concrete with FA (CF) and SP (SCF), the addition of SP resulted in a reduction in mass loss at all w/b ratios. At 0.45 w/b ratio, the mass loss was reduced from 2.94% in CF45 to 2.33% in SCF45, indicating a reduction of 20.67% For concrete with GGBS (CB) and SP (SCB), the use of SP also resulted in a reduction in mass loss at all w/b ratios. For instance, at 0.55 w/b ratio, the mass loss was reduced from 3.22% in CB55 to 2.67% in SCB55, indicating a reduction of 16.83%. In the case of concrete with MS (CM) and SP (SCM), the addition of SP resulted in a reduction in mass loss at all w/b ratios. At 0.5 w/b ratio, the mass loss was reduced from 3.14% in CM50 to 2.56% in SCM50, indicating a reduction of 18.4% given in Table 6.3.

Overall, it can be observed that the addition of SP resulted in a significant reduction in mass loss for all types of concrete mixtures. The addition of superplasticizer in concrete mixtures can enhance the workability and flowability of the concrete, which results in a denser and more compacted structure. This can lead to a reduction in the permeability of the concrete and decrease the rate of acid attack, resulting in lower mass loss. Additionally, superplasticizers can help to reduce the water content in the concrete mix, which can also contribute to a denser and more durable concrete structure.

6.4.1.4 Combined Effect of Mineral Admixture and Superplasticizer

The combined effect of mineral admixture and SP on mass loss was analyzed by comparing C to SCF, C to SCB, and C to SCM at all w/b ratios. The addition of mineral admixtures and SP reduced the mass loss of concrete significantly.

In the case of C to SCF comparison, it was observed that the addition of 30% FA and SP reduced the mass loss by 25.28%, 25.28%, 21.85%, and 20.65% for w/b ratios of 0.4, 0.45, 0.5, and 0.55, respectively. Similarly, the addition of 50% GGBS and SP in C to SCB comparison reduced the mass loss by 27.78%, 28.17%, 26%, and 26.67% for w/b ratios of 0.4, 0.45, 0.5, and 0.55, respectively. In the case of C to SCM comparison, the addition of 10% MS and SP reduced the mass loss by 26.39%, 27.16%, 24.73%, and 23.63% for w/b ratios of 0.4, 0.45, 0.5, and 0.55, respectively given in Table 6.3 and shown in Figure 6.29.

The main cause behind the reduction of mass loss due to the combined effect of mineral admixtures and SP is the formation of a more impermeable concrete matrix. The mineral admixtures and SP reduce the water-cement ratio by increasing the workability of concrete, which results in a denser concrete matrix with fewer voids. The denser matrix restricts the penetration of acidic ions and, thus, reduces the mass loss of concrete.

Overall, the addition of mineral admixtures and SP can significantly reduce the mass loss of concrete in acidic environments, and the reduction in mass loss is more pronounced when mineral admixtures such as GGBS are used.

6.4.2 Loss of Compressive Strength

The compressive strength of different concrete mix immersed in water for 28 days and then in acidic solution for 90 days is given in Table 6.3 and shown in Figure 6.30 along with 118 days of water curing. The percentage loss of compressive strength of concrete when immersed in acidic solution is given in Table 6.2 and shown in Figure 6.11.

When concrete is immersed in acid, it undergoes a chemical reaction known as acid attack. The acid reacts with the hydrated cement minerals in the concrete, leading to the breakdown of the calcium silicate hydrate (C-S-H) gel and the calcium hydroxide ($Ca(OH)_2$) crystals. This leads to the formation of calcium sulfate ($CaSO_4$) and other soluble salts, resulting in the loss of compressive strength of the concrete.

When cement is exposed to sulfuric acid, the reaction can be divided into four stages. In the first stage, the sulfuric acid dissociates in water to form hydrogen ions (H^+) and sulfate ions (SO_4^{2-}), as shown in Equation 6.1. Then, in the second stage, the hydrogen ions react with the calcium hydroxide ($Ca(OH)_2$) in the cement paste to form water and calcium ions (Ca_2^+), as shown in Equation 6.2. In the third stage, the sulfate ions combine with the calcium ions to form gypsum ($CaSO_4{\cdot}2H_2O$), as shown in Equation 6.3. In the final stage, the calcium ions can also combine with the aluminate ions (AlO_2^-) in the cement paste to form ettringite ($3CaO·Al_2O_3·3CaSO_4·32H_2O$), as shown in Equation 6.4. The overall reaction of H_2SO_4 with cement can lead to the formation of both gypsum and ettringite, which can cause damage to the cement paste and reduce its strength. This is because the formation of these compounds increases the porosity and reduces the integrity of the cement paste. As a result, the concrete may become more susceptible to further deterioration, such as cracking and spalling.

When cement is exposed to nitric acid, several reactions can occur. The overall reaction can be divided into three stages: In the first stage, nitric acid reacts with calcium hydroxide in the cement to form calcium nitrate and water, as shown in Equation 6.5, In the second stage, the formed calcium nitrate can react with more nitric acid to produce nitrogen dioxide, calcium nitrate, and water, as shown in Equation 6.6, In the third stage, if enough nitric acid is present, calcium nitrate can react further to produce more nitrogen dioxide, calcium nitrate, water, and oxygen, as shown in Equation 6.7. Overall, the reaction of cement with nitric acid can lead to the formation of nitrogen dioxide, which can cause damage to the cement paste and reduce its strength. The reaction can also result in the formation of calcium nitrate, which can contribute to the formation of efflorescence on the surface of the cement.

The chemical reactions that occur during acid attack can be represented as follows:

For sulfuric acid (H_2SO_4): Equation 6.1: The reaction of sulfuric acid with water results in the formation of hydrogen ions (H+) and hydrogen sulfate ions (HSO4-). Equation 6.2: The subsequent reaction involves the combination of hydrogen ions with calcium hydroxide, yielding calcium ions (Ca2+) and water. Equation 6.3: Further interaction of calcium ions with sulfate ions and water produces calcium sulfate dihydrate. Equation

6.4: A more complex reaction involves the combination of calcium ions, aluminate ions, sulfate ions, and water, resulting in the formation of a hydrated calcium aluminate sulfate compound.

$H_2SO_4 + H_2O \rightarrow H^+ + HSO_4^-$ Equation 6.1

$2H^+ + Ca(OH)2 \rightarrow Ca^{2+} + 2H_2O$ Equation 6.2

$Ca^{2+} + SO4^{2-} + 2H_2O \rightarrow CaSO4 \cdot 2H_2O$ Equation 6.3

$3Ca^{2+} + 2AlO_2^- + 3SO_4^{2-} + 32H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ Equation 6.4

For nitric acid (HNO_3): Equation 6.5: Nitric acid reacts with calcium hydroxide, leading to the formation of calcium nitrate and water. Equation 6.6: Subsequent reactions involve the conversion of calcium nitrate and additional nitric acid into nitrogen dioxide and calcium nitrate. Equation 6.7: Further reaction results in the generation of nitrogen dioxide, calcium nitrate, water, and oxygen. These equations describe the chemical transformations involving sulfuric acid and nitric acid in the presence of calcium hydroxide.

$HNO_3 + Ca(OH)_2 \rightarrow Ca(NO_3)_2 + 2H_2O$ Equation 6.5

$Ca(NO_3)_2 + 2HNO_3 \rightarrow 2NO_2 + Ca(NO_3)_2 + H_2O$ Equation 6.6

$Ca(NO_3)_2 + 4HNO_3 \rightarrow 2NO_2 + Ca(NO_3)_2 + 2H_2O + O_2$ Equation 6.7

The loss of compressive strength due to acid attack can be significant, especially in concretes with high water-to-binder (w/b) ratios. Therefore, it is important to consider the effects of acid attack when designing concrete mixtures for environments where exposure to acid is likely. The use of mineral admixtures, such as FA, MS and GGBS, and chemical admixtures, such as superplasticizers, can help mitigate the effects of acid attack on concrete [63], [86], [267], [270], [283], [284].

6.4.2.1 Effect of w/b

The effect of w/b ratio on strength loss due to acid attack was studied by comparing the percentage loss of strength of different concrete mixtures with varying w/b ratios. The data shows that as the w/b ratio increases, the percentage loss of strength due to acid attack also increases.

When comparing the 0.4 w/b to the other w/b, it can be observed that the percentage loss of strength due to acid attack increases as the w/b ratio increases. For example, in the C group, the percentage loss of strength due to acid attack increases from -12.88% for the C40 mixture to -22.01% for the C55 mixture. Similarly, in the CF group, the percentage loss of strength due to acid attack increases from -12.51% for the CF40 mixture to -21.49% for the CF55 mixture.

In the CB group, the percentage loss of strength due to acid attack increases from -11.83% for the CB40 mixture to -16.98% for the CB55 mixture. In the CM group, the percentage loss of strength due to acid attack increases from -12.1% for the CM40 mixture to -18.21% for the CM55 mixture.

In the SC group, the percentage loss of strength due to acid attack increases from -10.66% for the SC40 mixture to -17.43% for the SC55 mixture. In the SCF group, the percentage loss of strength due to acid attack increases from -12.11% for the SCF40 mixture to -18.88% for the SCF55 mixture. In the SCB group, the percentage loss of strength due to acid attack increases from -9.45% for the SCB40 mixture to -16.62% for the SCB55 mixture.

In the SCM group, the percentage loss of strength due to acid attack increases from -10.25% for the SCM40 mixture to -15.14% for the SCM55 mixture as given in

Table 6.3 and shown Figure 6.30.

When water is added to cement, a chemical reaction called hydration takes place, which forms a strong, hardened material called cement paste. The strength of the cement paste is directly related to the amount of cement particles that are hydrated and bound together by the reaction products. When the w/b ratio is increased, the amount of water in the mixture also increases, which means that the amount of available water for the hydration reaction decreases. As a result, the cement particles are not hydrated as effectively, and the strength of the resulting cement paste is reduced.

In the case of acid attack on concrete, the acidic solution can dissolve the hydrated cement paste and break the bonds between the cement particles. As a result, the strength of the concrete is reduced. When the w/b ratio is increased, the strength of the resulting cement paste is already reduced, which makes the concrete more vulnerable to acid attack and further reduces its strength.

Additionally, a higher w/b ratio can lead to more porosity in the concrete, which provides more pathways for the acid to penetrate and attack the cement paste. This can also contribute to a greater loss in strength.

Therefore, as the w/b ratio increases, the strength of the cement paste and the resulting concrete decreases, making it more susceptible to acid attack and leading to a greater loss in strength.

6.4.2.2 Effect of Mineral Admixture

In the comparison of different types of mineral admixtures, it was observed that the use of FA (CF), GGBS (CB), and MS (CM) resulted in lower strength loss when compared to the control mixture (C) across all the tested w/b ratios. However, the extent of strength loss reduction varied depending on the type of mineral admixture used and the w/b ratio. For instance, at w/b = 0.4, the use of CF, CB, and CM resulted in strength loss reductions of 12.51%, 11.83%, and 12.1%, respectively, whereas the control concrete (C) exhibited a strength loss of 12.88%. Similarly, at w/b = 0.55, the use of CF, CB, and CM resulted in strength loss reductions of 21.49%, 16.98%, and 18.21%, respectively, while the control concrete (C) exhibited a strength loss of 22.01%.These findings are presented in Table 6.3 and illustrated in Figure 6.30

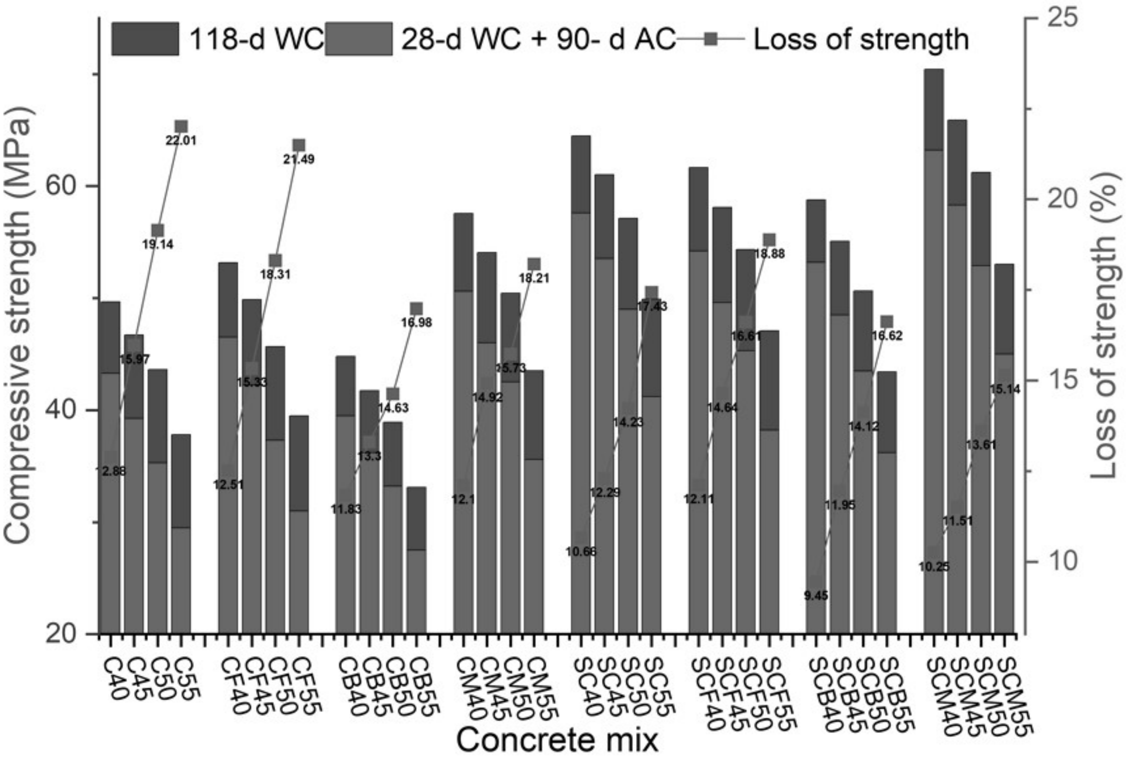

Figure 6.30 CS of 118-d WC and 118- combined curing (28-d WC +118 –AC) and % LOS

6.4.2.3 Effect of SP

The effect of SP on strength loss due to acid attack was also investigated at various w/b ratios, and the results were compared with those of concrete containing different types of mineral admixtures. The percentage of strength loss for each type of concrete mixture is shown in Table 6.3 and illustrated in Figure 6.30.

At all w/b ratios tested, the use of SP resulted in lower strength loss compared to the control mixture (C) without any additives. At w/b = 0.4, the use of SP (SC) resulted in a strength loss reduction of 10.66%, while control concrete (C) showed a strength loss of 12.88%. Similarly, at w/b = 0.55, the use of SP (SC) resulted in a strength loss reduction of 17.43%, while control concrete (C) showed a strength loss of 22.01%.

When comparing the effect of SP with different types of mineral admixtures, it was found that the use of SP resulted in lower strength loss. At w/b = 0.4 SCF resulted in a strength loss reduction of 12.11%, while CF showed a strength loss of 12.51%. Similarly, at w/b = 0.55, the use of SP with FA (SCF) resulted in a strength loss reduction of 18.88%, while CF showed a strength loss of 21.49%. At w/b = 0.4 SCB resulted in a strength loss reduction of 9.45%, while CB showed a strength loss of 11.83%. Similarly, at w/b = 0.55, the use of SP with GGBS (SCB) resulted in a strength loss reduction of 16.62%, while CB showed a strength loss of 16.98%. For MS admixed concrete at w/b = 0.4 SCM resulted in a strength loss reduction of 10.25%, while CM showed a strength loss of 12.1%. Similarly, at w/b = 0.55, the use of SP with MS (SCM) resulted in a strength loss reduction of 15.14%, while CM showed a strength loss of 18.21%.

The addition of SP (superplasticizer) can help reduce the water content required for a given workability, leading to a reduction in the w/b ratio. This, in turn, can improve the strength and durability of concrete. SP works by dispersing the cement particles and reducing the surface tension of the mixing water, allowing for improved particle packing and reduced void content [203] . As a result, the use of SP can help improve the resistance of concrete to acid attack by reducing the permeability and increasing the density of the concrete matrix [285]. Additionally, SP can also improve the workability of concrete, making it easier to place and consolidate, which can also improve the homogeneity and density of the concrete.

6.4.2.4 Combined Effect of Mineral Admixture and SP

The combined effect of mineral admixture and SP on strength loss due to acid attack was investigated at various w/b ratios. The results showed that the use of SP resulted in lower strength loss compared to the control mixture (C) without any additives at all w/b ratios tested.

When comparing the effect of SP with different types of mineral admixtures, it was found that the use of SP with mineral admixture resulted in lower strength loss. At w/b = 0.4, SCF resulted in a strength loss reduction of 12.11%, SCB showed a strength loss reduction of 9.45%, and SCM showed a strength loss reduction of 10.25%, compared to the control mixture (C) which showed a strength loss of 12.88%. Similarly, at w/b = 0.45, SCF resulted in a strength loss reduction of 14.64%, SCB showed a strength loss reduction of 11.95%, and SCM showed a strength loss reduction of 11.51%, compared to the control mixture (C) which showed a strength loss of 15.97%. At w/b = 0.5, SCF resulted in a strength loss reduction of 16.61%, SCB showed a strength loss reduction of 14.12%, and SCM showed a strength loss reduction of 13.61%, compared to the control mixture (C) which showed a strength loss of 19.14%. Finally, at w/b = 0.55, SCF resulted in a strength loss reduction of 18.88%, SCB showed a strength loss reduction of 16.62%, and SCM showed a strength loss reduction of 15.14%, compared to the control mixture (C) which showed a strength loss of 22.01%.

The combined use of SP and mineral admixtures was found to be more effective in reducing the strength loss of concrete due to acid attack than plain concrete without any additives. This is because the mineral admixtures, such as FA, GGBS, and MS, are known to enhance the durability of concrete by reducing the permeability of concrete and making it more resistant to chemical attacks [267], [286], [287]. When combined with SP, which is known to reduce the surface tension of water and improve the workability and homogeneity of concrete, the resulting concrete mixture is more resistant to acid attack.

Furthermore, the use of SP in combination with mineral admixtures can lead to improved microstructure of concrete, which can further enhance its resistance to acid attack. The combined effect of SP and mineral admixtures was found to be particularly effective at lower water-binder ratios, where the concrete is more prone to cracking and damage due to acid attack. Overall, the use of SP in combination with mineral admixtures can improve the durability of concrete and enhance its resistance to acid attack as given in

Table 6.3 and illustrated in Figure 6.30.

6.4.3 Efficiency of Admixtures as Inhibitors in Concrete

Steel reinforcement in concrete structures can be subjected to corrosion in acidic environments, leading to a reduction in structural integrity and service life. The corrosion of steel in concrete can occur due to the penetration of acid through the concrete cover and the subsequent breakdown of the passive film that protects the steel from corrosion.

In acidic environments, the pH of the concrete decreases, leading to an increase in the corrosion rate of steel reinforcement. Acidic environments can arise due to the presence of acid rain, chemical spills, or the immersion of concrete structures in acidic solutions.

The corrosion of steel reinforcement in concrete due to immersion in acid can be accelerated due to the presence of chloride ions. Chloride ions can penetrate the concrete cover and break down the passive film on the steel, leading to increased corrosion rates. The presence of mineral admixtures such as FA, MS, and GGBS in concrete can help to reduce the penetration of chloride ions and slow down the corrosion of steel reinforcement in acidic environments.

Similarly, the use of superplasticizers such as polycarboxylate-based additives can help to reduce the permeability of concrete and improve the durability of the concrete in acidic environments. The reduced permeability of concrete can help to limit the penetration of acid and other harmful substances, thereby reducing the corrosion of steel reinforcement and increasing the service life of the structure.

The corrosion of steel of different concrete mix immersed in water for 28 days and then in acidic solution for 90 days is given in Table 6.3 and shown in Figure 6.31.

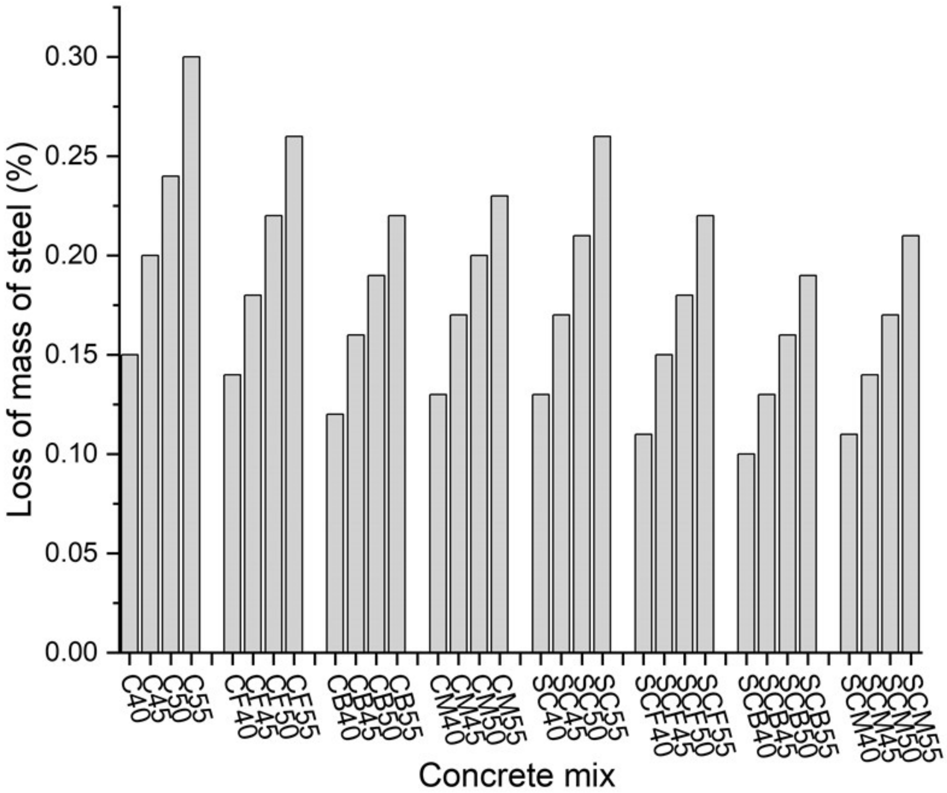

Figure 6.31 Percentage loss of steel mass of different concrete mix

6.4.3.1 Effect of w/b

The effect of w/b ratio on mass loss due to acid attack was studied by comparing the percentage loss of mass of steel of different concrete mixtures with varying w/b ratios.

The data shows that as the w/b ratio increases, the percentage loss of strength due to acid attack also increases as given in Table 6.3 and shown in Figure 6.31.

The percentage mass loss of steel due to acidic immersion varied for each group at different w/b ratios. For the C group, at a w/b ratio of 0.4, the percentage mass loss of steel was 0.15, which increased to 0.2 at 0.45 w/b (29.73% increase), 0.24 at 0.5 w/b (57.77% increase), and 0.3 at 0.55 w/b (92.57% increase). Similarly, for the CF group, the percentage mass loss of steel was 0.14 at 0.4 w/b, 0.18 at 0.45 w/b (28% increase), 0.22 at 0.5 w/b (50.42% increase), and 0.26 at 0.55 w/b (80.07% increase). For the CB group, the percentage mass loss of steel was 0.12 at 0.4 w/b, 0.16 at 0.45 w/b (27.63% increase), 0.19 at 0.5 w/b (50.98% increase), and 0.22 at 0.55 w/b (74.11% increase). Similarly, for the CM group, the percentage mass loss of steel was 0.13 at 0.4 w/b, 0.17 at 0.45 w/b (27.63% increase), 0.2 at 0.5 w/b (50.98% increase), and 0.23 at 0.55 w/b (74.39% increase).

For the SC group, the percentage mass loss of steel was 0.13 at 0.4 w/b, 0.17 at 0.45 w/b (33.1% increase), 0.21 at 0.5 w/b (64.26% increase), and 0.26 at 0.55 w/b (100.99% increase). Similarly, for the SCF group, the percentage mass loss of steel was 0.11 at 0.4 w/b, 0.15 at 0.45 w/b (32.27% increase), 0.18 at 0.5 w/b (62.76% increase), and 0.22 at 0.55 w/b (98.41% increase). For the SCB group, the percentage mass loss of steel was 0.1 at 0.4 w/b, 0.13 at 0.45 w/b (30.27% increase), 0.16 at 0.5 w/b (60% increase), and 0.19 at 0.55 w/b (94.59% increase). Similarly, for the SCM group, the percentage mass loss of steel was 0.11 at 0.4 w/b, 0.14 at 0.45 w/b (29.7% increase), 0.17 at 0.5 w/b (59.41% increase), and 0.21 at 0.55 w/b (94.6% increase).

As the w/b ratio increases, the amount of water available for the reaction with the cementitious material also increases, resulting in higher porosity and reduced strength.

Higher porosity means that there is more space available for the acidic solution to penetrate and react with the steel reinforcement in the concrete.

Acidic solutions can dissolve the protective oxide layer on the surface of the steel reinforcement, leading to corrosion. This corrosion process occurs more rapidly when there is a higher concentration of acid solution, as well as a higher exposure time. In the case of the present study, the increase in corrosion rate with increasing w/b ratio could be attributed to the higher concentration of acid solution available for a longer time due to increased porosity at higher w/b ratios.

6.4.3.2 Effect of Mineral admixture

The effect of mineral admixtures on the corrosion of steel in concrete was also studied. The comparison of the C group with CF, CB, and CM groups showed that the addition of FA, GGBS, and MS reduced the percentage mass loss of steel due to acidic immersion at all w/b ratios. For example, at a w/b ratio of 0.4, the percentage mass loss of steel for the C group was 0.15, while for the CF, CB, and CM groups, it was 0.14, 0.12, and 0.13, respectively which is 6.71%, 19.75% and 14.75% lower than the control concrete as shown in Figure 6.32

Similarly, the comparison of the SC group with SCF, SCB, and SCM groups showed that the addition of FA, GGBS, and MS reduced the percentage mass loss of steel due to acidic immersion at all w/b ratios. For instance, at a w/b ratio of 0.4, the percentage mass loss of steel for the SC group was 0.13, while for the SCF, SCB, and SCM groups, it was 0.11, 0.1, and 0.11, respectively which is 12.01%, 27.45% and 22.8% lower than the control concrete with SP as shown in Figure 6.33

As w/b ratio increases inhibition efficiency of mineral admixture also increases as given in Table 6.3 and shown in and Figure 6.33

The improvement in corrosion inhibition efficiency with the addition of mineral admixtures can be attributed to various factors. For example, fly ash and blast furnace slag contain high amounts of silica, which can react with calcium hydroxide to form additional C-S-H gel, leading to a denser and more impermeable concrete matrix. Micro silica, on the other hand, acts as a pozzolan and can react with the calcium hydroxide to form additional C-S-H gel, which can also lead to a denser and more impermeable concrete matrix. Additionally, the use of mineral admixtures can reduce the water content in the concrete, which can lead to a reduction in the diffusion of corrosive agents, such as chloride ions. Overall, the addition of mineral admixtures to concrete can improve its corrosion resistance and increase its durability.

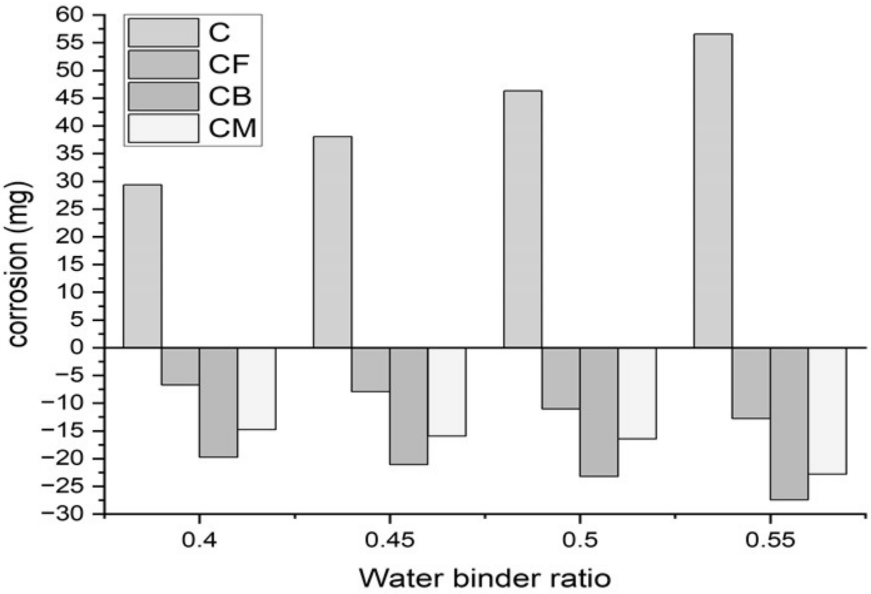

Figure 6.32 Steel weight loss and mineral admixture corrosion efficiency w.r.t control concrete without SP

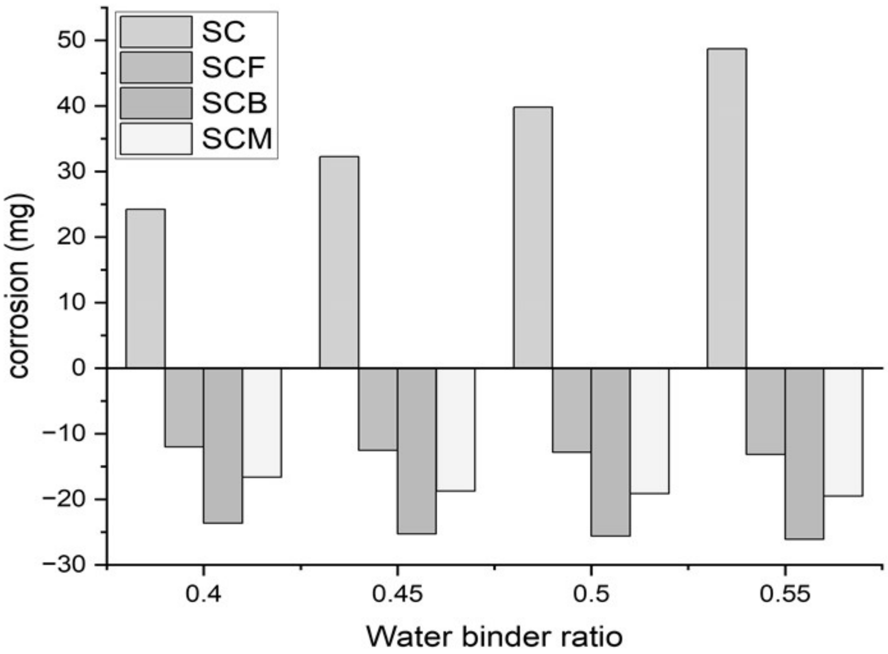

Figure 6.33 Steel weight loss and mineral admixture corrosion efficiency w.r.t control concrete with SP

6.4.3.3 Effect of SP

The effect of superplasticizer (SP) on the corrosion inhibition efficiency was also studied for all water to binder ratios. The comparison was made between the C group and SC group, CF group and SCF group, CB group and SCB group, and CM group and SCM group.

For the C group and SC group, at a w/b ratio of 0.4, the percentage mass loss of steel due to acidic immersion was 0.15 and 0.13, respectively. At a w/b ratio of 0.45, the percentage mass loss increased to 0.2 for the C group and 0.17 for the SC group. Similarly, at a w/b ratio of 0.5, the percentage mass loss increased to 0.24 for the C group and 0.21 for the SC group. At a w/b ratio of 0.55, the percentage mass loss further increased to 0.3 for the C group and 0.26 for the SC group. For the CF group and SCF group, at a w/b ratio of 0.4, the percentage mass loss of steel due to acidic immersion was 0.14 and 0.11, respectively. At a w/b ratio of 0.45, the percentage mass loss increased to 0.18 for the CF group and 0.15 for the SCF group. Similarly, at a w/b ratio of 0.5, the percentage mass loss increased to 0.22 for the CF group and 0.18 for the SCF group. At a w/b ratio of 0.55, the percentage mass loss further increased to 0.26 for the CF group and 0.22 for the SCF group. For the CB group and SCB group, at a w/b ratio of 0.4, the percentage mass loss of steel due to acidic immersion was 0.12 and 0.1, respectively. At a w/b ratio of 0.45, the percentage mass loss increased to 0.16 for the CB group and 0.13 for the SCB group. Similarly, at a w/b ratio of 0.5, the percentage mass loss increased to 0.19 for the CB group and 0.16 for the SCB group. At a w/b ratio of 0.55, the percentage mass loss further increased to 0.22 for the CB group and 0.19 for the SCB group. For the CM group and SCM group, at a w/b ratio of 0.4, the percentage mass loss of steel due to acidic immersion was 0.13 and 0.11, respectively. At a w/b ratio of 0.45, the percentage mass loss increased to 0.17 for the CM group and 0.14 for the SCM group. Similarly, at a w/b ratio of 0.5, the percentage mass loss increased to 0.2 for the CM group and 0.17 for the SCM group. At a w/b ratio of 0.55, the percentage mass loss further increased to 0.23 for the CM group and 0.21 for the SCM group.

It was observed that the percentage mass loss due to acidic immersion was lower in all groups that included superplasticizer (SC, SCF, SCB, and SCM) as compared to their respective groups without superplasticizer (C, CF, CB, and CM). This indicates that the superplasticizer has a positive effect on the corrosion inhibition efficiency of the concrete.

The addition of superplasticizers (SP) in concrete mixtures can decrease the corrosion rate of steel reinforcement. This is due to the fact that SP can enhance the workability and flowability of the fresh concrete mixture [88], [226], which leads to a more homogenous and compacted concrete structure. This, in turn, reduces the permeability of the concrete, making it more difficult for aggressive ions, such as chloride and sulfate ions, to penetrate the concrete and reach the steel reinforcement.

6.4.3.4 Combined Effect of Mineral Admixture and SP

The combined effect of mineral admixture and SP on corrosion due to acid attack was investigated at various w/b ratios. The results showed that the use of SP resulted in lower corrosion compared to the control mixture (C) without any additives at all w/b ratios tested.

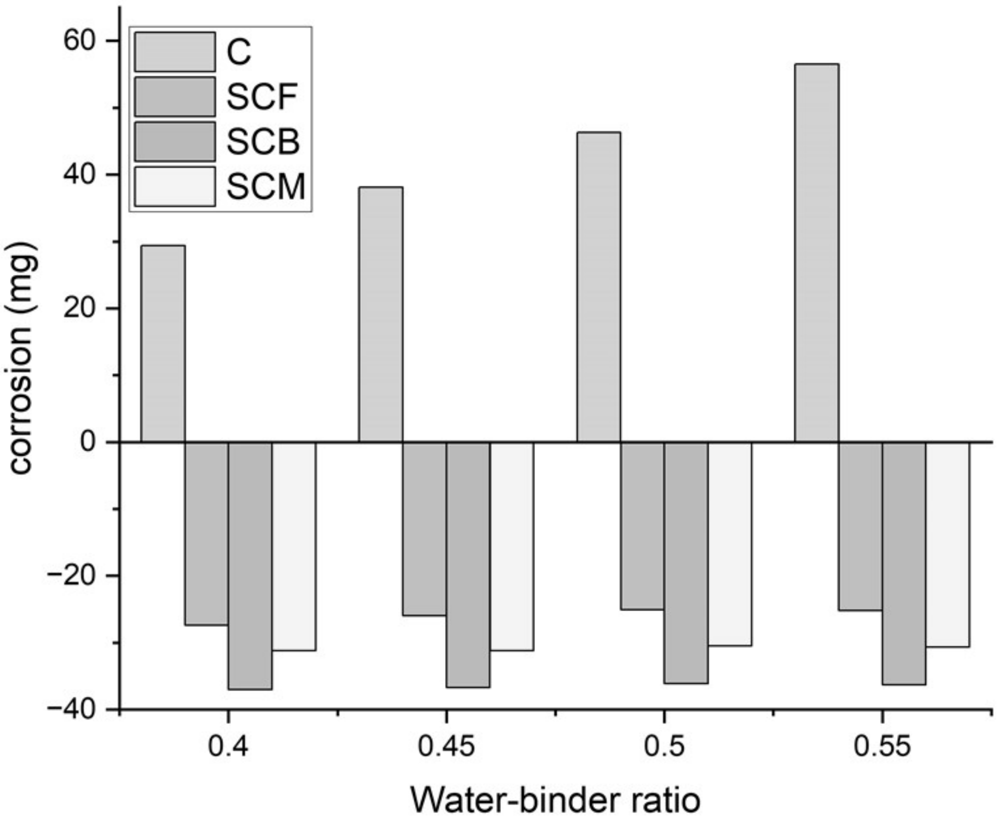

Figure 6.34 Steel weight loss and mineral admixture corrosion efficiency with SP w.r.t control concrete without SP

At w/b ratio of 0.4, the corrosion of steel bar of C was 29.36 mg and the inhibition efficiency of SCF was 27.38 %, SCB was 36.99%, and SCM was 31.2%. At w/b ratio of 0.45, the corrosion of steel bar of C was 38.09 mg and the inhibition efficiency of SCF was 25.96%, SCB was 36.73%, and SCM was 31.22%. At w/b ratio of 0.5, the corrosion of steel bar of C was 46.32 mg and the inhibition efficiency of SCF was 25.09%, SCB was 36.1%, and SCM was 30.48%. At w/b ratio of 0.55, the corrosion of steel bar of C was 48.7 mg, and the inhibition efficiency of SCF was 25.18%, SCB was 36.33%, and SCM was 30.67% that means lower corrosion than control concrete as shown in Figure 6.34 in which above horizontal; line mass loss of steel shown in mg and below horizontal line % inhibition efficiency of mineral admixture has been shown with respect to control concrete without SP.

Overall, it can be seen that SCB and SCM showed better inhibition efficiency compared to SCF at all water-to-binder ratios. Additionally, the inhibition efficiency decreased as the water-to-binder ratio increased for all samples.

The combination of superplasticizers (SP) and mineral admixtures in concrete mixtures can be more effective in reducing corrosion rates of steel reinforcement compared to their individual effects. This is because SP enhances the workability and flowability of the fresh concrete mixture, leading to a more homogenous and compacted concrete structure, which in turn reduces the permeability of the concrete. The addition of mineral admixtures such as fly ash, silica fume, and slag further decreases the permeability of the concrete due to their pozzolanic properties. The pozzolanic reaction results in the formation of calcium silicate hydrates (C-S-H) gel, which fills the pores in the concrete, making it more difficult for aggressive ions to penetrate and reach the steel reinforcement. The combination of SP and mineral admixtures also improves the microstructure of the concrete by reducing the porosity and increasing the density, resulting in a more corrosion-resistant concrete. Therefore, the combination of SP and mineral admixtures can provide a synergistic effect in reducing corrosion rates of steel reinforcement in concrete structures.

6.5 CONCLUSION

The addition of mineral admixtures and superplasticizers significantly reduced the water permeability of concrete compared to the control group. At all w/b ratios and testing periods, the SCM group consistently exhibited the lowest permeability coefficient, followed by the SCF and SCB groups. The use of mineral admixtures and superplasticizers can improve the durability of concrete by reducing its water permeability.

The addition of mineral admixtures and superplasticizer has a positive effect on the carbonation resistance of concrete. The results of the study show that the use of these additives can improve the durability of concrete in carbonating environments. Among the mineral admixtures tested, SCM showed the highest improvement in carbonation resistance, followed by SCF and SCB. However, all the mineral admixtures showed significant improvements in carbonation resistance when used in combination with superplasticizer. Therefore, the use of mineral admixtures and superplasticizer can be considered as an effective strategy for enhancing the carbonation resistance of concrete structures.

The addition of mineral admixtures and superplasticizers resulted in a significant reduction in the mass loss of concrete subjected to acid attack. The use of 30% FA and SP (SCF), 50% GGBS and SP (SCB), and 10% MS and SP (SCM) led to reduced mass loss by 20.65-25.28%, 26-28.17%, and 23.63-27.16%, respectively, compared to the control mixture (C) at various w/b ratios. Therefore, it can be concluded that the combined use of mineral admixtures and superplasticizers can improve the acid resistance of concrete.

The use of SP with mineral admixture resulted in lower strength loss due to acid attack compared to the control mixture without any additives at all w/b ratios tested. Among the mineral admixtures tested, SCF showed the highest strength loss reduction at all w/b ratios, followed by SCB and SCM. The results suggest that the combination of SP and mineral admixture can be an effective strategy to mitigate the strength loss of concrete under acid attack

The use of SP in combination with mineral admixtures resulted in lower corrosion rates in concrete due to acid attack compared to control concrete without any additives. At all w/b ratios tested, the inhibition efficiency of SCF, SCB, and SCM was higher than that of the control mixture. The highest inhibition efficiency was observed in SCB, followed by SCM and SCF. Overall, the results indicate that the combined use of mineral admixtures and SP can improve the durability of concrete against acid attack and reduce the corrosion rate of steel reinforcement.