CHAPTER 3

RESULTS AND DISCUSSION

3.1 PREPARATION OF BINARY BLENDED CONCRETE

3.1.1 General

The binary blended concrete was prepared by adding mineral admixtures for partial replacement of cement along with other ingredients. FA based and RHA based binary blended concrete specimens were prepared for M 20, M 30 and M 40 grades of concrete. The optimum replacement level of ASTM class F type FA and RHA was determined using compressive strength of the concrete.

3.1.2 Compressive Strength of Binary Blended Concrete

The compressive strength of M 20 grade control concrete specimen at the age of 28 days was found as 28.74 MPa. The early age (7 days) and later age (90 days) strength of M 20 grade control concrete were found as 19.41 MPa and 31.11 MPa respectively. When cement was replaced by FA from 5% to 25%, the compressive strength reduced from 18.13 MPa at 5% replacement to 10.47 MPa at 25% replacement after 7 days curing. The results of various cement replacement levels by FA after 7, 28 and 90 days curing of M 20 grade concrete specimens are shown in the Figure 3.1. The results of M 30 and M 40 grade concrete with various replacement levels are also shown in Figures 3.2 and 3.3 respectively. From Figures 3.1 to 3.3, it is observed that there is a gradual reduction in compressive strength of 7 days cured binary
blended concrete with increasing the percentage of FA content. The reduction in compressive strength at early age might be due to the non formation of secondary C-S-H gel and also slower pozzolanic reaction. Whereas, the compressive strength of 90 days cured concrete samples increased by increasing the replacement level of FA content upto 20 %, which is mainly due to the formation of secondary C-S-H gel. Further addition of FA (more than 20%) does not involve any reaction and act as only an inert material and hence compressive strength reduces (Ravina and Mehta 1986, Gopalakrishnan et al 2001 and Nathan Schwarz et al 2008). As per IS: 10262 – 1982, the theoretical target mean strength of 28 days curing of M 20, M 30 and M 40 grade concrete are 26.60, 38.25 and 48.25 MPa respectively. From the required theoretical target mean strength at 28 days and experimental results of 28 and 90 days cured specimens, it is found that optimum replacement of FA is 20% for M 20, M 30 and M 40 grade of concrete.

The results of 7, 28 and 90 days cured M 20 grade concrete using various cement replacement levels by RHA are shown in Figure 3.4. When cement was replaced by RHA from 5% to 25% for developing the RHA based binary blended concrete, the compressive strength reduced from 17.67 MPa at 5% replacement to 10.07 MPa at 25% replacement after 7 days curing due to slower pozzolanic reaction of RHA particle. Similar kinds of results were observed from M 30 concrete and M 40 grade concrete as shown in Figures 3.5 and 3.6. From Figures 3.4 to 3.6, it is observed that the compressive strength of 90 days cured concrete specimens increased by increasing the percentage of RHA content upto 18 % replacement level which is mainly due to the formation of secondary C-S-H gel. From the required theoretical target mean strength at 28 days and the experimental results of 28 and 90 days specimens, it is found that the optimum replacement level of RHA is 18% for developing the RHA based binary blended concrete (Raoul Jauberthie et al 2003).
Figure 3.1  Strength development of M 20 grade FA based binary blended concrete

Figure 3.2  Strength development of M 30 grade FA based binary blended concrete
Figure 3.3 Strength development of M 40 grade FA based binary blended concrete

Figure 3.4 Strength development of M 20 grade RHA based binary blended concrete
Figure 3.5  Strength development of M 30 grade RHA based binary blended concrete

Figure 3.6  Strength development of M 40 grade RHA based binary blended concrete
3.2 PREPARATION OF TERNARY BLENDED CONCRETE

The ternary blended concrete was prepared by adding a super fine mineral admixture namely Silica Fume (SF) as partial replacement of cement for all concrete grades of FA or RHA based binary blended concrete (M 20, M 30 and M 40 grades). The various replacement levels of SF such as 4%, 8% and 12% were used to determine the properties of concrete such as setting time of fresh concrete, hardened concrete and durable properties of concrete.

3.3 FRESH PROPERTIES OF TERNARY BLENDED CONCRETE

3.3.1 General

The fresh concrete properties such as workability based on slump value, air content and setting time of concrete were determined to ascertain the performance of fresh concrete.

3.3.2 Slump Value of Concrete

The slump values of control (PCC), binary and ternary blended concrete are shown in Figures 3.7 and 3.8. The M 20, M 30 and M 40 grade control concrete specimens have the slump value of 33mm, 28mm and 25mm respectively. The slump value of M 20, M 30 and M 40 grade 20% FA based binary blended concrete specimens were also found to be 35mm, 30mm and 26mm respectively. The addition of 20% FA increases the slump value of FA based binary blended concrete and it is mainly due to the ball bearing effect of spherical shaped FA particles. The slump value of 18% RHA binary blended concrete is found to approximately the same results of control concrete (Vanchai Sata et al 2007 and Chinprasirt et al 2007). The addition of the SF as second mineral admixture along with 18% RHA reduces the slump value of ternary blended concrete and the reduction is mainly due to the super fine nature of SF particles (Shweta Goyal et al 2008).
Figure 3.7 Slump value of FA based binary and ternary blended concrete

Figure 3.8 Slump value of RHA based binary and ternary blended concrete
3.3.3 Air Content

The results of investigation on air content of control, binary and ternary blended concrete are shown in Figures 3.9 and 3.10. The air content of M 20, M 30 and M 40 grade control concrete samples were 4.1%, 3.6% and 2.8% respectively. The air content of M 40 grade fresh concrete was found to be low compared to M 30 grade and M 20 grade of fresh concrete, which is due to the presence of more powder content and low w-c ratio. The addition of 20% FA reduces air content approximately 3.8%, 2.8% and 2.2% for M 20, M 30 and M 40 grade binary blended concrete respectively. The reduction of air content in FA based binary blended concrete is due to the pore filling effect of FA particles. The addition of 4% and 8% SF along with FA shows reduction of air content which is mainly due to the pore filling effect of superfine SF particles, where as the addition of 12% SF increases the air content which is mainly due to increasing water demand of SF particles.

The addition of 18% RHA reduces air content approximately 3.8%, 3.0% and 2.4% for M 20, M 30 and M 40 grade RHA based binary blended concrete respectively. The reduction of air content in RHA based binary blended concrete is due to pore filling effect of RHA particles. The addition of 4% and 8% SF along with 18% RHA reduces the air content approximately 3.5%, 2.4% and 2.1% for M 20, M 30 and M 40 grade concrete respectively compared to control concrete, where as the addition of 12% SF increases air content in all the specimens of M 20, M 30 and M 40 grade concrete than 4% and 8% replacement levels of SF due to increasing water demand of SF particles (Ramadoss and Nagamani 2008).
Figure 3.9 Air content of FA based binary and ternary blended concrete

Figure 3.10 Air content of RHA based binary and ternary blended concrete
3.3.4 Setting Time of Concrete

The penetration resistance curve was used to find the initial and final setting time of concrete and the details are shown in Figures 3.11 to 3.13. The initial and final setting time M 20 grade control concrete was found to be 5 hours 20 minutes and 7 hours 20 minutes respectively. The addition of more cement reduces initial and final setting time of concrete and hence the initial and final setting time of M 40 grade concrete is less compared to initial and final setting time of M 20 grade concrete.

![Penetration resistance curve of M 20 grade control and binary blended concretes](image)

Figure 3.11 Penetration resistance curve of M 20 grade control and binary blended concretes
Figure 3.12 Penetration resistance curve of M 20 grade FA and SF based ternary blended concrete

Figure 3.13 Penetration resistance curve of M 20 grade RHA and SF based ternary blended concrete
The results of initial and final setting time of M 20, M 30 and M 40 grade control, binary and ternary blended concrete specimens are shown in Figures 3.14 and 3.15. The initial and final setting time of FA based M 20 grade binary blended concrete were 7 hours 38 minutes and 9 hours 20 minutes respectively. The addition of 20% FA as partial replacement of cement in concrete increases initial setting time approximately 30% more than the initial setting time of control concrete and also increases the final setting time of binary blended concrete compared to the initial and final setting time of control concrete. From the result, it is observed that the replacement of cement by FA prolongs the setting properties of concrete considerably and it is mainly due to the slower pozzolanic action of FA particle (Mirza et al 2002). Similar results were also observed for M 30 and M 40 grade concrete specimens.

The addition of 18% RHA increases the initial and final setting time of M 20 grade binary blended concrete approximately 30% compared to initial and final setting time of control concrete. When mineral admixtures such as FA / RHA are added for partial replacement of cement, the relative cement content in concrete is reduced which slows down the rate of hydration process and also FA and RHA do not involve in any reaction during the initial hours and hence the setting time of blended concrete increases.

It is observed from Figures 3.14 and 3.15 that the addition of 4% and 8% SF as a second mineral admixture reduces both the initial and final setting time of M 20, M 30 and M 40 grade of FA / RHA ternary blended concrete compared to the initial and final setting time of the binary blended concrete whereas addition of 12% SF content increases both the initial and final setting time of FA / RHA based ternary blended concrete.
Figure 3.14  Initial and final setting time of control, FA based binary and ternary blended concrete
Figure 3.15 Initial and final setting time of control, RHA based binary and ternary blended concrete
3.4 HARDENED PROPERTIES OF TERNARY BLENDED CONCRETE

3.4.1 General

The hardened concrete properties such as compressive strength, splitting tensile strength, bond strength and elastic modulus were determined. The relationships between the compressive strength and the splitting tensile strength / elastic modulus of binary and ternary blended concrete were developed. The compressive strength of ternary blended concrete at the age of 7 and 28 days were predicted by accelerated curing method.

3.4.2 Compressive Strength

The compressive strength development of control, FA based binary and FA and SF based ternary blended concretes are shown in Figures 3.16 to 3.18. The strength at the age of 7 days control, binary and ternary blended concrete are also shown in Figure 3.19. The strength of M 20 grade control concrete at the age of 7 days was found to be 19.33 MPa whereas FA based binary blended concrete was found to be 12.15 MPa which is approximately 37% lesser than the compressive strength of control concrete. The addition of 8% SF in FA based blended concrete showed the compressive strength of 20.30 MPa in 7 days curing which is equal to the compressive strength of control concrete. The addition of 12% SF in FA based ternary blended concrete showed the compressive strength of 15.93 MPa which is lesser than the compressive strength of control concrete (19.33 MPa) at the age of 7 days. From Figures 3.16 to 3.18, it is observed that the 8% SF based M 20 grade ternary blended concrete showed higher compressive strength than the other mix combinations in all the curing periods such as 7, 28, 90 and 180 days. From Figure 3.19, similar kinds of variations were noticed for 7 days cured M 30 and M 40 grade of concrete.
The compressive strength development of control, RHA based binary and RHA and SF based ternary blended concrete specimens are shown in Figures 3.20 to 3.22. The strength at the age of 7 days control, binary and ternary blended concrete are also shown in Figure 3.23. The strength of M 20 grade control concrete at the age of 7 days was found to be 19.33 MPa whereas RHA based binary blended concrete was found to be 11.57 MPa which is 40% lesser than the compressive strength of control concrete. The addition of 8% SF in RHA based ternary blended concrete showed the compressive strength of 18.77 MPa in 7 days curing and which is approximately equal to the compressive strength of control concrete. The addition of 12% SF in RHA based ternary blended concrete showed the compressive strength of 14.57 MPa which is lesser than the compressive strength of control concrete (19.33 MPa) at the age of 7 days. From Figures 3.20 to 3.22, it is observed that 8% SF based M 20 grade ternary blended concrete showed higher compressive strength than the other mix combinations of RHA based blended concrete in all the curing periods such as 7, 28, 90 and 180 days. Similar kinds of variations were also observed for M 30 and M 40 grade of concrete.

After 28 days curing period, compressive strength of M 20 grade FA and RHA based binary blended concrete were 27.11 and 26.76 MPa respectively which are slightly lesser than the compressive strength of control concrete. In the mean time, the 90 and 180 days cured binary blended concrete specimens showed higher compressive strength than the compressive strength of control concrete. Similar kinds of variations were also observed for M 30 and M 40 grade of concrete. It shows that the binary blended concrete obtained the maximum strength at later ages due to the formation of secondary C-S-H gel. The higher compressive strength of ternary blended concrete in both early ages and later ages is due to the overall improvement in the homogeneity of concrete (Poon et al 2006).
Figure 3.16 Compressive strength developments of FA and SF based M 20 grade ternary blended concretes

Figure 3.17 Compressive strength developments of FA and SF based M 30 grade ternary blended concretes
Figure 3.18 Compressive strength developments of FA and SF based M40 grade ternary blended concretes

Figure 3.19 Compressive strength of 7 days cured FA and SF based ternary blended concretes
Figure 3.20 Compressive strength developments of RHA and SF based M 20 grade ternary blended concretes

Figure 3.21 Compressive strength developments of RHA and SF based M 30 grade ternary blended concretes
Figure 3.22  Compressive strength developments of RHA and SF based M 40 grade ternary blended concrete

Figure 3.23  Compressive strength of 7 days cured RHA and SF based ternary blended concretes
3.4.3 Splitting Tensile Strength

The splitting tensile strength of control concrete, FA based binary blended concrete (BFC 20) and FA and SF based ternary blended concrete are shown in Figures 3.24 to 3.26. The splitting tensile strength at the age of 7 days control, binary and ternary blended concrete are also shown in Figure 3.27. From Figure 3.27, the splitting tensile strength of M 20 grade control concrete at the age of 7 days was found to be 2.12 MPa whereas FA based binary blended concrete was found to be 1.43 MPa which is approximately 32% lesser than the splitting tensile strength of control concrete. The addition of 8% SF in FA based ternary blended concrete showed the splitting tensile strength of 2.57 MPa in 7 days curing which is slightly higher than the splitting tensile strength of control concrete. The addition of 12% SF in FA based ternary blended concrete showed the compressive strength of 1.52 MPa which is lesser than the splitting tensile strength of control concrete (2.12MPa) at the age of 7 days. From Figures 3.24 to 3.26, it is observed that the 8% SF based M 20 grade ternary blended concrete showed higher splitting tensile strength than the other mix combinations in all the curing periods such as 7, 28, 90 and 180 days. Similar kinds of variations were also observed for M 30 and M 40 grade of FA based ternary blended concrete.

The splitting tensile strength of RHA and SF based ternary blended are shown in Figures 3.28 to 3.30. The splitting tensile strength at the age of 7 days control, binary and ternary blended concrete are shown in Figure 3.31. From Figure 3.31, it is observed that the splitting tensile strength of RHA based binary blended concrete (BRC 18) is lower than the splitting tensile strength of control concrete. Upto 8% replacement of SF, the splitting tensile strength of 7 days cured RHA and SF based ternary blended concrete was found to be increased. Similar kinds of variations were observed for M 30 and M 40 grade of RHA based ternary blended concrete.
Figure 3.24  Splitting tensile strength development of FA and SF based M 20 grade concrete specimens

Figure 3.25  Splitting tensile strength development of FA and SF based M 30 grade concrete specimens
Figure 3.26  Splitting tensile strength development of FA and SF based M 40 grade concrete specimens

Figure 3.27  Splitting tensile strength of 7 days cured FA and SF based ternary blended concretes
Figure 3.28  Splitting tensile strength development of RHA and SF based M 20 grade concrete specimens

Figure 3.29  Splitting tensile strength development of RHA and SF based M 30 grade concrete specimens
Figure 3.30  Splitting tensile strength development of RHA and SF based M 40 grade concrete specimens

Figure 3.31  Splitting tensile strength of 7 days cured RHA and SF based ternary blended concretes
3.4.4 Relationship between Compressive Strength and Splitting tensile Strength of Ternary Blended Concrete

From Figure 3.32, the relationship between compressive strength and splitting tensile strength of control concrete was found to be $f_t = 0.53(f_{ck})^{0.5}$ and it is also noted that the relationship between compressive strength and splitting tensile strength of control concrete was match with ACI 318 R-95 recommended relationship [$f_t = 0.54(f_{ck})^{0.5}$]. The present experimental results were not matched with the IS: 456-2000 recommended relationship since the IS: 456-2000 recommended relationship was meant for compressive strength and flexural tensile strength of concrete. In the mean time, the relationship between compressive strength and splitting tensile strength of blended concrete differ from the code recommendations (Figure 3.33). From the analysis of literature given in Table 3.1, the intercept constant of the relationship is found to be varied and it is also found that the 0.5 power law is not fit for blended concrete and varies with respect to the nature of admixture used, type of concrete etc., (Ahemed and Shah 1985, Oluokun et al 1991 and Rashid et al 2002) and hence the new relationship for binary and ternary blended concrete was determined based on regression analysis.

The best combinations of mineral admixtures based on the compressive strength and splitting tensile strength such as 20% FA + 8% SF and 18%RHA + 8% SF were considered for finding the relationship between compressive strength and splitting tensile strength of ternary blended concrete. Based on the regression analysis (Figure 3.33), the relationship between the compressive strength and the splitting tensile strength of FA based binary blended concrete was found to be $f_t = 0.42(f_{ck})^{0.59}$ and that of RHA based binary blended concrete was found to be $f_t = 0.43(f_{ck})^{0.56}$. From Figure 3.34, the relationship between compressive strength and splitting tensile strength for FA and SF based ternary blended concrete was found to be $f_t = 0.48(f_{ck})^{0.6}$ and the same relationship for RHA and SF based ternary
blended concrete was found to be \( f_t = 0.44(f_{ck})^{0.6} \). It is found that the relationship developed for ternary blended concrete is matched with the findings of Ahemed and Shah 1985 and Rashid et al 2002.

Table 3.1 Properties of regression equation for the relationship between compressive strength and splitting tensile strength from other sources

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<th>Properties of regression equation ( f_t = a(f_{ck})^b )</th>
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<td>2</td>
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<td>3</td>
<td>Oluokun et al (1991)</td>
<td>Intercept (a): 0.584, Slope (b): 0.79</td>
</tr>
<tr>
<td>4</td>
<td>Rashid et al (2002)</td>
<td>Intercept (a): 0.47, Slope (b): 0.56</td>
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</table>

Figure 3.32 Relationship between compressive strength and splitting tensile strength of control concrete
Figure 3.33 Relationship between compressive strength and splitting tensile strength of binary blended concrete

Figure 3.34 Comparison of the relationship between compressive strength and splitting tensile strength of ternary blended concrete with various research findings
3.4.5 Bond Strength

Bond strength of concrete was calculated by measuring the pull out force corresponding to 0.25 mm slip of reinforcement (Saraswathy and Ha-Won Song 2007). The details are given in Figures 3.35 to 3.37. The load slip curves of 28 days cured M 20 grade control, FA based binary blended (BFC 20) and RHA based binary blended (BRC 18) specimens are shown in Figure 3.35. The load slip curves of 28 days cured M 20 grade FA based binary (0% SF replacement level) and FA and SF based ternary blended concrete respectively are shown in Figures 3.36 and load slip curves of 28 days cured M 20 grade FA based binary and RHA and SF based ternary blended concrete respectively are shown in Figure 3.37.

The bond strength of control, FA based binary blended (BFC 20) and FA and SF based ternary blended concretes are shown in Figures 3.38 to 3.40. The bond strength at the age of 7 days control, binary and ternary blended concrete are also shown in Figure 3.41. From Figure 3.41, the bond strength of M 20 grade control concrete at the age of 7 days was found to be 1.17 MPa and the bond strength of M 20 grade FA based binary blended concrete was found to be 1.36 MPa which is 16% higher than the bond strength of control concrete. The addition of 8% SF in FA based ternary blended concrete showed the bond strength of 1.74 MPa at the age of 7 days curing which is 50% higher than the bond strength of control concrete. The addition of 12% SF in FA based blended concrete showed the compressive strength of 1.27 MPa which is lesser than the bond strength of binary blended concrete (1.36 MPa) at the age of 7 days. From Figures 3.38 to 3.40, it is observed that 8% SF based M 20 grade ternary blended concrete showed higher bond strength than the other mix combinations of FA based blended concrete for all the curing periods such as 28, 90 and 180 days. Similar kind of variations was observed for M 30 and M 40 grade of concrete.
The bond strength of RHA and SF based ternary blended are shown in Figures 3.42 to 3.44. The bond strength at the age of 7 days cured control, binary and ternary blended concrete are also shown in Figure 3.45. From Figure 3.45, it is observed that the bond strength of RHA based binary blended concrete (BRC 18) is low than that of the control concrete. The bond strength of 7 days cured RHA and SF based ternary blended concrete increased up to 8% replacement level of SF. Similar kinds of variations were also observed for M 30 and M 40 grade of RHA based ternary blended concrete. The addition of 12% SF in RHA based blended concrete shows the bond strength of 0.87 MPa which is lesser than the bond strength of control and also binary blended concrete at the age of 7 days. Based on the results and its graphical representations, the bond strength of FA / RHA and SF based ternary blended concrete with 8% SF have shown higher bond strength than the bond strength of control concrete during early age (7 days) of curing.

![Load slip curves for control and binary blended M 20 grade concrete after 28 days curing](image-url)

**Figure 3.35** Load slip curves for control and binary blended M 20 grade concrete after 28 days curing
Figure 3.36  Load slip curves for M 20 grade 28 days cured FA and SF based ternary blended concrete

Figure 3.37  Load slip curves for M 20 grade 28 days cured RHA and SF based ternary blended concrete
Figure 3.38  Bond strength variations of M 20 grade FA and SF based ternary blended concrete

Figure 3.39  Bond strength variations of M 30 grade FA and SF based ternary blended concrete
Figure 3.40  Bond strength variations of M 40 grade FA and SF based ternary blended concrete

Figure 3.41  Bond strength comparison of FA based binary and ternary blended concrete with control concrete after 7 days curing
Figure 3.42  Bond strength variations of M 20 grade RHA and SF based ternary blended concrete

Figure 3.43  Bond strength variations of M 30 grade RHA and SF based ternary blended concrete
Figure 3.44  Bond strength variations of M 40 grade RHA and SF based ternary blended concrete

Figure 3.45  Bond strength comparison of RHA based binary and ternary blended concrete with control concrete after 7 days curing
3.4.6 Elastic Modulus

The elastic modulus variation of 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.46 and 3.47 respectively. The elastic modulus of RHA based binary and RHA and SF based ternary blended concrete are shown in Figure 3.48 and 3.49 respectively.

From Figure 3.46, the elastic modulus of M 20 grade control concrete at the age of 7 days is found to be 21.31 GPa and the elastic modulus of M 20 grade based binary blended concrete is found to be 20.07 GPa, which is slightly lower than the elastic modulus of control concrete. The addition of 8% SF in FA based ternary blended concrete showed the elastic modulus of 21.57 GPa in 7 days curing which is slightly higher than the elastic modulus of control concrete. The addition of 12% SF in FA based blended concrete showed the elastic modulus of 20.73 GPa which is lesser than the elastic modulus of control concrete (21.31 GPa) at the age of 7 days. From Figures 3.46, it is observed that the 8% SF based M 20 grade ternary blended concrete showed higher elastic modulus than the other mix combinations. Similar kinds of variations were also observed for M 30 and M 40 grade of FA based ternary blended concrete.

After 28 days curing period, the elastic modulus of M 20 grade control, FA based binary concrete specimens were 25.55 and 24.03 GPa respectively. The addition of 4%, 8% and 12% SF in FA based ternary blended concrete showed the elastic modulus of 22.61, 25.53 and 24.67 GPa. Similar variations were also observed in RHA based binary and ternary blended M 20, M 30 and M 40 grade concrete specimens. Based on the results obtained from elastic modulus, the specimens contain 8% replacement of cement by SF had slightly higher elastic modulus than elastic modulus of the control and binary blended concrete.
Figure 3.46  Elastic modulus comparison of FA based binary and ternary blended concrete with control concrete after 7 days curing

Figure 3.47  Elastic modulus comparison of FA based binary and ternary blended concrete with control concrete after 28 days curing
Figure 3.48  Elastic modulus comparison of RHA based binary and ternary blended concrete with control concrete after 7 days curing

Figure 3.49  Elastic modulus comparison of RHA based binary and ternary blended concrete with control concrete after 28 days curing
3.4.7 Relationship between Compressive Strength and Elastic Modulus of Ternary Blended Concrete

As per IS: 456-2000, the relationship between the compressive strength and the elastic modulus is mentioned as \( E_c = 5(f_{ck})^{0.5} \) and ACI 318 R-95 has recommended the same relationship as \( E_c = 4.73(f_{ck})^{0.5} \). From the regression analysis, the relationship between the compressive strength and the elastic modulus of control concrete \([E_c = 4.75(f_{ck})^{0.5023}]\) is found to match with ACI 318 R-95 (Figure 3.50). As per the Figure 3.51, it was observed that the relationship between the compressive strength and the elastic modulus of FA / RHA based binary blended concrete results were differing from the IS: 456-2000 code recommendations. From the analysis of literature (Table 3.2), it is found that the 0.5 power law is also not fit for blended concrete and varies with respect to the nature of admixture used, type of concrete etc., (Ahemed and Shah 1985 and Rashid et al 2002) and hence the new relationship between the compressive strength and the elastic modulus for binary and ternary blended concrete was determined based on regression analysis.

The best combinations of mineral admixtures based on the compressive strength and splitting tensile strength such as 20% FA + 8% SF and 18% RHA + 8% SF were considered for finding the relationship between compressive strength and the elastic modulus of ternary blended concrete. Based on the regression analysis curves shown in Figure 3.51, the relationship between the compressive strength and the elastic modulus of FA based binary blended concrete was found to be \( E_c = 4.3(f_{ck})^{0.55} \) and that of RHA based binary blended concrete was found to be \( E_c = 4.1(f_{ck})^{0.6} \). As per Figure 3.52, the relationship between compressive strength and elastic modulus for FA and SF based ternary blended concrete was found to be \( E_c = 4.6(f_{ck})^{0.56} \) and the same relationship for RHA and SF based ternary blended concrete was found
to be $E_c = 4.4(f_{ck})^{0.6}$. It is found that the relationship developed for ternary blended concrete is closely associated with ACI 318 R-95 recommendation and the findings of Oluokun et al 1991. The comparison of results with other research findings for validity is also shown in Figure 3.52.

Table 3.2 Properties of regression equation for the relationship between compressive strength and elastic modulus from other sources

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![Figure 3.50 Relationship between compressive strength and elastic modulus of control concrete](image)

Experimental results of control concrete

Figure 3.50 Relationship between compressive strength and elastic modulus of control concrete
Figure 3.51 Relationship between compressive strength and elastic modulus of binary blended concrete

Figure 3.52 Relationship between compressive strength and elastic modulus of FA and RHA based ternary blended concrete
3.5 PERMEATION STUDIES

3.5.1 General

Permeability is the most important fundamental cause of disintegration of concrete. The permeation related studies such as effective porosity, saturated water absorption and sorptivity tests were conducted to understand the permeability behaviour of concrete (Saricimen et al 1995, Gopalakrishnan et al 2001 and Saraswathy and Ha-Won Song 2007). Apart from this, SEM analyses of 7 days cured concrete samples were carried out to understand the micro-structural properties of concrete at early ages.

3.5.2 Effective Porosity

The effective porosity results of 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.53 and 3.54 respectively. The effective porosity of RHA based binary and RHA and SF based ternary blended concrete are shown in Figure 3.55 and 3.56 respectively.

From Figure 3.53, the effective porosity of 7 days cured M 20, M 30 and M 40 grade control concrete were 9.59%, 8.52% and 8.01% respectively. The effective porosity of 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete were 9.87%, 8.81% and 8.63% respectively. The slight increase in effective porosity was observed in 7 days cured FA based binary blended concrete due to slower pozzolanic reaction of FA particles. The reduction of effective porosity was observed for 28 days cured concrete compared to 7 days cured concrete. The percentage of reduction of effective porosity of 28 days cured binary blended concrete is
high compared to control concrete due to the formation of secondary C-S-H gel.

The reduction of effective porosity was observed in 7 days cured FA and SF based ternary blended concrete and the results are shown in Figure 3.54. The maximum reduction of effective porosity was observed in 8% replacement of SF in ternary blended concrete. The addition of 12% SF in FA based ternary blended concrete showed higher effective porosity than 8% SF replacement level. The reduction of effective porosity is due to the formation of early secondary hydration product and pore filling action of SF particles.

From Figure 3.54, the effective porosity of 28 days cured M 20 grade ternary blended concrete were observed as 6.52%, 6.48% and 6.51% at the replacement level of 4%, 8% and 12% SF respectively and it was observed that the effective porosity of ternary blended concrete was almost equal in all the replacement level and similar kind of results were also noticed in M 30 and M 40 grade ternary blended concrete.

The effective porosity results of RHA based ternary blended concrete are shown in Figures 3.55 and 3.56. The reduction of effective porosity was noticed for all the replacement level of SF such as 4%, 8% and 12% compared to control and binary blended concrete at 7 days curing period. The maximum reduction of effective porosity was also observed in 8% replacement of SF in ternary blended concrete. The addition of 12% SF in RHA based blended concrete showed higher effective porosity than 8% SF replacement level due to reduction of cement content which reduces the quantity of Ca(OH)₂ formation. It is observed from the results that the SF reduces the effective porosity during early ages and FA / RHA reduces the effective porosity during later ages (Khan 2003).
Figure 3.53 Porosity of 7 days cured FA and SF based ternary blended concretes

Figure 3.54 Porosity of 28 days cured FA and SF based ternary blended concretes
Figure 3.55 Porosity of 7 days cured RHA and SF based ternary blended concretes

Figure 3.56 Porosity of 28 days cured RHA and SF based ternary blended concretes
3.5.3 Saturated Water Absorption

Saturated water absorption (SWA) results of 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.57 and 3.58 respectively. The SWA of RHA based binary and RHA and SF based ternary blended concrete are shown in Figures 3.59 and 3.60 respectively.

From Figure 3.57, the SWA of 7 days cured M 20, M 30 and M 40 grade control concrete were 5.06%, 4.94% and 4.13% respectively. The reduction of SWA was observed in 28 days cured control concrete specimen. The SWA of 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete were 5.21%, 5.14% and 4.67% respectively. The increase in SWA was observed in 7 days cured FA based binary blended concrete due to more porosity. Whereas reduction of SWA was observed in 28 days cured FA based binary blended concrete due to the formation of secondary C-S-H gel. Similar kinds of observations were also noticed in M 20, M 30 and M 40 grade RHA based binary blended concrete.

The reduction of SWA was observed from 7 days cured FA and SF based ternary blended concrete and the results are shown in Figure 3.57. The reduction of SWA is due to the formation of early secondary hydration product and pore filling action of SF particles. The maximum reduction (upto 48%) of SWA was observed in 8% replacement of SF in ternary blended concrete. The addition of 12% SF in FA based blended concrete showed higher SWA than 8% SF replacement level. From Figure 3.58, similar variations of SWA results were observed from the 28 days cured M 20, M 30 and M 40 grade ternary blended concrete.

The SWA results of RHA based ternary blended concrete are shown in Figure 3.59. The reduction of SWA was noticed for all the replacement level of SF such as 4%, 8% and 12% compared to that of control and binary blended concrete. The maximum reduction of SWA was also
observed in 8% replacement of SF in ternary blended concrete (Figure 3.60). The addition of 12% SF in RHA based ternary blended concrete showed higher SWA than 8%SF replacement level. It is observed from the results that the SF reduces SWA during early ages whereas FA / RHA reduce SWA during later ages (Ramadoss and Nagamani 2008).

Figure 3.57 Saturated water absorption of 7 days cured FA and SF based ternary blended concretes

Figure 3.58 Saturated water absorption of 28 days cured FA and SF based ternary blended concretes
Figure 3.59 Saturated water absorption of 7 days cured RHA and SF based ternary blended concretes

![Saturated water absorption graph for 7 days cured RHA and SF based ternary blended concretes](image)

Figure 3.60 Saturated water absorption of 28 days cured RHA and SF based ternary blended concretes

![Saturated water absorption graph for 28 days cured RHA and SF based ternary blended concretes](image)

### 3.5.4 Sorptivity

The sorptivity test results of 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.61 and 3.62 respectively. The sorptivity of RHA based binary and RHA and SF based ternary blended concrete are shown in Figures 3.63 and 3.64 respectively.
The sorptivity of 7 days cured M 20, M 30 and M 40 grade control concrete specimens were \(8.72 \times 10^{-6}\), \(7.16 \times 10^{-6}\), \(6.23 \times 10^{-6}\) m/\(\sqrt{s}\) respectively (Figure 3.61). From Figure 3.62, the reduction of sorptivity was observed in 28 days cured control concrete specimen compared to the sorptivity of 7 days cured control concrete. The reduction of sorptivity was also noticed while the grade of concrete increased. The sorptivity of 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete were \(9.94 \times 10^{-6}\), \(7.73 \times 10^{-6}\), \(6.57 \times 10^{-6}\) m/\(\sqrt{s}\) respectively. The increase in sorptivity was observed in 7 days cured FA based binary blended concrete due to the slower pozzolanic reaction of FA particles. Whereas reduction of sorptivity was observed in 28 days cured FA based binary blended concrete due to the formation of secondary C-S-H gel. The capillary voids present in the surface concrete are sealed by the formation of secondary C-S-H gel and reduces the capillary suction of water. Similar kinds of observations were also noticed in M 20, M 30 and M 40 grade RHA based binary blended concrete.

The reduction of sorptivity was observed in 7days cured FA and SF based ternary blended concrete and the results are shown in Figure 3.61. The reduction of sorptivity at early age is due to the formation of secondary hydration product and pore filling action of SF particles. The maximum reduction of sorptivity was observed in 8% replacement of SF in ternary blended concrete. The addition of 12% SF in FA based ternary blended concrete showed higher sorptivity than 8% SF replacement level. The early secondary hydration product due to SF improves the microstructure of concrete and reduces the surface concrete pores (Anurag Misra et al 2007, Nathan Schwarz et al 2008 and Ramadoss and Nagamani 2008). From Figure 3.62, further reduction of sorptivity results were noticed from the 28 days cured M 20, M 30 and M 40 grade ternary blended concrete. The reduction of sorptivity was observed in 7days cured RHA and SF based ternary blended concrete and the results are shown in Figure 3.63. The maximum reduction of sorptivity was observed also in 8% replacement of SF in RHA based ternary blended concrete. The addition of 12% SF in RHA based ternary blended
concrete showed higher sorptivity than 8% SF replacement level. From Figure 3.64, further reduction of sorptivity results were noticed in the 28 days cured M 20, M 30 and M 40 grade RHA based ternary blended concrete. It is observed from the results that the SF particles contribute to the reduction of sorptivity during early period and FA / RHA particles contribute to the reduction of sorptivity during later age.

**Figure 3.61**  Sorptivity of 7 days cured FA and SF based ternary blended concretes

**Figure 3.62**  Sorptivity of 28 days cured FA and SF based ternary blended concretes
Figure 3.63 Sorptivity of 7 days cured RHA and SF based ternary blended concretes

Figure 3.64 Sorptivity of 28 days cured RHA and SF based ternary blended concretes
3.5.5 Scanning Electron Microscopy Analysis

The microstructure of concrete samples was analysed using scanning electron microscopy (SEM). The SEM micrograph for 7 days cured M 20 grade control concrete is shown in Figure 3.65 and SEM micrograph for the binary blended concrete and the ternary blended concrete specimens are shown in Figure 3.66. It is observed from the SEM analysis that the 7 days cured control concrete has micro structural voids and cracks and binary blended concrete has some un-hydrated mineral admixture particles such as FA and RHA. Thus, the incorporation of FA and also the incorporation of RHA increase the porosity of the cement paste but reduce the average pore size of the cement paste. The SEM results of 8% SF based ternary blended concrete have shown a dense microstructure due to the early secondary gel formation. Based on the SEM analysis of 12% SF based ternary blended concrete, there are some micro voids and un-hydrated SF particles present. The addition of 12% SF in FA/RHA based blended concrete showed higher porosity than 8% SF replacement level due to insufficient quantity of Ca(OH)$_2$ formation.

![SEM micrograph of 7 days cured control concrete](image)

**Figure 3.65 SEM micrograph of 7 days cured control concrete**
a) FA based binary blended concrete  

b) RHA based binary blended concrete  

c) 20%FA and 8%SF based ternary blended concrete  

d) 20%FA and 12%SF based ternary blended concrete  

e) 18%RHA and 8%SF based ternary blended concrete  

f) 18%RHA and 12%SF based ternary blended concrete

Figure 3.66 SEM micrograph of 7 days cured M 20 grade blended concrete
3.6 STUDIES ON CORROSION PERFORMANCE OF CONCRETE

3.6.1 General

Electrochemical techniques like open circuit corrosion potential study, impressed voltage test and non-electrochemical technique namely gravimetric weight loss study are used to examine the corrosion performance of embedded steel in the ternary blended concrete.

3.6.2 Open Circuit Corrosion Potential Studies

The open circuit corrosion potential of steel rebars in control concrete, binary blended concrete and ternary blended concrete were plotted against the number of cycles of exposure as shown in Figures 3.67 to 3.78. One cycle of exposure represents 3 days wetting and 4 days drying in 3%NaCl solution.

The results of open circuit potential study for 7 days cured M 20, M 30 and M 40 grade control concrete, FA based binary blended concrete and FA and SF based ternary blended concrete specimens are shown in Figures 3.67 to 3.72. The OCP of 7 days cured M 20 and M 30 control concrete specimens were found to be less than the threshold value of open circuit potential (-270mV) during the initial period, which indicates that all the rebars are in active condition of corrosion. The 7 days cured M 40 grade control concrete specimen reaches the threshold potential level after 4 cycles of exposure whereas 28 days cured specimens reach the threshold potential level after 10 cycles of exposure. From Figures 3.67 to 3.72, it is observed that the corrosion of embedded rebars in the control concrete initiated at the early stages compared to binary and ternary blended concrete (Saraswathy et al 2001 and Saricimen et al 2002).
The FA based binary blended M 20 grade concrete specimens have shown a lower open circuit potential than that of the control concrete. The 7 days cured FA based binary blended M 20, M 30 and M 40 grade concrete specimens reach the threshold value of open circuit corrosion potential after 6, 18 and 36 cycles of exposure respectively. The specimens of 28 days cured M 20 and M 30 grade FA based binary blended concrete reach the threshold value of corrosion potential after 19 and 31 cycles of exposure respectively. From the results, it is found that there is no indication of corrosion initiation of 28 days cured M 40 grade concrete specimens through out the study.

The results of open circuit potential study for M 20, M 30 and M 40 grade control concrete, RHA based binary blended concrete and RHA and SF based ternary blended concrete specimens are shown in Figures 3.73 to 3.78. The 7 days cured RHA based binary blended M 20 grade concrete specimens also showed lower corrosion potential during initial period. The 7 days cured M 20, M 30 and M 40 grade RHA based binary blended concrete specimens reach the threshold value of corrosion potential after 4, 12 and 14 cycles of exposure respectively. The 28 days cured M 20, M 30 and M 40 grade RHA based binary blended concrete specimens showed the threshold value of corrosion potential after 8, 26 and 44 cycles of exposure respectively in 3% NaCl solution (Anwar Hussain et al 2005 and Saraswathy and Ha-Won Song 2007). The details of corrosion initiation are given in Table 3.3.

The corrosion initiation was noticed in all the specimens of 7 days cured M 20 grade FA and SF based ternary blended concrete. The corrosion initiation was also noticed in 28 days cured M 20 grade FA and SF based ternary blended TFS 4 and TFS 12 specimens. From the results, it is observed that corrosion potential are lesser than the threshold value upto the study period of 48 cycles for 28 days cured M 20 grade FA and SF based ternary blended concrete and hence no possibility of corrosion initiation.
The corrosion initiation of 28 days cured M 30 grade FA and SF based ternary blended concrete TFS 4 and TFS 12 specimens was noticed after 37 and 48 cycles respectively, whereas the 8% SF based M 30 grade ternary blended concrete (TFS 8) did not show any corrosion initiation during the study period of 48 cycles of exposure. The corrosion initiation for 28 days cured 4% SF added FA based ternary blended concrete (TFS 4) was noticed after 48 cycles of exposure. Corrosion initiation was not noticed during the entire period for M 40 grade FA and SF based ternary blended concrete specimen. The similar kinds of observations were also noticed for the RHA and SF based ternary blended concrete.

### Table 3.3  Corrosion initiation period of rebar in number of wetting and drying cycles in 3% NaCl solution *

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>M 20 grade</th>
<th>M 30 grade</th>
<th>M 40 grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 days</td>
<td>28 days</td>
<td>7 days</td>
</tr>
<tr>
<td>PCC</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>BFC 20</td>
<td>6</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>TFS 4</td>
<td>13</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>TFS 8</td>
<td>33</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TFS 12</td>
<td>32</td>
<td>46</td>
<td>38</td>
</tr>
<tr>
<td>BRC 18</td>
<td>4</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>TRS 4</td>
<td>10</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>TRS 8</td>
<td>22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TRS 12</td>
<td>38</td>
<td>-</td>
<td>46</td>
</tr>
</tbody>
</table>

* One cycle represents 3 days wetting and 4 days drying in 3%NaCl solution.
Figure 3.67 Open circuit potentials of rebar in 7 days cured M 20 grade control, FA based binary and ternary blended concrete specimen

Figure 3.68 Open circuit potentials of rebar in 28 days cured M 20 grade control, FA based binary and ternary blended concrete specimen
Figure 3.69 Open circuit potentials of rebar in 7 days cured M 30 grade control, FA based binary and ternary blended concrete specimen

Figure 3.70 Open circuit potentials of rebar in 28 days cured M 30 grade control, FA based binary and ternary blended concrete specimen
Figure 3.71 Open circuit potentials of rebar in 7 days cured M 40 grade control, FA based binary and ternary blended concrete specimen

Figure 3.72 Open circuit potentials of rebar in 28 days cured M 40 grade control, FA based binary and ternary blended concrete specimen
Figure 3.73  Open circuit potentials of rebar in 7 days cured M 20 grade control, RHA based binary and ternary blended concrete specimen

Figure 3.74  Open circuit potentials of rebar in 28 days cured M 20 grade control, RHA based binary and ternary blended concrete specimen
Figure 3.75 Open circuit potentials of rebar in 7 days cured M 30 grade control, RHA based binary and ternary blended concrete specimen

Figure 3.76 Open circuit potentials of rebar in 28 days cured M 30 grade control, RHA based binary and ternary blended concrete specimen
Figure 3.77  Open circuit potentials of rebar in 7 days cured M 40 grade control, RHA based binary and ternary blended concrete specimen

Figure 3.78  Open circuit potentials of rebar in 28 days cured M 40 grade control, RHA based binary and ternary blended concrete specimen
3.6.3 Impressed Voltage Test

The time at which first crack on the concrete was calculated by using the impressed voltage test. The impressed voltage test results of 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.79 and 3.80 respectively. The impressed voltage test of RHA based binary and RHA and SF based ternary blended concrete are shown in Figure 3.81 and 3.82 respectively.

The time taken for crack of 7 days cured M 20, M 30 and M 40 grade control concrete specimens were 80, 97 and 112 hours respectively. From Figure 3.79, it is observed that the 28 days cured control concrete takes more time to crack the specimen than the 7 days cured control concrete.

The time taken for cracking the 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete were 92, 106 and 130 hours respectively. The increase in time taken to crack the FA based binary blended concrete specimen is only a marginal compared to 7 days cured control concrete due to pore refinement action of FA particles. Due to the formation of secondary C-S-H gel 28 days cured FA based binary blended concrete taken more time to crack the specimen compared to control concrete. Similar kinds of observations were also noticed for M 20, M 30 and M 40 grade of RHA based binary blended concrete.

The addition of SF in FA based blended concrete further improved the crack time due to the formation of early secondary hydration product and pore filling action of SF particles and the results are shown in Figure 3.79 and
3.80. The maximum improvement was noticed in 8% replacement of SF in ternary blended concrete. Similar kinds of observations were also noticed from both 7 and 28 days cured RHA based ternary blended concrete and shown in Figures 3.81 and 3.82.

The presence of FA and RHA in blended concrete improves the concrete properties and originates the improvement in time to crack the specimens against accelerated corrosion techniques (Saraswathy et al 2007). The presence of SF in the ternary blended system further improves the quality of concrete. The pore size refinement due to the secondary hydration process of FA / RHA and SF with Ca(OH)$_2$ fills the capillary voids and improve the permeability characteristics of blended concrete (Tae-Hyun Ha et al 2007).

![Bar chart](image)

**Figure 3.79** Time to crack 7 days cured control, FA based binary and ternary blended concrete specimen
Figure 3.80  Time to crack 28 days cured control, FA based binary and ternary blended concrete specimen

Figure 3.81  Time to crack 7 days cured control, RHA based binary and ternary blended concrete specimen
Figure 3.82  Time to crack 28 days cured control, RHA based binary and ternary blended concrete specimen

3.6.4 Gravimetric Weight Loss Measurement

The results of weight loss of embedded rebar after 180 days (6 cycles of wetting and drying) are given in Table 3.4. The maximum weight loss of embedded rebar was observed in 7 days cured M 20 grade control concrete specimen. The weight loss of rebar decreased with increasing curing period and also reduction of weight loss was observed for M 40 grade of concrete compared to M 30 and M 20 grade of concrete The weight loss of embedded rebar in ternary blended and binary concrete was less compared to control concrete. The weight loss of 7 days cured M 20 grade FA and RHA based binary blended concrete is found to be 25.14% and 25.29% respectively. Similar kinds of result were also observed for M 30 and M 40 grade of concrete. The significant reduction in weight loss was observed for 7 and 28 days cured FA / RHA and SF based ternary blended M 20, M 30 and M 40 grade of concrete compared to binary and control concrete and the results are given in Table 3.10. The maximum reduction of weight loss of rebar was observed for 8% SF based ternary blended concrete.
Table 3.4  Weight loss of rebar in control, binary and ternary blended concrete

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>Weight loss of rebar (%)</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M 20 grade</td>
<td>M 30 grade</td>
<td>M 40 grade</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 days</td>
<td>28 days</td>
<td>7 days</td>
<td>28 days</td>
<td>7 days</td>
</tr>
<tr>
<td>PCC</td>
<td>25.38</td>
<td>19.18</td>
<td>18.61</td>
<td>14.67</td>
<td>12.27</td>
</tr>
<tr>
<td>BFC 20</td>
<td>25.14</td>
<td>17.20</td>
<td>18.01</td>
<td>12.68</td>
<td>11.97</td>
</tr>
<tr>
<td>TFS 4</td>
<td>19.61</td>
<td>14.35</td>
<td>17.08</td>
<td>11.05</td>
<td>10.91</td>
</tr>
<tr>
<td>TFS 8</td>
<td>12.74</td>
<td>8.19</td>
<td>11.99</td>
<td>7.09</td>
<td>9.37</td>
</tr>
<tr>
<td>TFS 12</td>
<td>16.18</td>
<td>12.69</td>
<td>14.93</td>
<td>10.25</td>
<td>10.25</td>
</tr>
<tr>
<td>BRC 18</td>
<td>25.29</td>
<td>18.10</td>
<td>18.47</td>
<td>13.58</td>
<td>12.96</td>
</tr>
<tr>
<td>TRS 4</td>
<td>19.86</td>
<td>15.52</td>
<td>17.31</td>
<td>13.12</td>
<td>12.56</td>
</tr>
<tr>
<td>TRS 8</td>
<td>14.04</td>
<td>9.18</td>
<td>12.57</td>
<td>7.97</td>
<td>11.92</td>
</tr>
<tr>
<td>TRS 12</td>
<td>17.76</td>
<td>14.61</td>
<td>15.30</td>
<td>13.64</td>
<td>12.23</td>
</tr>
</tbody>
</table>

The corrosion rate of embedded rebar was calculated from the results of weight loss measurement after 180 days exposed in 3% NaCl solution. The corrosion rate of embedded rebar represented in terms of in millimeter per year (mmpy) (Saraswathy and Ha-Won Song 2007).

The corrosion rate of embedded rebar in 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.83 and 3.84. The corrosion rate of embedded rebar in RHA based binary and RHA and SF based ternary blended concrete are shown in Figure 3.85 and 3.86.
From the graphical analysis (Figure 3.83), it is found that the corrosion rate of rebar embedded in 7 days cured M 20, M 30 and M 40 grade control concrete specimens are 0.0068, 0.0048 and 0.0034 mmpy respectively.

The corrosion rate of rebar embedded in 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete were 0.0067, 0.0045 and 0.0031 mmpy respectively. The reduction of corrosion rate of rebar in 7 days cured FA based binary blended concrete is marginally less compared to the control concrete due to pore refinement action of FA particles. The formation dense microstructure of 28 days cured FA based blended concrete due to the secondary C-S-H gel reduces the entry of salt solution causing corrosion and hence corrosion rate of rebar embedded in 28 days cured FA based binary blended concrete is less compared to 7 days cured FA based blended concrete. Similar kinds of results were noticed for RHA based binary blended M 20, M 30 and M 40 grade of concretes.

The corrosion rate of rebars embedded in 7days cured FA and SF based ternary blended concrete are shown in Figure 3.83. From the figure, it is observed that the corrosion rate of rebar embedded in 7 days cured M 20 grade ternary blended concrete is only half of the times than that of control concrete specimen due to the formation of early secondary hydration product and pore filling action of SF particles which reduces diffusion rate of chloride ions. The corrosion rate of rebar embedded in 8% SF mixed FA based ternary blended concrete was observed as low value compared to all the other mix proportions (Figure 3.83 and 3.84). Similar kinds of trends were also observed for 7 and 28 days cured SF mixed RHA based ternary blended concrete (Figure 3.85 and 3.86).
**Figure 3.83** Comparison of corrosion rate of 7 days curing FA based binary and ternary blended concrete with control concrete

**Figure 3.84** Comparison of corrosion rate of 28 days curing FA based binary and ternary blended concrete with control concrete
Figure 3.85  Comparison of corrosion rate of 7 days curing RHA based binary and ternary blended concrete with control concrete

Figure 3.86  Comparison of corrosion rate of 28 days curing RHA based binary and ternary blended concrete with control concrete
3.7 STUDIES ON CHLORIDE PERMEABILITY

3.7.1 General

The permeability of chloride ions through the control, binary and ternary blended concrete was determined by conducting rapid chloride penetration test, macro-cell current and free chloride content.

3.7.2 Rapid Chloride Penetration Test

The total charge passed through 7 and 28 days cured M 20, M 30 and M 40 grade control, FA based binary and FA and SF based ternary blended concrete specimens are shown in Figures 3.87 and 3.88 respectively. The total charge passed through RHA based blended concrete is shown in Figures 3.89 and 3.90.

The total charge passed through 7 days cured M 20, M 30 and M 40 grade control concrete specimens were 3107, 2926 and 2698 coulombs respectively. The total charge passed through 28 days cured M 20, M 30 and M 40 grade control concrete specimen were 2852, 2490 and 2346 coulombs respectively. The reduction of the total charge passed through 28 days cured control concrete specimen compared to 7 days cured control concrete is due to the improvement of the microstructure of concrete.

The concrete quality was assessed as per the limits given in ASTM C 1202 based on the degree of chloride ion penetrability (Srinivasan et al 2007) and the details are given in the Table 3.5. Based on the results of 28 days cured control concrete specimens, the degree of chloride ion penetrability was found to be moderate.
Table 3.5 ASTM limits of Chloride ion permeability

<table>
<thead>
<tr>
<th>Charge passed (Coulombs)</th>
<th>Chloride ion penetrability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 4000</td>
<td>High</td>
</tr>
<tr>
<td>2000 - 4000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1000 - 2000</td>
<td>Low</td>
</tr>
<tr>
<td>100 - 1000</td>
<td>Very low</td>
</tr>
<tr>
<td>&lt; 100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

The total charge passed through 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete were 2518, 2180 and 1810 coulombs respectively and found the degree of chloride ion penetrability was found to be moderate as per ASTM limits. The total charge passed through 7 days cured binary blended concrete is almost equal to the total charge passed through 7 days cured control concrete. This indicates that the FA particle does not have any reaction during early period only it acted as filler material. Total charge passed through 28 days cured FA based binary blended concrete was found less compared to control concrete, which indicates the formation of secondary C-S-H gel (Prabakar et al 2007). Similar kinds of observations were also noticed for M 20, M 30 and M 40 grade of RHA based binary blended concrete.

The total charge passed through 7 days cured FA and SF based ternary blended concrete are shown in Figure 3.87. The total charge passed through 7 days cured 4%, 8% and 12% SF based ternary blended concrete was significantly less compared to the control concrete specimen and FA based binary blended concrete due to the formation of early secondary hydration product and pore filling action of SF particles (Ghrici et al 2007 and Gastaldini et al 2007). From the results, it is found that only one third of total charge was passed through 7 days cured M 20 grade 8% SF based ternary blended concrete compared to control concrete. From graphical analysis (Figures 3.87 and 3.88), it is found that total charge passed through 28 days cured M 20, M 30 and M 40 grade of concrete was less compared to 7 days
cured concrete (Raghuprasad et al 2007). Similar kinds of observations were also noticed for 7 and 28 days cured RHA based ternary blended concrete (Figures 3.89 and 3.90). Based on total charge passed through ternary blended concrete specimens, the degree of chloride ion penetrability was found to be low for 7 days cured specimens and very low for 28 days cured specimens.

Figure 3.87 Variations of total charge (RCPT value) passed through 7 days cured FA and SF based blended concrete

Figure 3.88 Variations of total charge (RCPT value) passed through 28 days cured specimen FA and SF based blended concrete
Figure 3.9 Variations of total charge (RCPT value) passed through 7 days cured RHA and SF based blended concrete

Figure 3.90 Variations of total charge (RCPT value) passed through 28 days cured specimen RHA and SF based blended concrete
3.7.3  **Macro-cell Current Study**

The Macro-cell current results of 7 and 28 days cured M 20, M 30 and M 40 grade, control, FA based binary and FA and SF ternary blended concrete are shown in Figures 3.91 to 3.96. The macro-cell current results of RHA based binary and RHA and SF based ternary blended are shown in Figures 3.97 to 3.102. From the results it is observed that the M 20, M 30 and M 40 grade control concrete specimens showed a negligible macro-cell current upto 3 cycles of exposure. After 6 cycles, the control concrete specimen shows a sharp rise in macro-cell current. For 7 days cured FA and RHA based binary blended concrete (BFC-20 / BRC-18) specimens had lesser macro-cell current than that of control concrete specimen. It is also observed that the 28 days cured binary blended concrete showed only half of the macro-cell current flow compared to the macro-cell current flow of control concrete. The difference in macro-cell current flow between control and binary blended concrete is almost equal at early whereas significant difference was noted at later age and it is mainly due the slow pozzolanic reaction of FA particles at early age and formation of secondary hydration product at later age. Similar trend of results were noticed for 7 and 28 days cured RHA based binary blended concrete also.

The SF based ternary blended concrete specimens for all the replacement levels such as 4%, 8% and 12% of SF showed less macro-cell current flow compared to binary and control concrete. The 12% SF mixed FA based blended concrete showed higher macro-cell current flow than 8% SF mixed FA based blended concrete. Similar variations in the results were also noticed in both 7 and 28 days cured RHA based M 20, M 30 and M 40 grade ternary blended concrete. From the graphical results, it can be concluded that the ternary blended concrete containing 8% SF replacement level showed good resistance to chloride penetration than the control and binary blended concrete due to pore filling action of mineral admixture and also formation of dense concrete by the early secondary hydration products.
Figure 3.91 Macro-cell current vs Number of cycles of exposure for 7 days cured M 20 grade FA based blended concrete

Figure 3.92 Macro-cell current vs Number of cycles of exposure for 28 days cured M 20 grade FA based blended concrete
Figure 3.93 Macro-cell current vs Number of cycles of exposure for 7 days cured M 30 grade FA based blended concrete

Figure 3.94 Macro-cell current vs Number of cycles of exposure for 28 days cured M 30 grade FA based blended concrete
Figure 3.95  Macro-cell current vs Number of cycles of exposure for 7 days cured M 40 grade FA based blended concrete

Figure 3.96  Macro-cell current vs Number of cycles of exposure for 28 days cured M 40 grade FA based blended concrete
Figure 3.97  Macro-cell current vs Number of cycles of exposure for 7 days cured M 20 grade RHA based blended concrete

Figure 3.98  Macro-cell current vs Number of cycles of exposure for 28 days cured M 20 grade RHA based blended concrete
Figure 3.99  Macro-cell current vs Number of cycles of exposure for 7 days cured M 30 grade RHA based blended concrete

Figure 3.100  Macro-cell current vs Number of cycles of exposure for 28 days cured M 30 grade RHA based blended concrete
Figure 3.101  Macro-cell current vs Number of cycles of exposure for 7 days cured M 40 grade RHA based blended concrete

Figure 3.102  Macro-cell current vs Number of cycles of exposure for 28 days cured M 40 grade RHA based blended concrete
3.7.4 Free Chloride Content

The free chloride contents present in the concrete was calculated and reported in Figures 3.103 to 3.114. It is observed from the profile curves that the free chloride contents decreases with increasing depth from the surface of the concrete and also the free chloride contents reduced with increasing grade of concrete. For 7 days cured control concrete, more amount of free chloride was noticed whereas for 28 days cured control concrete less amount of free chloride was noticed beyond 20mm distance from surface of the concrete.

The difference of free chloride contents present in the 7 days cured control and binary blended concrete is only marginal. It is also observed that the significant difference of free chloride content of 28 days cured control and FA based binary blended concrete and the FA based binary blended concrete is shown only two third of the free chloride content present in control concrete due to the formation of secondary C-S-H gel. Similar type of variation was also noticed in 7 and 28 days cured RHA based binary blended concrete (Ampadu et al 1999).

The specimens of both 7 and 28 days cured 4%, 8% and 12% SF based ternary blended concrete showed a negligible amount of free chloride content beyond 20mm distance from surface of the concrete. The addition of 12% SF showed more free chloride content than the 8% SF replacement levels in FA / RHA based ternary blended concrete.
Figure 3.103 Free chloride profiles for 7 days cured FA based M 20 grade concrete

Figure 3.104 Free chloride profiles for 28 days cured FA based M 20 grade concrete
Figure 3.105  Free chloride profiles for 7 days cured FA based M 30 grade concrete

Figure 3.106  Free chloride profiles for 28 days cured FA based M 30 grade concrete
Figure 3.107  Free chloride profiles for 7 days cured FA based M 40 grade concrete

Figure 3.108  Free chloride profiles for 28 days cured FA based M 40 grade concrete
Figure 3.109  Free chloride profiles for 7 days cured RHA based M 20 grade concrete

Figure 3.110  Free chloride profiles for 28 days cured RHA based M 20 grade concrete
Figure 3.111 Free chloride profiles for 7 days cured RHA based M 30 grade concrete

Figure 3.112 Free chloride profiles for 28 days cured RHA based M 30 grade concrete
Figure 3.113  Free chloride profiles for 7 days cured RHA based M 40 grade concrete

Figure 3.114  Free chloride profiles for 28 days cured RHA based M 40 grade concrete
3.8 STUDIES ON SULPHATE RESISTANCE

3.8.1 General

The performance of control, binary and ternary blended concrete against sulphate resistance was carried out by conducting various experimental tests such as expansion of mortar prism and strength deterioration factor.

3.8.2 Expansion (Length Change) of Mortar Prism

The expansion of FA based binary and ternary blended mortar prism are shown in Figures 3.11 to 3.120. It is observed that the expansion of control prism was more than the blended mortar prism when immersed in 5% Na$_2$SO$_4$ solution. The specimens of 7 days cured M 20 grade control concrete were disintegrated after the immersion of 32 weeks in 5% Na$_2$SO$_4$ solution. The expansion of blended mortar prism shows lower value than the control specimen. The expansion of 7 and 28 days cured M 20 grade FA based binary blended mortar specimens were found to be 0.108% and 0.075% respectively. It was also observed that the M 30 and M 40 grade mortar specimens show lower value of expansion than the M 20 grade specimens. The 28 days cured specimens show little expansion over the 7 days cured specimens for all grades of concrete. The expansion of RHA based binary blended mortar prism specimens after immersion in 5% Na$_2$SO$_4$ are shown in Figures 3.121 to 3.126. The expansion of RHA based blended mortar was little high compared to FA blended mortar prisms (Prasad et al 2006 and Sahmaran et al 2007).

The addition of 4%, 8% and 12% SF along with FA reduces micropores of the concrete during the early curing period. From Figures 3.115 to
3.120, it is observed that the ternary blended concrete with 8% replacement level shows the lowest expansion of mortar prism compared to 4% and 12% SF mixed ternary blended concrete. The expansion values of 7 and 28 days cured M 20 grade 8% SF ternary blended mortar specimens were found to be 0.056% and 0.041% respectively after 32 weeks immersed in 5% Na₂SO₄ solution, which is 6% expansion compared to control concrete specimens. The expansion values of 7 and 28 days cured 8% RHA based ternary blended concrete (TRS-8) specimens found to be 0.081% and 0.055% respectively which is 8% expansion compared to control concrete specimens. It was also observed that the M 40 and M 30 grade ternary blended mortar prism specimen showed less expansion compared to M 20 grade of concrete.

![Figure 3.115 Expansion of FA based 7 days cured M 20 grade mortar prism after immersion in 5% Na₂SO₄ solution](image-url)
Figure 3.116  Expansion of FA based 28 days cured M 20 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution

Figure 3.117  Expansion of FA based 7 days cured M 30 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution
Figure 3.18 Expansion of FA based 28 days cured M 30 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution

Figure 3.19 Expansion of FA based 7 days cured M 40 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution
Figure 3.120  Expansion of FA based 28 days cured M 40 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution

Figure 3.121  Expansion of RHA based 7 days cured M 20 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution
Figure 3.122 Expansion of RHA based 28 days cured M 20 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution

Figure 3.123 Expansion of RHA based 7 days cured M 30 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution
Figure 3.124 Expansion of RHA based 28 days cured M 30 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution

Figure 3.125 Expansion of RHA based 7 days cured M 40 grade mortar prism after immersion in 5% Na$_2$SO$_4$ solution
3.8.3 Strength Deterioration Factor (SDF)

The SDF due to the sulphate attack was calculated and the results are shown in Figures 3.127 to 3.138. From Figures 3.127 to 3.138, it is observed that only less than 5% SDF was noticed for all the concrete specimens during the initial immersion period. The rate of change of SDF of control concrete was found to be more compared to blended concrete.

The SDF for ternary blended concrete was found to be less compared to the control and binary concrete. From Figures 3.127 to 3.132, the SDF of 7 and 28 days cured M 20 grade control specimen was found to be 48% and 37% respectively; where as the SDF of 7 and 28 days cured M 20 grade FA based binary blended concrete (BFC 20) was found to be 25% and 13% respectively. The SDF of 7 and 28 days cured M 20 grade 8% SF mixed 20% FA based ternary blended concrete (TFS 8) specimen was found to be...
only 11% and 7% respectively. Similar kind of results was also found for M 30 and M 40 grade of concretes.

The SDF of RHA based binary and ternary blended concrete specimens are shown in Figures 3.133 to 3.138. The SDF of 7 and 28 days cured M 20 grade RHA based binary blended concrete (BRC 18) specimens were 28% and 15% respectively. The SDF of 7 and 28 days cured M 20 grade 8%SF mixed RHA based ternary blended concrete (TFS-8) specimen was found to be 16% and 8% respectively. The SDF of M 40 grade 8% SF mixed RHA based ternary blended concrete specimen was found to be less than the SDF of M 20 and M 30 grade concrete specimen. The SDF of SF mixed FA / RHA based ternary blended was found be approximately 70% to 75%, lower than the control concrete (Han-Young Moon et al 2003 and Chai Jaturapitakkul et al 2007).

![Figure 3.127](image)

**Figure 3.127** SDF for 7 days cured M 20 grade control, FA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution
Figure 3.128  SDF for 28 days cured M 20 grade control, FA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution

Figure 3.129  SDF for 7 days cured M 30 grade control, FA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution
Figure 3.130  SDF for 28 days cured M 30 grade control, FA based binary and ternary blended concrete due to immersion in 5% Na₂SO₄ solution

Figure 3.131  SDF for 7 days cured M 40 grade control, FA based binary and ternary blended concrete due to immersion in 5% Na₂SO₄ solution
Figure 3.132  SDF for 28 days cured M 40 grade control, FA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution

Figure 3.133  SDF for 7 days cured M 20 grade control, RHA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution
Figure 3.134  SDF for 28 days cured M 20 grade control, RHA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution

Figure 3.135  SDF for 7 days cured M 30 grade control, RHA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution
Figure 3.136  SDF for 28 days cured M 30 grade control, RHA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution

Figure 3.137  SDF for 7 days cured M 40 grade control, RHA based binary and ternary blended concrete due to immersion in 5% Na$_2$SO$_4$ solution
3.9 STUDIES ON ACID RESISTANCE

3.9.1 General

The acid resistance of control, binary and ternary blended concrete was determined based on mass loss and strength deterioration factor of concrete after 32 weeks immersed in 5% H₂SO₄ solutions.

3.9.2 Mass Loss

The mass loss results of control, binary and ternary blended concrete due to acid attack are shown in Figures 3.139 to 3.150. The mass loss of 7 and 28 days cured M 20 grade control concrete specimens was observed as 23.6% and 22.0% respectively where as the reduction of mass loss was noticed in 7 and 28 days cured M 40 grade control concrete specimen compared to the M 30 and M 20 grade control concrete. It is observed from
the results that the mass losses of the control concrete specimens were reduced with increasing the grade of concrete and the curing period. The 7 days cured FA / RHA based binary blended concrete (BFC 20 / BRC 18) had only marginal reduction of mass losses during the early immersion period. The mass loss of 28 days cure FA based binary blended concrete specimens was found to be 30% to 40% less compared to control concrete when immersed in 5% \( \text{H}_2\text{SO}_4 \) solutions. The binary blended concrete specimen showed significant difference in mass loss compared to the control concrete due to the formation of secondary C-S-H gel. Similar kinds of variations were also observed for RHA based binary blended concrete.

The reduction of mass losses of 7 days cured SF mixed FA ternary blended concrete was found to be approximately half the value of control concrete whereas 28 days cured specimens had two third reductions of mass losses compared to control concrete. The ternary blended concrete prepared with 20% FA / 18% RHA and 8% SF replacement levels had very good resistance to acid attack (Al-Tamimi and Sonebi 2003 and Narayana et al 2007).

![Graph showing mass loss of FA based 7 days cured M 20 grade concrete after immersion in 5% \( \text{H}_2\text{SO}_4 \) solution](image)

**Figure 3.139**  Mass loss of FA based 7 days cured M 20 grade concrete after immersion in 5% \( \text{H}_2\text{SO}_4 \) solution
Figure 3.140  Mass loss of FA based 28 days cured M 20 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution

Figure 3.141  Mass loss of FA based 7 days cured M 30 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution
Figure 3.142  Mass loss of FA based 28 days cured M 30 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution

Figure 3.143  Mass loss of FA based 7 days cured M 40 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution
Figure 3.144  Mass loss of FA based 28 days cured M 40 grade concrete after immersion in 5% H$_2$SO$_4$ solution

Figure 3.145  Mass loss of RHA based 7 days cured M 20 grade concrete after immersion in 5% H$_2$SO$_4$ solution
Figure 3.146  Mass loss of RHA based 28 days cured M 20 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution

Figure 3.147  Mass loss of RHA based 7 days cured M 30 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution
Figure 3.148 Mass loss of RHA based 28 days cured M 30 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution

Figure 3.149 Mass loss of RHA based 7 days cured M 40 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution
Figure 3.150  Mass loss of RHA based 28 days cured M 40 grade concrete after immersion in 5% $\text{H}_2\text{SO}_4$ solution

3.9.3  Strength Deterioration Factor (SDF)

The SDF results are shown in Figures 3.151 to 3.162. The 7 days cured control concrete specimens are severely affected by acid attack. The rate of SDF of M 20 grade control concrete specimen was found to be very high during initial immersed period. The SDF of 7 and 28 days cured M 20 grade control specimen was about found to be 91% and 82% respectively. The SDF of 7 and 28 days cured M 40 grade of control concrete specimen was found to be less compared to M 30 and M 20 grade of control concrete.

The SDF of 7 and 28 days cured FA based binary blended concrete (BFC 20) was found to be less than the control concrete. From Figures 3.151 and 3.152, it is observed that the SDF of 7 and 28 days cured M 20 grade FA based binary blended concrete was found to be 62% and 44% respectively. From Figures 3.153 and 3.156, it is also observed that the SDF of 7 and 28 days cured M 30 and M 40 grade binary blended concrete was found to be less
than the M 20 grade of concrete. Similar trend was observed for RHA based binary blended concrete also and results are shown in Figures 3.157 to 3.162.

The SDF of 7 and 28 days cured M 20 grade 8%SF mixed FA based ternary blended concrete (TFS 8) specimen was found to be only 20% and 16% respectively which is approximately 75% lesser than the control concrete and 50% lesser than the FA based binary blended concrete. Similar kind of results was also found for M 30 and M 40 grade of 8%SF mixed FA based ternary blended concrete and the results are shown in Figures 3.155 and 3.158. The SDF of 7 and 28 days cured M 20 grade 8% SF mixed 18% RHA based ternary blended concrete (TFS-8) specimen was found to be 30% and 22% respectively and the results are shown in Figures 3.157 to 3.162. Similar kind of results was also found for M 30 and M 40 grade 8% SF mixed 18% RHA based ternary blended concrete specimens. The SDF of SF mixed FA / RHA based ternary blended was found be approximately 70% lower than the control concrete and 50% lower than the binary blended concrete.

![Figure 3.151](image_url)  
**Figure 3.151**  SDF for FA based 7 days cured M 20 grade concrete due to immersion in 5% $\text{H}_2\text{SO}_4$ solution
Figure 3.152  SDF for FA based 28 days cured M 20 grade concrete due to immersion in 5% H₂SO₄ solution

Figure 3.153  SDF for FA based 7 days cured M 30 grade concrete due to immersion in 5% H₂SO₄ solution
Figure 3.154  SDF for FA based 28 days cured M 30 grade concrete due to immersion in 5% H$_2$SO$_4$ solution

Figure 3.155  SDF for FA based 7 days cured M 40 grade concrete due to immersion in 5% H$_2$SO$_4$ solution
Figure 3.156  SDF for FA based 28 days cured M 40 grade concrete due to immersion in 5% H₂SO₄ solution

Figure 3.157  SDF for RHA based 7 days cured M 20 grade concrete due to immersion in 5% H₂SO₄ solution
Figure 3.158  SDF for RHA based 28 days cured M 20 grade concrete due to immersion in 5% $\text{H}_2\text{SO}_4$ solution

Figure 3.159  SDF for RHA based 7 days cured M 30 grade concrete due to immersion in 5% $\text{H}_2\text{SO}_4$ solution
Figure 3.160  SDF for RHA based 28 days cured M 30 grade concrete due to immersion in 5% H$_2$SO$_4$ solution

Figure 3.161  SDF for RHA based 7 days cured M 40 grade concrete due to immersion in 5% H$_2$SO$_4$ solution
3.10 STUDIES ON CARBONATION OF CONCRETE

3.10.1 General

When carbon dioxide present in the atmosphere, it penetrates into concrete and reacts with calcium hydroxide in the presence of moisture and leads to calcium carbonates which reduce the alkalinity of concrete and this process is called carbonation of concrete. The carbonation depth of concrete was measured by spraying a solution of phenolphthalein over the freshly broken surface of concrete.

3.10.2 Depth of Carbonation

The carbonation depth of 7 and 28 days cured control, binary and ternary blended M 20, M 30 and M 40 grade concrete specimens is shown in Figures 3.163 to 3.166. The average carbonation depth of 7 days cured M 20,
M 30 and M 40 grade control concrete specimens were 2.89, 2.07 and 1.35 mm respectively and also 28 days cured specimens of M 20, M 30 and M 40 grade control concrete specimens were 2.47, 1.63 and 1.02 mm respectively. The reduction of carbonation depth was observed with increasing the grade of concrete.

The carbonation depth of 7 days cured M 20, M 30 and M 40 grade FA based binary blended concrete (BFC-20) were 3.17, 2.33 and 1.57 mm respectively and 28 days cured M 20, M 30 and M 40 grade FA based binary blended concrete specimens were 2.59, 1.77 and 1.18 mm respectively. The 7 and 28 days cured FA based binary blended concrete had higher carbonation depth than the control concrete (Haque and Kawamura, 1992). Similar kinds of variations were also observed for RHA based binary blended concrete. The increase in carbonation depth of the binary blended concrete is due to the reduction of cement content replaced by FA / RHA.

The 7 days cured M 20, M 30 and M 40 grade SF mixed FA based ternary blended concrete specimens showed low carbonation depth compared to control and binary blended concrete whereas 28 days cured M 20 and M 30 grade SF mixed FA based ternary blended concrete specimens had only negligible amount depth of carbonation. Among all the replacement level of SF such as 4%, 8% and 12%, the ternary blended concrete with 8% SF had better performance than the other replacement levels of SF. From the result it is found that no carbonation was observed for 28 days cured M 40 grade ternary blended concrete. Addition of SF initiated early stage hydration process which improves impermeability of concrete and hence the entry of carbon dioxide into concrete is reduced (Jayobroto Burman Roy 2008).
Figure 3.163 Carbonation depth variations of 7 days cured control and FA based blended concrete

Figure 3.164 Carbonation depth variations of 28 days cured control and FA based blended concrete
Figure 3.165  Carbonation depth variations of 7 days cured control and RHA based blended concrete

Figure 3.166  Carbonation depth variations of 28 days cured control and RHA based blended concrete
3.11 COST COMPARISON OF CONCRETE

The present market rates of cement, sand, coarse aggregate, FA, RHA and SF are considered for finding the cost of concrete mix per m³ and details are given in Tables 3.6 and 3.7. The cost of FA based binary blended concrete is approximately 8% less than the cost of control concrete and RHA based binary blended concrete is approximately 4% less than the cost of control concrete. The cost of 8% SF mixed with 20% FA based ternary blended concrete is approximately 1% higher than the cost of control concrete whereas 8% SF mixed 18% RHA based ternary blended concrete was found to approximately 5% higher than the cost of control concrete. The cost of RHA based ternary blended concrete is more than the cost of FA based ternary blended concrete and it is due the cost of preparation of RHA from the rice husk whereas abundant quantity FA is available in thermal power plants. The freight charge of FA from the source is the cost of FA.

Though the cost of ternary blended concrete is marginally higher than the cost of control concrete, the benefits of ternary blended concrete such as reducing the setting time, increasing the early age strength, improving the corrosion resistance, enhancing the micro-structural properties and improving the resistance against chemical attack are much higher than the control concrete and binary blended concrete. The better enhancement of above said durability properties could improve the service life of concrete structures.
Table 3.6 Market rates of concrete ingredients

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<th>Cost per kg (in rupees)</th>
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<tr>
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<td>Sand</td>
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</tr>
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<td>3</td>
<td>Coarse aggregate</td>
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</tr>
<tr>
<td>5</td>
<td>SF</td>
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Table 3.7 Cost of concrete / m³

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<th>Cost of concrete / m³ (in rupees)</th>
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<td>FA based</td>
<td>3900 ($78)</td>
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<tr>
<td></td>
<td>RHA based</td>
<td>4050 ($81)</td>
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