Performance of Self Compacting Concrete Exposed to Marine Environment

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Abstract:- Enhanced durability of concrete plays a crucial role in the serviceability of structures in marine environments. In this study, performance of self compacting concrete (SCC) blended with Fly Ash (FA) and Silica Fume (SF) in the form of binary and ternary mixtures in the simulated marine environment is investigated. This study aimed at utilization of high volumes of FA, up to 60% replacement of Ordinary Portland Cement (OPC), for development of sustainable and durable SCC located in marine environment. SCC was examined for fresh as well as hardened state characteristics like flowability, compressive strength, split tensile strength and durability characteristics such as sorptivity and chloride ion penetration resistance. The results showed that SCC can be prepared with FA and SF up to 40% and 10% replacement of OPC respectively. There was a remarkable improvement in the durability performance of SCC in ternary mixtures containing 30% FA and 10% SF. At later ages, SCC in ternary mixtures showed improved strength in marine environment.The experimental investigation indicated improved performance of high-volume FA based SCC in marine environments.

I. INTRODUCTION

Self-compacting concrete (SCC) is a special type of innovative concrete which can be placed and compacted under its own weight, without any vibration effort and without segregation and bleeding due to cohesiveness. SCC completely fills the formwork even in the situation of heavy reinforcement. The concept of SCC was given by Okamura in 1986, and the prototype was at the University of Tokyo in 1988 [1,2]. SCC has many advantages in comparison to conventional concrete, including: (1) speedy construction; (2) reducing labor cost and noise pollution; (3) better placement due to improved workability (4) good filling ability of concrete in densely reinforced structural members; (5) good interfacial transitional zone between mortar and aggregate or reinforcement; (6) improved durability. SCC has key fresh properties like flowability, passing ability and segregation resistance. Fresh characteristics of SCC are mainly achieved by increasing fines, particle size less than 0.125mm as defined by The European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) [3]. Because it requires more utilization of Ordinary Portland Cement (OPC) and chemical admixtures for attaining fresh characteristics, the SCC didn’t become popular as conventional concrete in construction industry. High OPC content usually introduces problems like high heat of hydration and high shrinkage, which in turn leads the severe cracking and damages the structural integrity by the attack of harmful substances into the concrete matrix [4]. Moreover, the consumption of natural resources and carbon dioxide emissions associated with OPC can cause serious environmental impacts [5]. In past few years, numerous efforts [5–12] have been done for producing sustainable SCC by replacing OPC with supplementary cementitious materials (SCMs) such as fly ash (FA), silica fume (SF), nano silica (NS), ground granulated blast-furnace slag (GGBS) and metakaolin (MK). Replacing OPC with these SCMs not only improves the performance of concrete but also lowers the cost of SCC. In addition, use of SCMs in construction industry minimizes the landfilling and undesirable depletion of natural resources.

Marine concrete is subjected to some of the harshest conditions in the engineering environment [13]. The actual life of marine concrete structures is usually much shorter than the designed service time due to various attacks from seawater [14],[15]. Chloride-induced reinforcement corrosion is regarded as the primary durability issues [16],[17]. The seawater chemically interacts with the cementitious materials and deteriorate the concrete exposed in the marine environment [18]. Chlorides, present in seawater, directly affect durability of concrete by instigating corrosion of the reinforcement steel. It is important to safeguard steel reinforcement from corrosion for long-term serviceability of concrete. Since all aggressive ions and chemicals penetrate through microcracks and porous structure of concrete, deformation and transport properties such as shrinkage, permeability, capillary absorption, porosity, and chloride diffusion are widely used to determine concrete durability. It is well-known that densification of concrete improves the microstructure and lowers the ingress of external aggressive ions. Blending OPC with SCMs is effective in densification of the microstructure and reducing the external attack on concrete.

FA from thermal power plants [19] and SF from silicon metal alloys or silicon metal production [20],[21] have been used as SCMs in construction industry for last few decades. It is evident from the previous research [22],[23],[24],[25],[26] that the addition of these SCMs improve the performance and microstructure of concrete due to their pozzolanic reactivity and ability to fill the micropores respectively. FA and SF, being pozzolanic in nature, designated type II additives following the EFNARC guidelines could significantly be used in improving the long-term performance of concrete.

Previously, researchers investigated properties of SCC in marine environments using blends of OPC and SCMs at lower replacement levels. Further detailed information on the optimum utilization of SCMs in SCC for durability indicators is limited. There is a knowledge gap in examining the performance of SCC modified with mineral admixture such as SF and FA, at higher replacement levels, in the marine environment. This study aims at performance-based investigation of SCC, designed using varying proportions of SF, FA and binary admixtures (SF+FA) as replacement of OPC up to 70%, in simulated marine environment. High volume FA based SCC was examined for durability indicators including the chloride migration and sorptivity besides fresh and other hardened characteristics. The significance of this research is utilization of high-volume FA, which otherwise be landfilled, in development of sustainable SCC in marine environment.

II. MATERIALS AND METHODS

A. *Materials*

ASTM type II OPC was used to produce various mixtures. In addition, SF and Class F FA were used as mineral admixtures. Table 1 summarizes physical properties and chemical composition of the OPC, FA and SF.

Natural crushed limestone aggregate (NCA) having maximum size of 12mm and specific gravity 2.67 was sourced from Margala Hill quarry. Natural siliceous sand from Lawrencepur Qibla Bandi was used as natural fine aggregates (NFA). Particle size distribution of NCA and NFA is shown in Figure 1. Characteristics of NCA and NFA are presented in table 2. The petrographic thin section analysis of NCA was carried out to check potential alkali aggregate reactivity. Petrographic description is shown in Figure 2. It was revealed that NCA has neither alkali carbonate (ACR) nor alkali silica (ASR) reaction potential. NCA therefore, be safely used as an aggregate with OPC.

A third generation polycarboxylate based superplasticizer, consisting of 48.15% maximum solid content, was used as water reducing admixture.

Available items	FA	SF	OPC
SiO_2 (Silica)	54.12	93.48	20.77
Al_2O_3 (Alumina)	15.42	0.39	5.2
Fe_2O_3 (Iron Oxide)	2.16	0.16	3.5
CaO (Lime)	5.9	1.12	62.89
MgO (Magnesia)	0.8	0.22	2.2
SO_3 (Sulphuric Anhydride)	1.6	0.34	2.56
LOI (Loss on Ignition)	4.8	3.32	2.04
IR (Insoluble Residue)	-	-	0.56
Physical Requirements:			
Standard Consistency	-	-	29.45
Initial setting time(minutes)	-	-	130
Final setting time (minutes)	-	-	185
Fineness (Blaine)(cm^2/gm)	-	-	3046
Le-Chatlier’s expansion(mm)	-	-	1

Table 1: Temperature and wildlife count in the three areas covered by the study

	NCA	NFA
Los Angles Abrasion Value	18.96%	
Crushing Value	23.81%	-
Impact Value	17.45%	-
Specific Gravity	2.67	2.72
Water Absorption	0.80%	1.20%
Fineness Modulus	-	1.84
Unit Weight (Rodded)	1557 kg/m^3	1540 kg/m^3
Unit Weight (Loose)	1446 kg/m^3	1443 kg/m^3
Flakiness Index	26.40%	-
Elongation Index	20.50%	-

Table 2: Characteristics of NCA and NFA

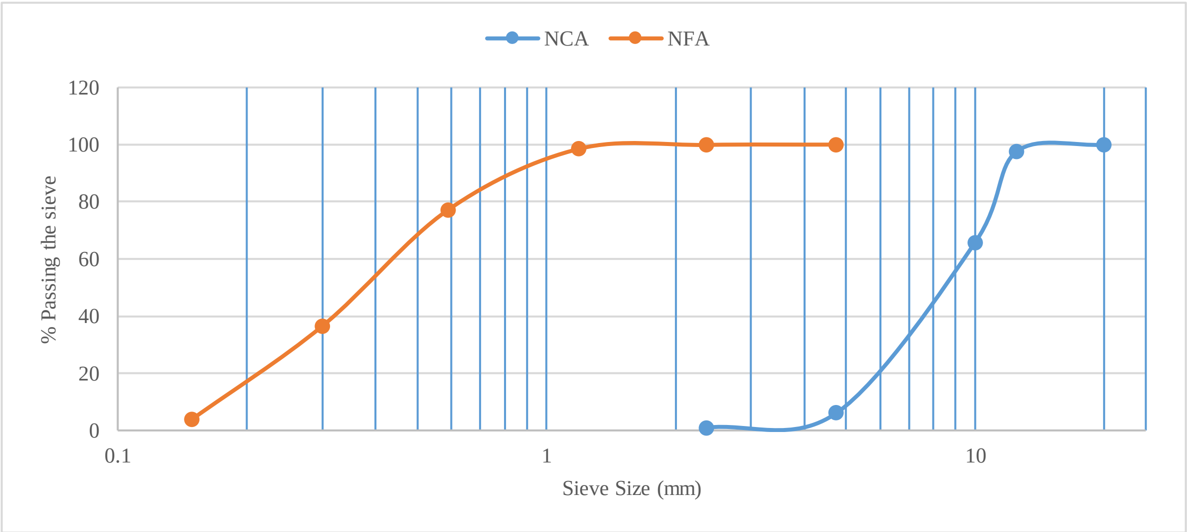


Fig. 1: Particle size distribution of aggregates

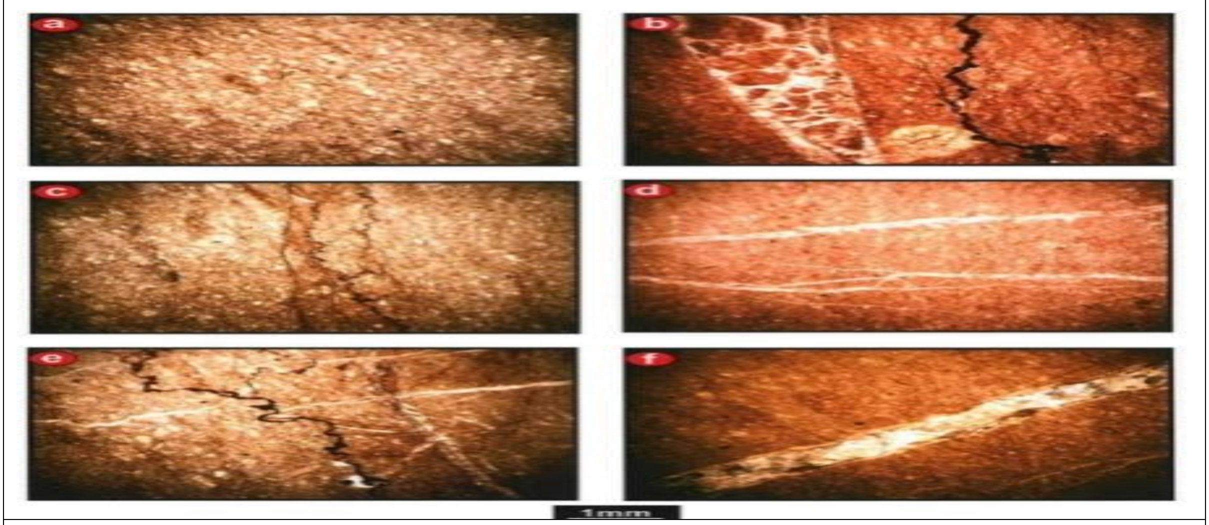


Fig. 2: Petrographic Image of coarse aggregates

B. *Simulation of Marine Environment in laboratory*

The exposure conditions of reinforced concrete structures in real marine environment can be classified into atmospheric (A), tidal (T), and submerged (S) zones [27]. A test chamber was designed to simulate marine environment considering submerged zones. Seawater was simulated in accordance with ASTM D1141 [28] that has the ion concentration as mentioned in table 3. The temperature of simulated seawater was maintained at about 20°C. To achieve this temperature, the test chamber was installed with aquarium rods and a small electric pump was installed for continuous circulation of dissolved salts. A blower was arranged on top of the test chamber to balance the humidity and temperature distribution of the air.

Conc.[mg/l]	Cl^{-}	Na^{+}	Mg^{2+}	SO_4^{2-}	Ca^{2+}	K^{+}	CO_3^{2-}
Simulated Water	21870	11862	1080	2911	443	401	151
ASTM D1141-98 [28]	19845	11024	1314	2766	418	397	145

Table 3: Concentrations of the main ions in simulated marine water

C. *Mix Proportions and sample preparation*

Mix design was carried out with the trial-and-error method in accordance with EFNARC specifications [3]. A total of 57 concrete mixtures were designed with a constant water/binder ratio of 0.32 and a total binder content of 600kg/m^3, 550kg/m^3 and 500kg/m^3. Concrete mixtures contain SF and FA at various replacement levels by weight of concrete. Table 4 represents each variation as a weight of constituents for 1m^3 of concrete. The abbreviations for labeling the mixtures were adopted in such a way that each designation clearly defines the main parameters and their replacement levels.

Concrete Mix ID	w/b	Water	Binder (kg/m^3)			Aggregates (kg/m^3)		SP (%)
			OPC	SF	FA	NFA	NCA	
Mix Type-I (Binder content 600kg/m^3)								
C600	0.32	192	600	0	0	840	960	1.2
600M10FA	0.32	192	540	0	60	840	960	1.2
600M20FA	0.32	192	480	0	120	840	960	1.1
600M30FA	0.32	192	420	0	180	840	960	1.08
600M40FA	0.32	192	360	0	240	840	960	1
600M50FA	0.32	192	300	0	300	840	960	0.99
600M60FA	0.32	192	240	0	360	840	960	0.98
600M5SF10FA	0.32	192	510	30	60	840	960	1.1
600M10SF10FA	0.32	192	480	60	60	840	960	1.2
600M5SF20FA	0.32	192	450	30	120	840	960	1.01
600M10SF20FA	0.32	192	420	60	120	840	960	1.08
600M5SF30FA	0.32	192	390	30	180	840	960	1
600M10SF30FA	0.32	192	360	60	180	840	960	1.02
600M5SF40FA	0.32	192	330	30	240	840	960	0.95
600M10SF40FA	0.32	192	300	60	240	840	960	0.98
600M5SF50FA	0.32	192	270	30	300	840	960	0.85
600M10SF50FA	0.32	192	240	60	300	840	960	0.88
600M5SF60FA	0.32	192	210	30	360	840	960	0.87
600M10SF60FA	0.32	192	180	60	360	840	960	0.92
Mix Type-II (Binder content 550kg/m^3)								
C550	0.32	176	550	0	0	881	969	1.4
550M10FA	0.32	176	495	0	55	881	969	1.4
550M20FA	0.32	176	440	0	110	881	969	1.31
550M30FA	0.32	176	385	0	165	881	969	1.3
550M40FA	0.32	176	330	0	220	881	969	1.27
550M50FA	0.32	176	275	0	275	881	969	1.2
550M60FA	0.32	176	220	0	330	881	969	1.17
550M5SF10FA	0.32	176	467.5	27.5	55	881	969	1.36
550M10SF10FA	0.32	176	440	55	55	881	969	1.39
550M5SF20FA	0.32	176	412.5	27.5	110	881	969	1.32
550M10SF20FA	0.32	176	385	55	110	881	969	1.4
550M5SF30FA	0.32	176	357.5	27.5	165	881	969	1.2
550M10SF30FA	0.32	176	330	55	165	881	969	1.3
550M5SF40FA	0.32	176	302.5	27.5	220	881	969	1.1
550M10SF40FA	0.32	176	275	55	220	881	969	1.15
550M5SF50FA	0.32	176	247.5	27.5	275	881	969	1.01
550M10SF50FA	0.32	176	220	55	275	881	969	1.09
550M5SF60FA	0.32	176	192.5	27.5	330	881	969	1
550M10SF60FA	0.32	176	165	55	330	881	969	1.05
Mix Type-III (Binder content 500kg/m^3)								
C500	0.32	160	500	0	0	900	1000	1.51
500M10FA	0.32	160	450	0	50	900	1000	1.5
500M20FA	0.32	160	400	0	100	900	1000	1.5
500M30FA	0.32	160	350	0	150	900	1000	1.45
500M40FA	0.32	160	300	0	200	900	1000	1.41
500M50FA	0.32	160	250	0	250	900	1000	1.3
500M60FA	0.32	160	200	0	300	900	1000	1.29
500M5SF10FA	0.32	160	425	25	50	900	1000	1.3
500M10SF10FA	0.32	160	400	50	50	900	1000	1.38
500M5SF20FA	0.32	160	375	25	100	900	1000	1.32
500M10SF20FA	0.32	160	350	50	100	900	1000	1.4
500M5SF30FA	0.32	160	325	25	150	900	1000	1.23
500M10SF30FA	0.32	160	300	50	150	900	1000	1.3
500M5SF40FA	0.32	160	275	25	200	900	1000	1.28
500M10SF40FA	0.32	160	250	50	200	900	1000	1.34
500M5SF50FA	0.32	160	225	25	250	900	1000	1.17
500M10SF50FA	0.32	160	200	50	250	900	1000	1.22
500M5SF60FA	0.32	160	175	25	300	900	1000	1.11

500M10SF60FA	0.32	160	150	50	300	900	1000	1.08

Table 4: Mix proportions of SCC for 1m3 of concrete

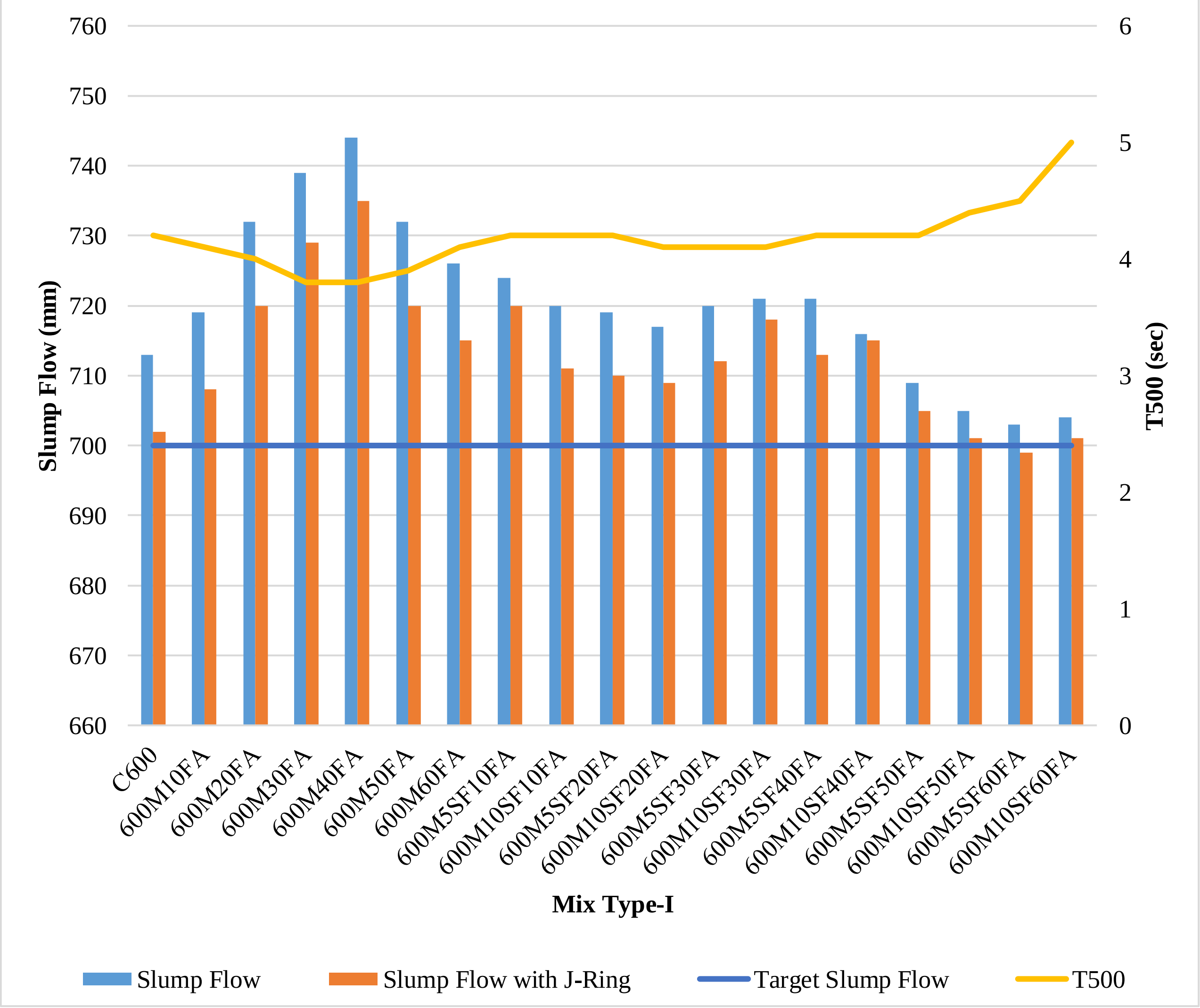
Sample preparation was carried out in accordance with the EFNARC specifications [3]. The fresh properties for certain workability parameters including slump flow, T_{500}, L-Box and J-ring were determined according to EFNARC [3] guidelines. Mechanical properties, i.e., axial compression test, ultrasonic pulse velocity and splitting tensile strength test were determined according to the American Standards ASTM C39 [29], ASTM C597 [30] and ASTM C496 [31] respectively. Water absorption and chloride ion penetration in all specimens were determined according to ASTM C1585 [32] and NT Build 492 [33] respectively.

III. RESULTS AND DISCUSSION

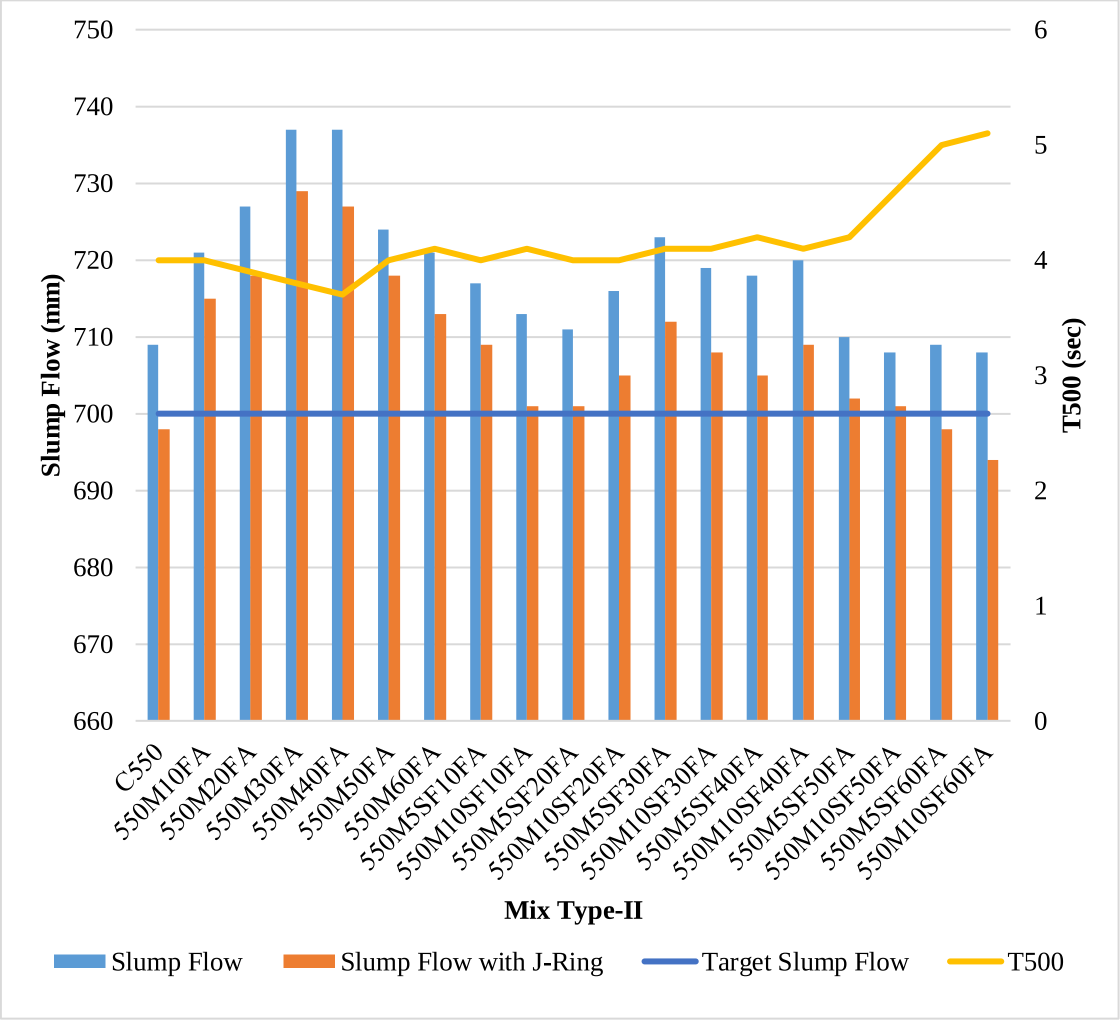
A. *Fresh Properties*

Figure 3 indicates the results of workability parameters i.e., slump flow with and without J-Ring, T_{500} and Visual stability index (VSI). All mixes were classified as SF2/VS2 type SCC as per EFNARC guidelines [3]. It was noticeable that slump flow continues to increase with the increase in amount of FA. The increase in flow is most probably because of ball bearing effect due to spherical nature of FA [3]. Similar results are reported by different researchers [34], [35], [36], [37] & [38]. With the addition of SF, the slump flow decreases with increasing levels of replacement. The decrease in slump is attributed to larger specific surface area of SF, the same is reported previously by several researchers [35], [39] & [40].

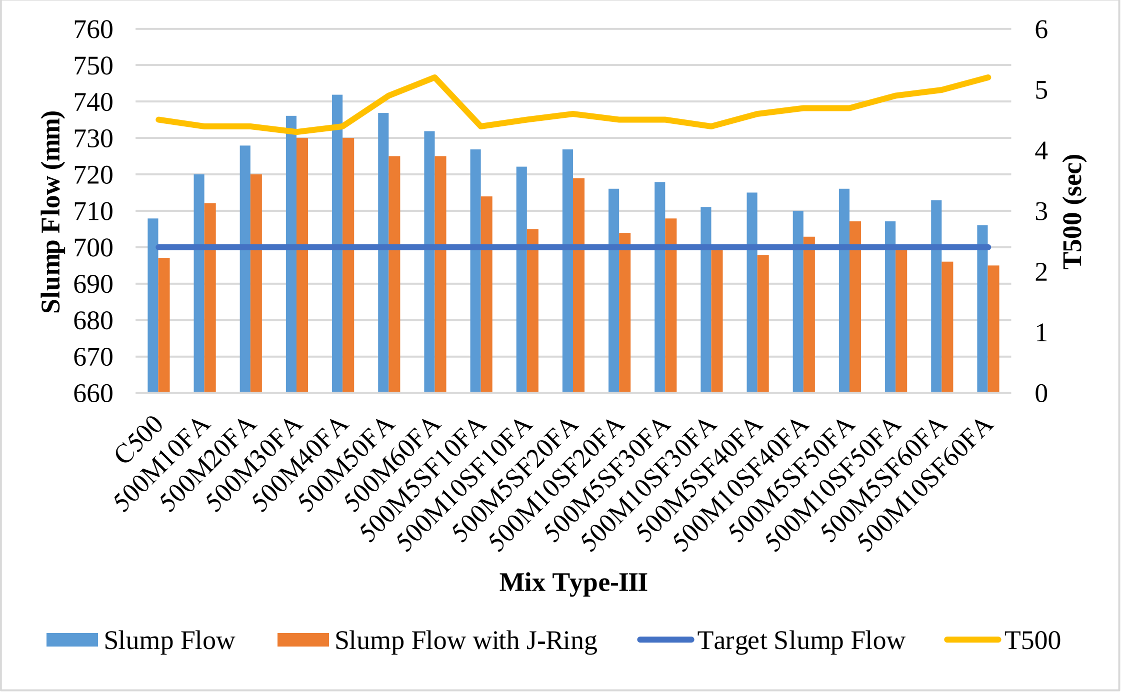
The passing ability (PA) of SCC is assessed using L-Box with three bars. All samples showed PA>0.8. PA significantly reduces with increasing FA, this is attributed to the cohesiveness of mixtures [3]&[41].



(a)


Slump Flow (mm)
750
740
730
720
710
700
690
680
670
660
T500 (sec)
6
5
4
3
2
1
0
C550
550M10FA
550M20FA
550M30FA
550M40FA
550M50FA
550M60FA
550M5SF10FA
550M10SF10FA
550M5SF20FA
550M10SF20FA
550M5SF30FA
550M10SF30FA
550M5SF40FA
550M10SF40FA
550M5SF50FA
550M10SF50FA
550M5SF60FA
550M10SF60FA
Mix Type-II
Slump Flow
Slump Flow with J-Ring
Target Slump Flow
T500

(b)


Slump Flow (mm)
760
750
740
730
720
710
700
690
680
670
660
T500 (sec)
6
5
4
3
2
1
0
C500
500M10FA
500M20FA
500M30FA
500M40FA
500M50FA
500M60FA
500M5SF10FA
500M10SF10FA
500M5SF20FA
500M10SF20FA
500M5SF30FA
500M10SF30FA
500M5SF40FA
500M10SF40FA
500M5SF50FA
500M10SF50FA
500M5SF60FA
500M10SF60FA
Mix Type-III
Slump Flow
Slump Flow with J-Ring
Target Slump Flow
T500

(c)

Fig. 3: a) Slump flow and T500 for Mix Type-I, b) Slump flow and T500 for Mix Type-II, c) Slump flow and T500 for Mix Type-III, d) Visual stability index (VSI)

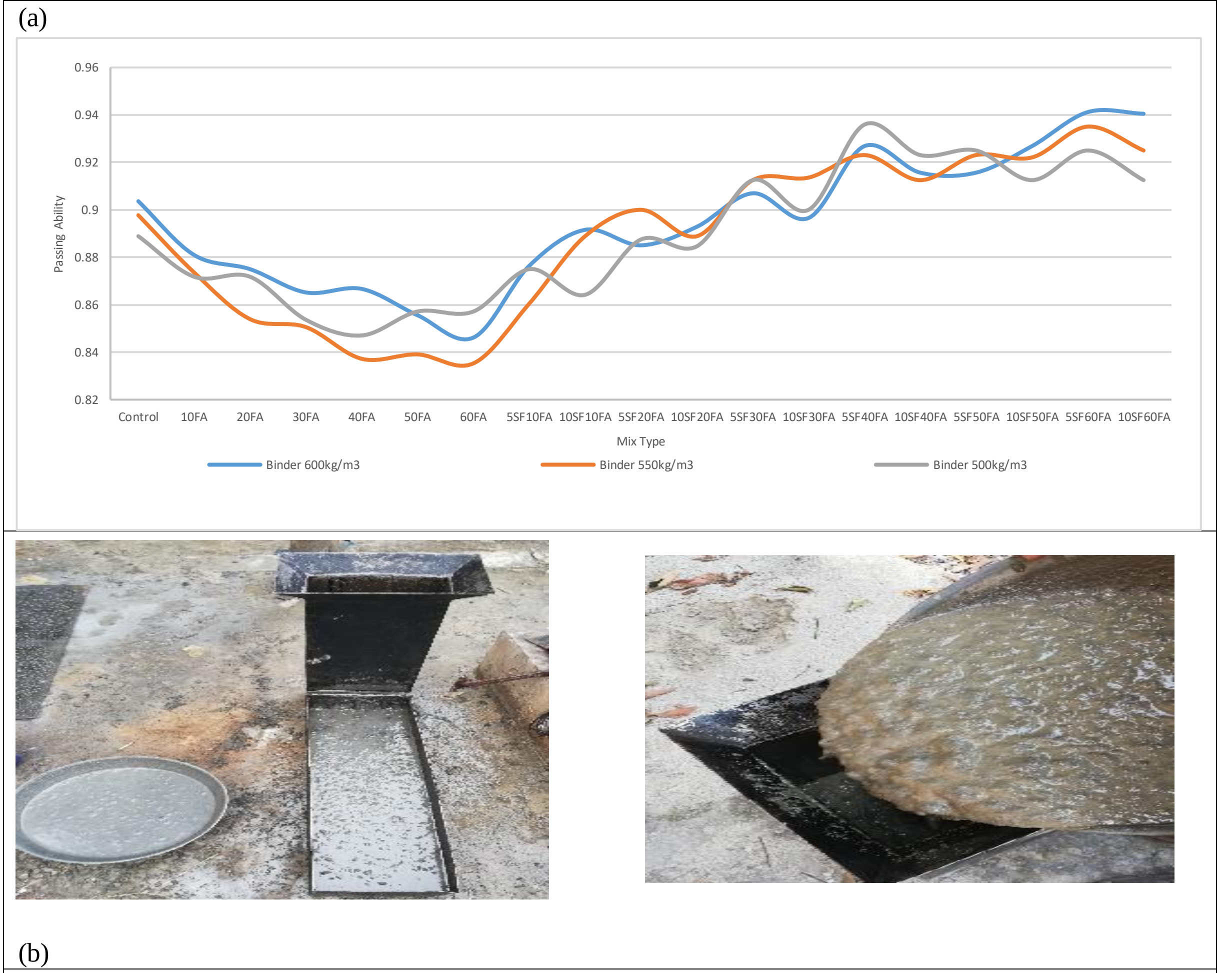
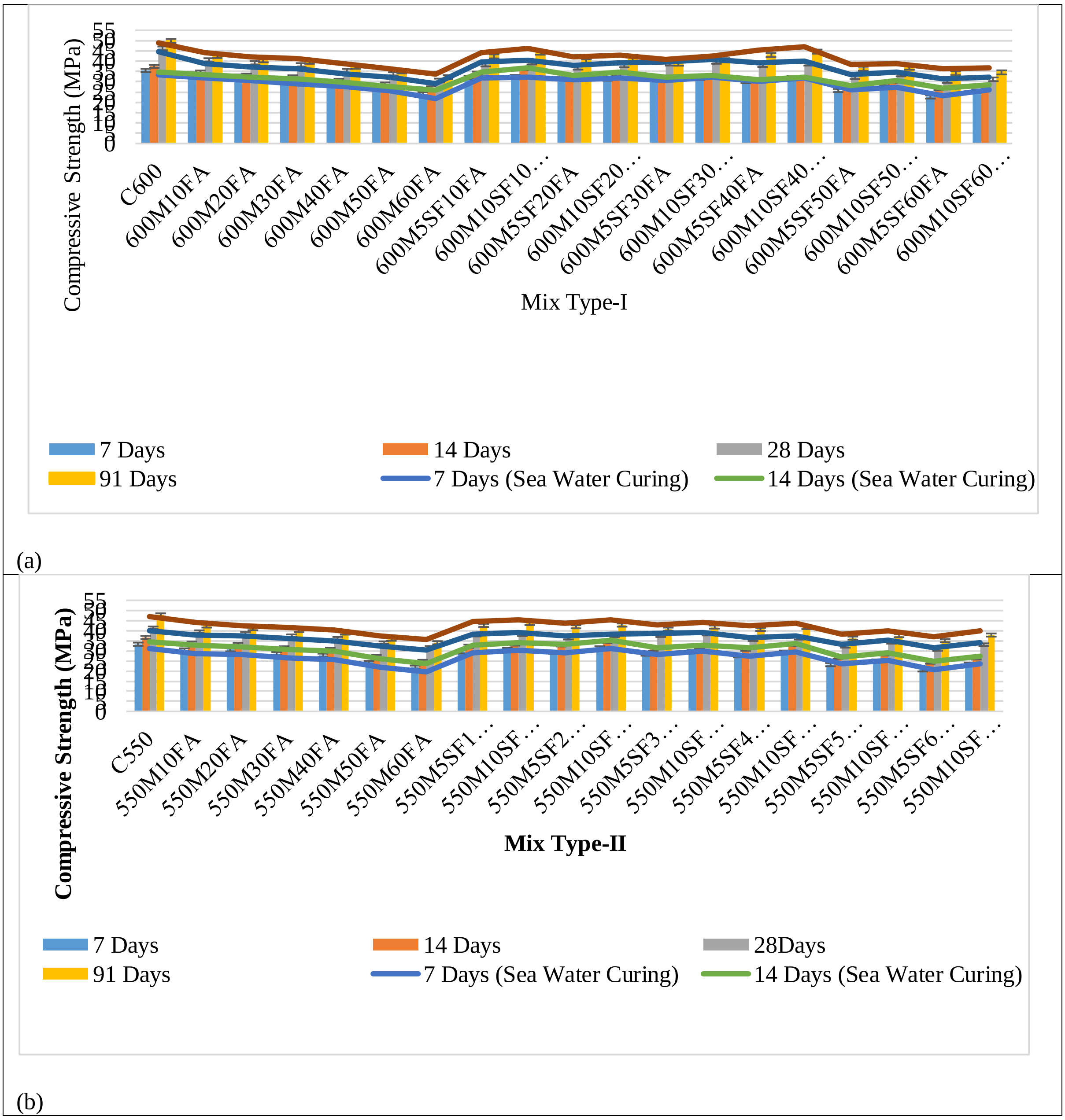
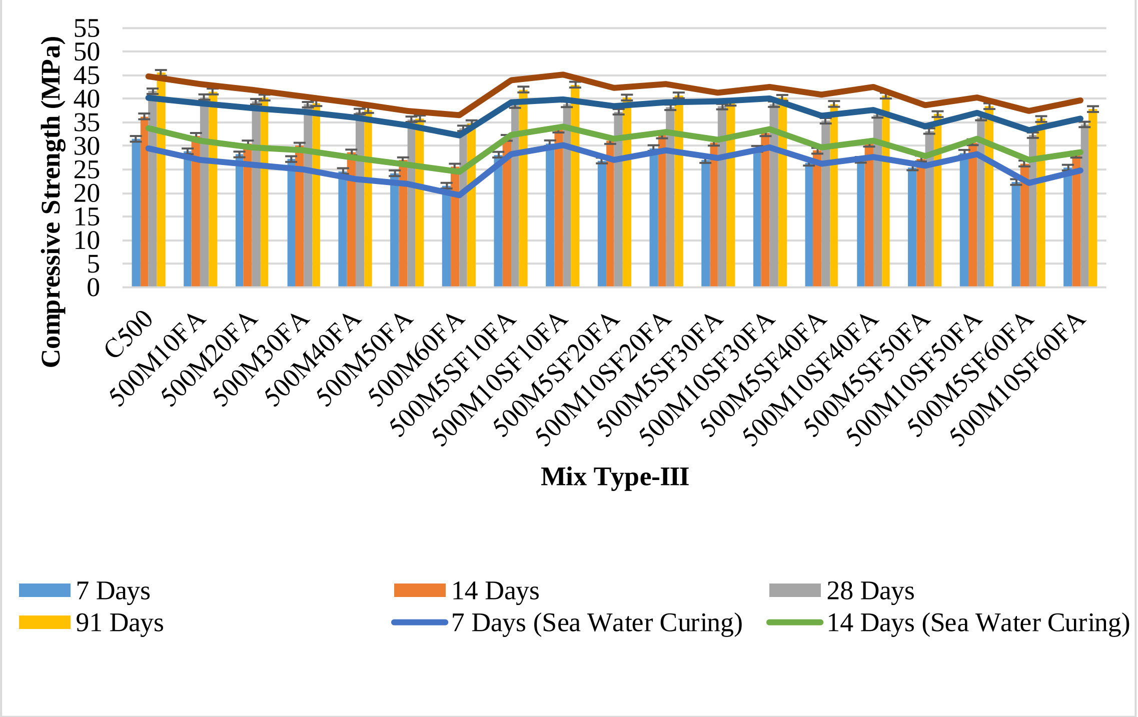


Fig. 4: a) L-Box Ratio, b) L-Box experiment

B. Compressive Strength

Figure 5 indicates the experimental results of compressive strength at 7, 14, 28 and 91 days period of maturity. It has been observed that the initial rate of strength gain for mixes containing FA was low that increases with age and gains maximum strength at 91 days in this study. The possible reason of delay in strength is the slow pozzolanic reactions in concrete due to low calcium content in Class F FA that might resulted in the development of calcium silicate hydrate (C-S-H) gel which causes densification of SCC thus, results in increasing compressive strength with the age, as reported earlier by a few researchers [43],[44]. This effect was more significant with higher replacement levels [42]. In all design types, the optimum value of FA was observed to be at 40% replacement of OPC that gives the maximum 28 days compressive strength. The strength development was 87%, 84%, 82%, 76%, 72% and 65% for 10%, 20%, 30%, 40%, 50% and 60% replacement of OPC with FA, respectively for Mix Type-I. Strength development for Mix Type-II and III was 95%, 93%, 91%, 87%, 81%, 76% and 97%, 94%, 93%, 89%, 85%, 80% for same replacement levels. Strength development was rapid in mixes containing lesser amounts of FA. It was observed that there was an enhancement in strength by adding binary admixtures (SF+FA). Strength of control mixes decreased when cured in simulated sea water. Strength of mixes containing FA, when cured in sea water, showed decrease in strength at early age as compared to the strength of similar mixes cured in normal water. Similar findings are discussed in previous research [51]. The strength of mixes containing binary admixtures (SF+FA) showed similar strength at early age in both types of curing. However, at later ages, binary admixtures (SF+FA) showed improved strength when cured in sea water as compared to normal water cured specimens. The improvement in strength at later ages, is due to pozzolanic reactivity of FA that made the concrete resilient to sea water.



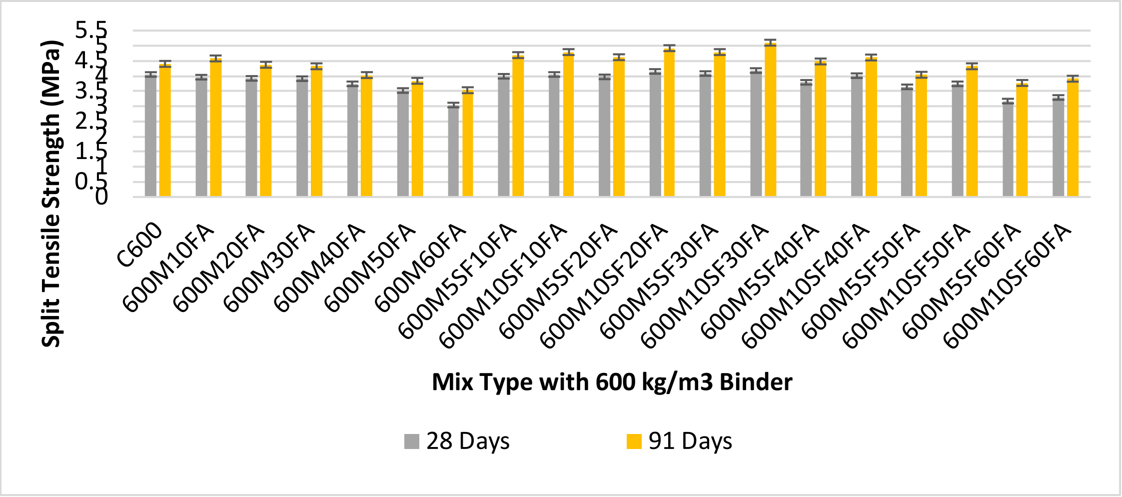


(c)

Fig. 5: a) Compressive Strength for Mix Type-I, b) Compressive Strength for Mix Type-II, c) Compressive Strength for Mix Type-III, d) Experimental Setup

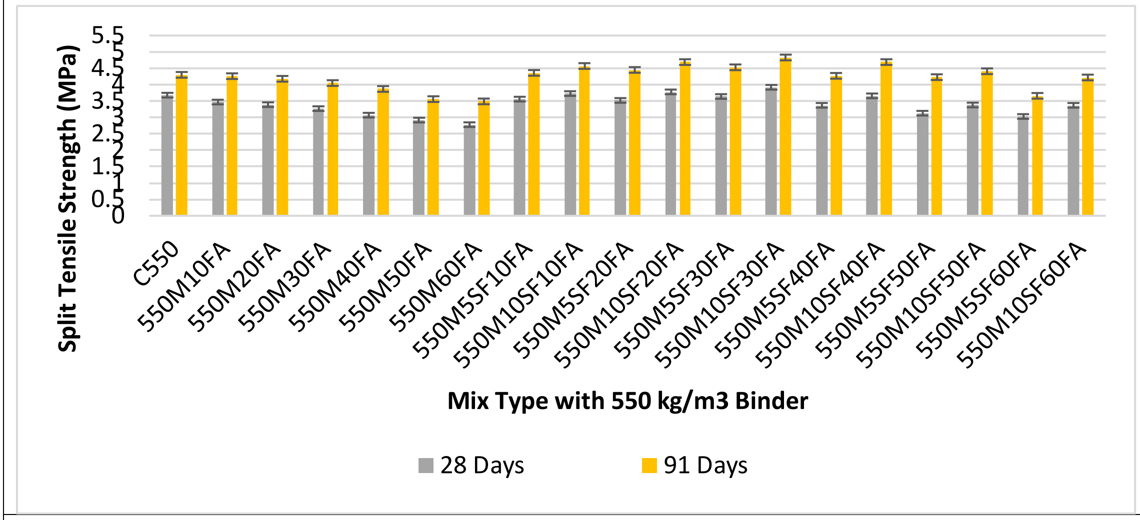
C. *Splitting Tensile Strength*

The split tensile test method does not give true tensile strength but the failure pattern of specimens under splitting action of loads gives a fair idea about the tensile strength of the material [45]. Split tensile strength at 28 and 91 days are shown in Figure6. It was observed that the replacement of OPC with FA and SF affected the spilt tensile strength at 28 days and 91 days in similar way as it affected the compressive strength. The results are in line with that of compressive strength. 28 days tensile strength continues to decrease in mixes containing FA only and with the addition of SF 28 days tensile strength becomes comparable with control mix. On contrary, tensile strength increases significantly with age for all mixes and the maximum tensile strength was noticed in mixes containing 30%FA+10%SF. The increase in split tensile strength was ascribed to the filling effects of fine particles of binary admixtures. Split tensile strength was recorded max 11% and 12 % of compressive strength at 28 days and 91 days respectively for mix containing 30%FA+10%SF.

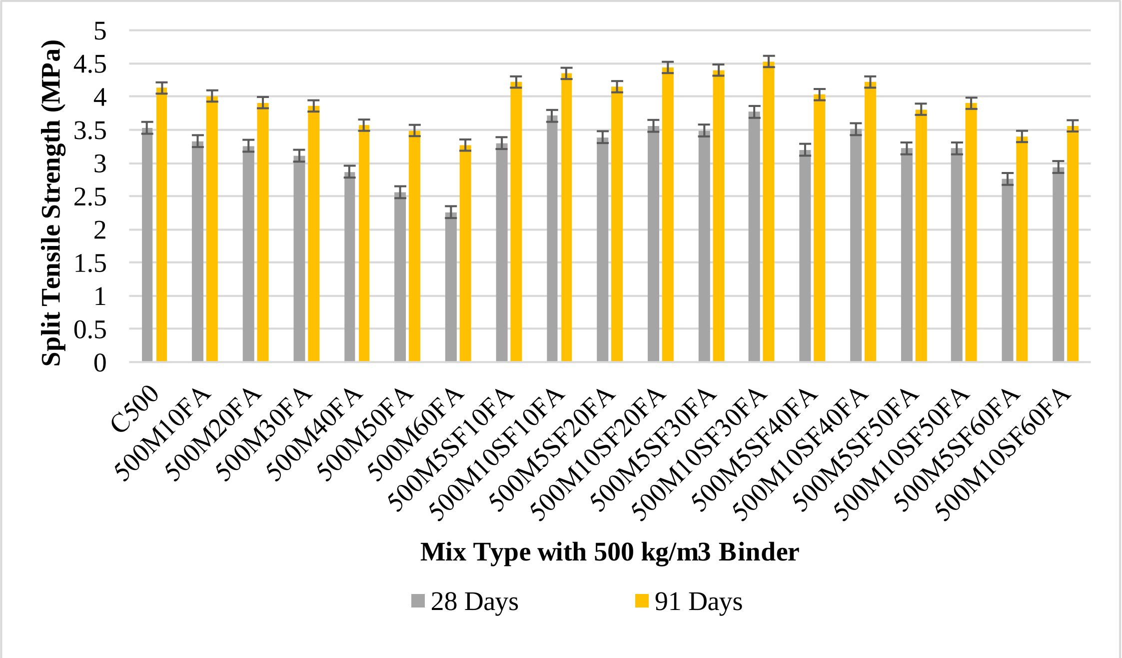

Split Tensile Strength (MPa)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
C600
600M10FA
600M20FA
600M30FA
600M40FA
600M50FA
600M60FA
600M5SF10FA
600M10SF10FA
600M5SF20FA
600M10SF20FA
600M5SF30FA
600M10SF30FA
600M5SF40FA
600M10SF40FA
600M5SF50FA
600M10SF50FA
600M5SF60FA
600M10SF60FA
Mix Type with 600 kg/m3 Binder
28 Days
91 Days

(a)

(b)


Split Tensile Strength (MPa)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
C550
550M10FA
550M20FA
550M30FA
550M40FA
550M50FA
550M60FA
550M5SF10FA
550M10SF10FA
550M5SF20FA
550M10SF20FA
550M5SF30FA
550M10SF30FA
550M5SF40FA
550M10SF40FA
550M5SF50FA
550M10SF50FA
550M5SF60FA
550M10SF60FA
Mix Type with 550 kg/m3 Binder
28 Days
91 Days

(c)


Split Tensile Strength (MPa)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
C500
500M10FA
500M20FA
500M30FA
500M40FA
500M50FA
500M60FA
500M5SF10FA
500M10SF10FA
500M5SF20FA
500M10SF20FA
500M5SF30FA
500M10SF30FA
500M5SF40FA
500M10SF40FA
500M5SF50FA
500M10SF50FA
500M5SF60FA
500M10SF60FA
Mix Type with 500 kg/m3 Binder
28 Days
91 Days

(d)

Fig. 6: a) Split tensile strength for C600, b) Split tensile strength for C550, c) Split tensile strength for C500, d) Experimental Setup

The variation of ultrasonic pulse velocity in design mixes at 91 days is presented in Figure 7. The UPV has also been compared with compressive strength at the same age. It was revealed that the UPV variation was in close relation that of the compressive strength. The UPV was lower for mixes with higher FA content that was improved by the addition of SF. All the mixes had UPV in the range of 3.59km/s to 4.62km/s. The maximum UPV value of 4.62km/s was obtained in mix containing 10%SF+40%FA. UPV value was observed to decrease with increase in the content of FA in SCC mixes and theminimum value 3.59km/s was recorded in mix with 60% FA. Generally, the UPV is a function of porosity, and it decreases with the increasing of porosity [46]. The presence of pores, non-homogeneity, feeble particle packing, and miscellaneous imperfections are the probable causes for the observed drops in UPV values [47]. The concrete is categorized as “excellent,” “good,” “doubtful,” “poor,” and “very poor” for UPV values of 4500 m/s and above, 3500–4500; 3000–3500; 2000–3000; and 2000 m/s, respectively, in line with previous research [48].

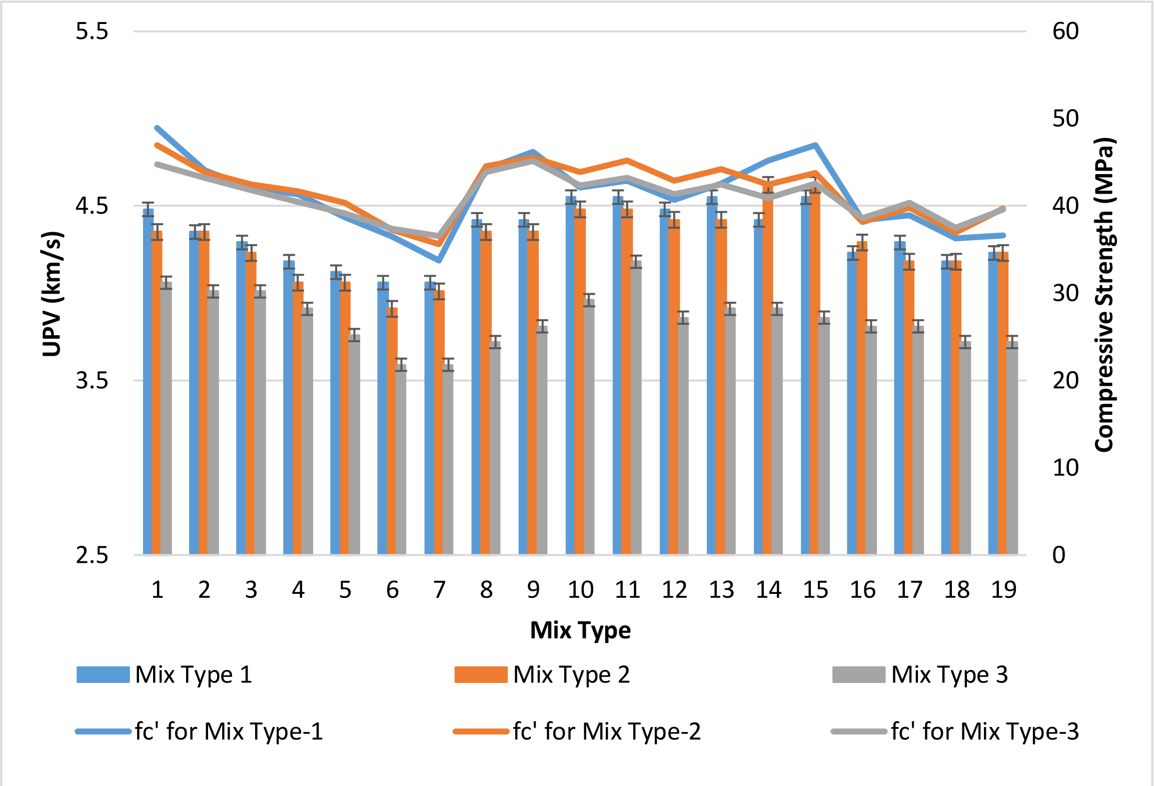


Fig. 7: Comparison of Compressive Strength and Ultrasonic pulse velocity for Mix Type I, II & II

D. Sorptivity

The sorptivity coefficient was measured at 28 and 91 days. The results are shown in Figure 8. It was revealed that the sorpitivity was gradually reduced with binary admixtures and with age in all type of mixes. The concrete with 60%FA exhibited about 90% of control mix sorptivity. The concrete with binary admixtures further reduced the sorptivity. On average, concrete with binary admixtures 10%SF+60%FA exhibited about 81% of sorptivity as measured for control mix. The FA particles are finer comparing to OPC as the FA had a higher specific surface area of 430 m^2kg^{-1} whereas OPC had a specific surface area of 360 m^2kg^{-1} [44]. It is an established fact through literature [49][50] that FA as a binder reduce the interconnecting voids and reduce the thickness of transition zone between the binder and aggregates. Therefore, the concrete composed of FA has lower capillary pores. The use of FA and SF blends together in the ternary system seemed to be the most effective in the reduction of sorptivity index [48]. For example, the least sorptivity 0.0028 $mm/sec^{1/2}$ was recorded for 10%SF+60%FA concrete in all mix types. This is also in line with the results of previous research [48].

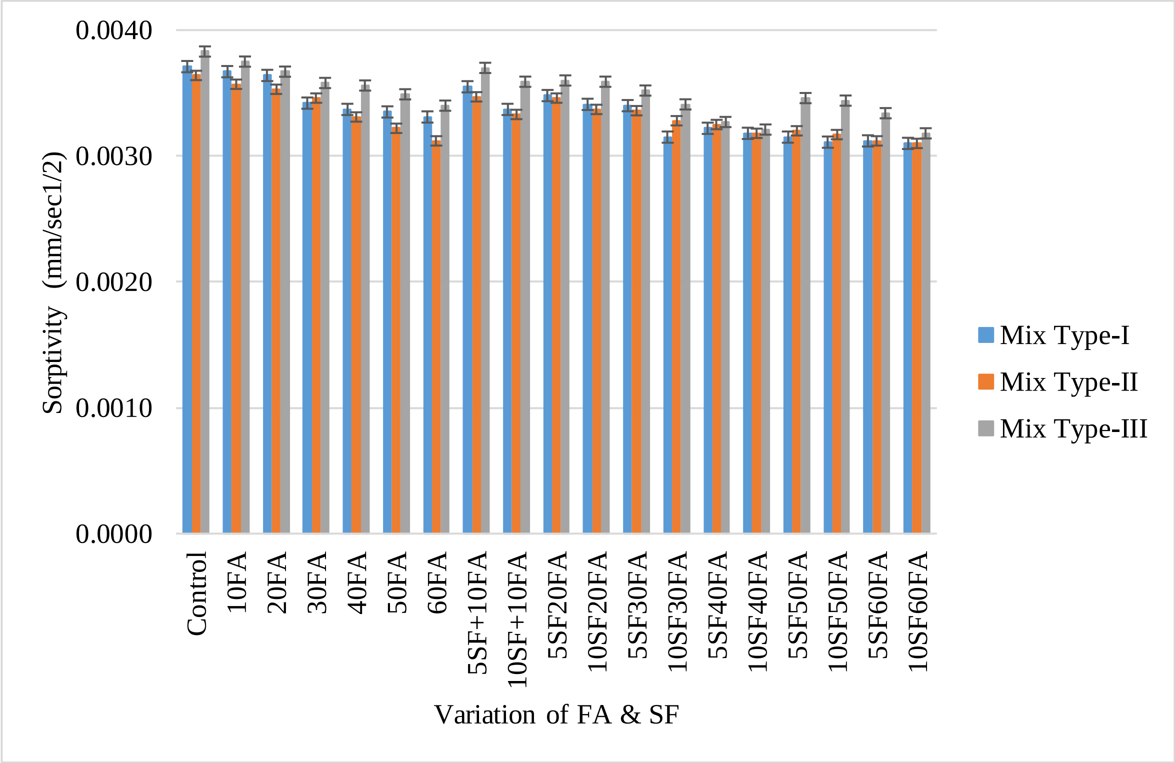


Fig. 8: Sorptivity coefficient for Mix Type I, II & II

E. Non steady state chloride migration coefficient

The durability of concrete in marine environment is mainly dependent on its resistance towards Cl- ion penetration. Non steady state chloride migration coefficient (D_{nnsm}) was determined according to NT build 492 [33]. Through published literature, it was summarized that D_{nnsm} is inversely related to the quality of concrete [52],[53],[54],[55],[56]. D_{nnsm} was measured at 91 days of concrete maturity and reported in Figure 9. It was revealed that with the addition of FA, concrete showed more resistance towards chloride ion penetration. And concrete with binary admixtures (SF+FA) showed even better resistance towards chlorides till 10%SF+30%FA that gives the maximum value of D_{nnsm} $1.746x10^{-12}$ m^2/s. After this level of replacement, the resistance of concrete towards chlorides becomes almost steady. According to Chinese standard JGJ/T 193–2009 [55], the chloride penetration resistance is evaluated as five levels (poor, relatively poor, relatively good, good and very good) based on the value of D_{nnsm}, and the chloride penetration resistance being very good for D_{nnsm} less than $1.5x10^{-12}$ m^2/s [52][54]. Whereas [53] concluded, using the coulomb and surface resistivity limits, that D_{nssm} value between 12×10^{-12} m^2/s and 17×10^{-12} m^2/s represent the cut off between the moderate to high chloride penetration resistance, and 20×10^{-12} m^2/s to 25×10^{-12} m^2/s may represent the limit between the low to moderate chloride penetration resistance of concrete. All the mixes, in this study, showedgood chloride penetration resistance as the maximum recorded value of D_{nssm} was $6.323x10^{-12}$ m^2/s.

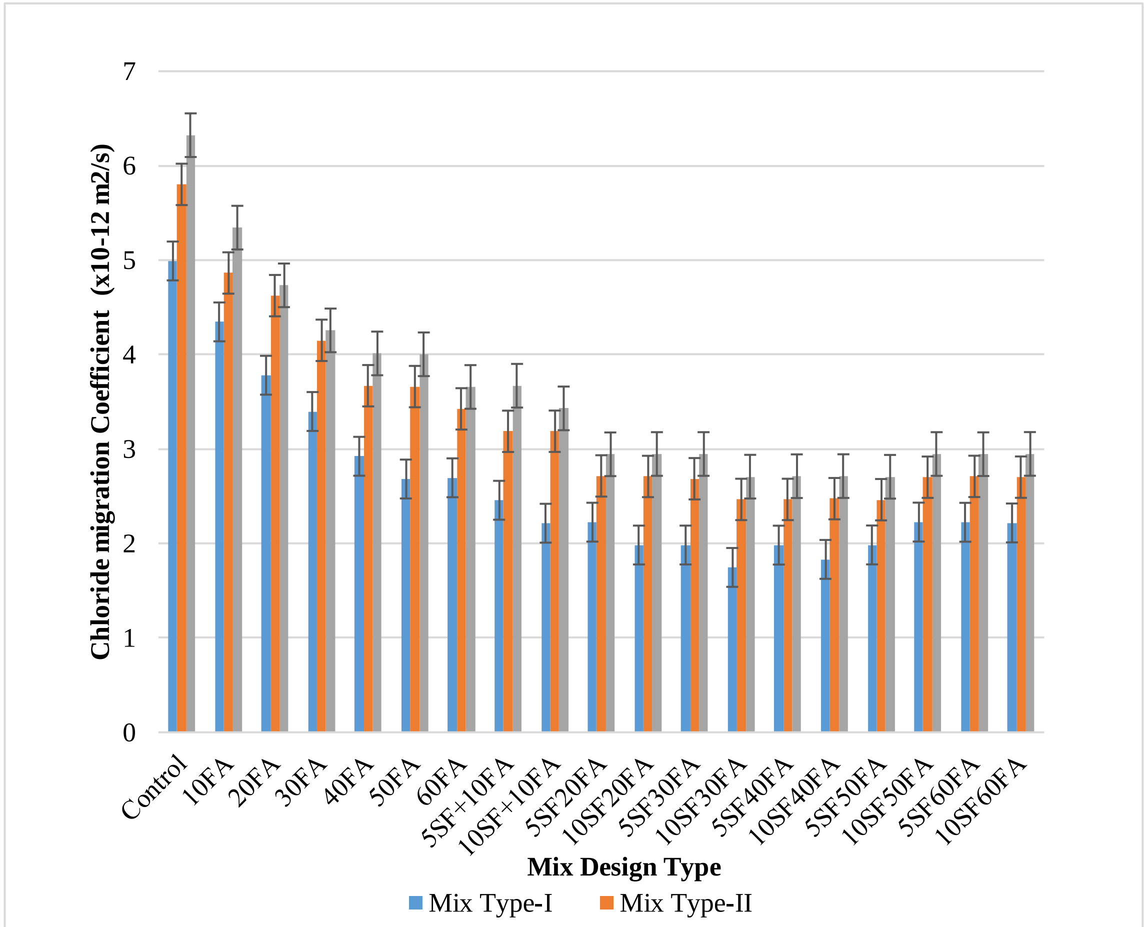


Fig. 9: Non steady state chloride migration coefficient for Mix Type I, II & II. Error bars represent the standard error

IV. CONCLUSIONS

Class F FA and SF was used as a partial replacement of OPC in developing SCC, in line with EFNARC [3] guidelines, with improved characteristics for marine environment. Compressive strength was evaluated for normal water curing and simulated sea water curing in controlled environment. The experimental work evaluated the effectiveness of partial replacement of OPC on the mechanical and durability characteristics of SCC. Following conclusions are drawn:

- SCC can be prepared in binary and ternary mixes using FA up to 40% and SF up to 10% replacement level of OPC. Further increase in FA affected the flowability and early age compressive strength of SCC. Increase in SF drastically affected the flowability of concrete.
- With the addition of FA, SCC showed a decrease in compressive strength at early age. However, compressive strength was improved at later ages in normal water as well as in sea water. The maximum strength was achieved in SCC with binary admixture 10%SF+40%FA.
- The tensile strength increases significantly with age for all mixes and the maximum tensile strength was noticed in SCC containing 30%FA+10%SF. Split tensile strength was recorded max 11% and 12 % of compressive strength at 28 days and 91 days respectively.
- The UPV was lower for mixes with higher percentage FA that was improved with the addition of SF. All the mixes had UPV in the range of 3.59 km/s to 4.62 km/s. The maximum UPV value of 4.62 km/s was obtained in SCC containing 10%SF+40%FA.
- It was revealed that the sorpitivity was gradually reduced with binary admixtures and with age in all type of mixes. The concrete with 60%FA exhibited about 90% of control mix sorptivity. The concrete with binary admixtures further reduced the sorptivity. On average, concrete with binary admixtures 10%SF+60%FA exhibited about 81% of control mix sorptivity.
- With the addition of FA, concrete showed more resistance towards chloride ion penetration. And concrete with binary admixtures 10%SF+30%FA showed maximum resistance towards chlorides.

- **Data Availability:** The data used to support the findings of this study are available from the corresponding author upon request.
- **Conflicts of Interest:** The authors declare that they have no conflicts of interest.

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