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Synergistic effects of fly ash and hooked steel fibers on strength and durability properties of high strength recycled aggregate concrete

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ABSTRACT

To deal with the rising environmental issues, more attention is now being given to recycled-aggregate concrete to partly meet the demands of the construction industry. However, recycled concrete is inferior in mechanical and durability performance compared to its counterpart natural-aggregate concrete. In this study, an effective approach is presented to improve the strength and durability performance of recycled concrete using supplementary materials, namely fly ash and hooked steel fiber. Low calcium refined fly ash was used at 0%, 15%, and 30% by mass replacement of cement with three different doses of steel fiber (0%, 0.5% and 1%). Mixes were evaluated based on results of several strength (compressive strength, splitting-tensile strength, and flexural strength) and durability tests (water absorption, acid attack resistance, and chloride-ion penetration). The results showed that incorporating both steel fiber and fly ash in recycled concrete significantly improves its mechanical performance and the proposed concrete can be markedly upgraded. The strength testing revealed that a synergistic effect of 15% fly ash and 1% steel fiber upgraded the flexural, splitting-tensile, and compressive strength of recycled concrete by 73–78%, 39–50%, and 13–23%, respectively. Fly ash minimized the negative effects of both recycled coarse aggregates and steel fiber incorporation on water and chloride-ion permeability resistance of concrete. Additionally, both fly ash and steel fiber were remarkably useful in increasing the acid attack resistance of concrete.

List of Acronyms

AAR	Acid attack resistance
CNA	Coarse natural-aggregates
CP	Chloride penetration
CRA	Coarse recycled-aggregates
FA	Fly ash
f_{CS}	Compressive-strength
f_{FS}	Flexural-strength
f_{STS}	splitting-tensile strength
HSF	Hooked steel fibers
NC	Natural-aggregate concrete
RC	Recycled-aggregate concrete
WA	Water absorption

1. Introduction

The construction-industry is responsible for many environmental issues, specifically due to producing and transportation of construction materials (e.g., aggregates and cement). Thus, environment protection agencies have been pressurizing cement and aggregate industries to cut-off their needs for raw materials and fuels. Worldwide demand for fine and coarse aggregates has increased beyond 52 billion tons per year (Freedonia, 2016). The major impacts of mining aggregate on environmental quality include the loss of habitat of different living species and fertile land, noise and air pollution, soil erosion, and changes in the visual scenery of the area (Langer and Arbogast, 2002). On the other side, construction and demolition waste (CDW) have also increased remarkably over the last decade. Impacts of CDW on the environment

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include loss of vital spaces, shortage of landfills, difficulties in solid waste management, etc. CDW can also increase the toxicity levels of soils (Kurda et al., 2018b). For example, China produced more than 15 billion tons of CDW in 2016 (Tai et al., 2017). Europe produces about 320–380 million tons of CDW annually (Pacheco et al., 2017). CDW can simply be recycled for reuse in RC. Accordingly, the mentioned issues can be partially resolved using CRA in the concrete production (Benhelal et al., 2013; Kurda et al., 2018a; Tai et al., 2017) with some loss in the mechanical behavior and durability (Ali and Qureshi, 2019a, 2019b; Kurad et al., 2017; Masood et al., 2019). Nevertheless, replacing CNA with CRA decreases the carbon emissions associated with concrete manufacturing (Braga et al., 2017; Hendriks and Janssen, 2003; Kurad et al., 2017).

Various techniques have been suggested by scientists to upgrade the durability and mechanical characteristics of RC. One of the most popular approach to improvise the characteristic of RC is by using mineral admixtures, i.e. FA (Ahmed, 2011; Ali et al., 2020a; Kurda et al., 2018a; Lima et al., 2013; Shin et al., 2014), silica fume (Çakır and Sofyanlı, 2015; Dilbas et al., 2014; Huoth et al., 2014; Xie et al., 2018b), bentonite and metakaolin (Jadhav et al., 2015; Kapoor et al., 2017; Kou et al., 2011; Masood et al., 2019; Muduli and Mukharjee, 2019; Singh and Singh, 2016), blast furnace-slag (Ann et al., 2008; Çakır, 2014; Kou et al., 2011; Majhi et al., 2018). The incorporation of mineral admixtures is a "common-practice" in the construction sector to enhance the performance of NC. Researchers (Ali et al., 2019a; Kou et al., 2011; Kurad et al., 2017; Kurda et al., 2019) have shown that mineral admixtures give more benefit to RC compared to NC. It is because free portlandite (CH) present in CRA has a strong tendency to react with the binder matrix that strengthens the "interfacial transition-zone" (ITZ) between binder matrix and aggregates of RAC but no such reactions at ITZs are possible in NC.

Compared to other available mineral admixtures, FA is available in abundant quantities, especially in the developing countries. FA is the waste product of coal power plants. Its carbon footprint mainly depends upon its transportation distance from the coal power-plant to the "construction-site". FA reduces the early age mechanical performance but it has benefits in the long term performance, i.e. enhanced later-age durability and strength, reduction in permeability and expansion due to "alkali silica" reaction (Faraj et al., 2019; Hefni et al., 2018; Shehata and Thomas, 2000; Thomas et al., 1999; Uysal and Akyuncu, 2012). FA is also beneficial to the workability of concrete (Kou et al., 2011; Kurda et al., 2017; Nawaz et al., 2020). FA can offset the negative effect of the CRA-incorporation on the workability of concrete (Kurda et al., 2017; Nawaz et al., 2020) that helps in minimizing the requirement of superplasticizer to maintain target workability. Apart from carbonation resistance, it is also very well known that FA is more beneficial to upgrade the durability characteristics of RC rather than its mechanical performance (Kurad et al., 2017; Kurda et al., 2018a). Kou et al. (2011, 2007) reported that the mechanical strength of RC with 25% FA was noticeably lower and higher than the control mix (without FA), respectively at 28 and 90-days. They showed that 35% FA reduced the mechanical strength by more than 20% and 10% at 28 and 90-days, respectively but *CP* resistance of mixes containing 25–35% FA was still higher than that of the control mix at both 28 and 90-days. Kurad et al. (2017), Kurda et al. (2018a, 2018c, 2017) investigated a wide range of concretes with varying incorporation levels of FA and recycled-aggregate (as a substitution of sand and gravel). They also showed that FA at 30% level was more useful to durability performance (*WA*, sorptivity, and *CP*) (Kurda et al., 2019, 2018c) of RC compared to its mechanical performance. Therefore, the incorporation of FA alone is not enough to enhance the overall characteristics of RC. This calls for the adoption of techniques that improves both durability and mechanical characteristics of RC.

It is proven that the addition of fibre (Ali and Qureshi, 2019b; Carneiro et al., 2014; Das et al., 2018; Kizilkanat et al., 2015; Mastali and Dalvand, 2016; Xie et al., 2018a) enhances the mechanical behavior of RC. Fiber-reinforcement is a very promising way to upgrade the f_{STS} (Nili and Afroughsabet, 2010; Passuello et al., 2009), f_{FS} (Alberti et al., 2017; Biolzi and Cattaneo, 2017), and energy absorption capacity (Afroughsabet and Ozbakkaloglu, 2015; Lee, 2017) of cement-based composites. Fiber-reinforcement along with RC can be very helpful to resolve the issues of ductility and sustainability associated with conventional plain cement concrete. Ali et al. (2019b), Ali and Qureshi (2018) showed that fiber-reinforced mixes have a higher "f_{STS}-to- f_{CS}" which means fiber-reinforcement mainly contribute to enhance the fracture resistance of the material. Nevertheless, fiber addition may negatively affect concrete permeability (Ali and Qureshi, 2019c; Koushkbaghi et al., 2019) because inclusion of fibers increases the connectivity of pores and microchannels in the binder matrix that facilitates the penetration of water and harmful chemicals (Ali et al., 2020b). It is obvious that the advantage of improved mechanical performance due to fibers comes at the loss of some durability. Some studies have reported that the permeability-resistance of fiber-reinforced concretes can be upgraded by the inclusion of mineral-admixtures (Karahan and Atiş, 2011; Koushkbaghi et al., 2019; Şahmaran and Li, 2009; Zhang and Li, 2013).

There are very few scientific studies that simultaneously have studied the influence of "mineral-admixtures" and fibers on the mechanical-properties of RC, and to the best information of authors, no systematic study was found exploring the coupling-effects of mineral admixtures and fibers, namely hooked steel fibers (HSF) and FA on the durability performance of RC. Xie et al.(2018b) and Nazarimofrad et al. (2017) studied that the composite influence of steel fibers (SF) and silica fume on impact behavior and f_{CS} of RC. Both of these studies showed the usefulness of composite addition of silica-fume and SF in terms of improved compressive toughness and load-deflection behavior. Afroughsabet et al. (2017) investigated the combined-effect of HSF and finely ground slag on the durability and mechanical characteristics of RC. They reported that RC of high quality compared to plain NC, is that incorporating both slag and HSF. Qureshi et al. (2020) reported an overall improvement in the efficiency of fiber-reinforcement with the addition of mineral admixtures (silica fume, fly ash and slag). Despite reporting improvement in the performance of RC, these studies (Afroughsabet et al., 2017; Nazarimofrad et al., 2017; Qureshi et al., 2020; Xie et al., 2018b) did not systematically evaluated the benefits of the combined incorporation of "mineral admixtures" and fiber on the properties of RC, for example, evaluation of the net changes or gains in the durability and mechanical performance which occur when fiber and mineral admixture are simultaneously used. Previous studies were limited to a small number of mixes and only one curing age (namely 28-days) that was not sufficient to confirm the synergistic benefits of fibers and mineral admixtures in a methodical way.

The primary aim of this research is to study the combined effects of FA and HSF on the durability and strength performance of RC. As shown before, the HSF, FA and CRA incorporation may have mixed effects (positive and negatives) on the properties of concrete. After an extensive review, we selected the mentioned materials at different percentages to be simultaneously used in concrete to eliminate their negative influence by synergistic effect. For that purpose, two mix families (RC and NC) were made and, in each of these two concrete-families, FA was used at three different levels (0%, 15%, and 30%) with 0%, 0.5% and 1% volume fraction of HSF. Both durability (*WA, CP* and *AAR*), and strength parameters (f_{CS}, f_{STS}, and f_{FS}) were evaluated for each concrete mixture. Relationships are also developed between the studied parameters to understand the dependency of parameters on each other. Generally, the ultimate goal of this research is to obtain an RC that is simultaneously sustainable, durable and strong.

2. Materials and methodology

2.1. Properties of materials

2.1.1. Binders

The type, specific gravity and specific surface area of cement used in the concrete mixes were Type-I based on ASTM C150 (2018), 3.11 and 2650 cm^2/g, respectively. In addition, very low-calcium content FA is used as a cement substitute and it qualified as Type F of coal ash based on ASTM C618 (2017). Table 1 shows the chemical compositions of both cement and FA. Table 2 shows the physical properties of these binding materials.

2.1.2. Aggregates

CNA used in this work is the crushed limestone of the Margalla brand. CNA was used as coarse aggregate to make the NC family. In addition, concrete pieces with $f_{CS} = 35$ MPa are manually crushed and sieved to obtain CRA. The CRA was used as a substitute of CNA to produce the RC family. An overview of the CRA is shown in Fig. 1. The maximum particle size of both coarse aggregates was 12.5 mm. Both coarse aggregates lie well within the limits of ASTM C33 (2018), see Fig. 2.

The properties of both CRA and CNA are given in Table 3. The fine-aggregate utilized in this work is obtained from Lawrancepur-quarry (pit sand). Petrographic analysis of Lawrancepur sand showed that it was mainly composed of siliceous rock fragments. Its mineral composition was >60% quartz, and about 40% consisted of granite, biotite, felspar, slate, magnetite. The properties of fine-aggregate are given in Table 3.

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2.1.3. Hooked steel fibers

HSF used in this research were cold-drawn steel fibers glued together (Fig. 3). The glue of HSF bundles was water-soluble, and filaments of HSF easily separated during the preparation of concrete mix. The diameter and length of the HSF are 900 μm and 35 mm, respectively. These fibers have 1200 MPa tensile strength. Density of these fibers was about 7750 kg/m^3.

2.1.4. Superplasticizer and water

Superplasticizer (SP) used to control workability in this research is Viscocrete 3110. Clean tap water is used for the preparation of all mixes.

2.2. Composition of concrete mixtures

In this research 18 mixes are produced using the absolute volume approach, see Table 4. Two concrete families (NC and RC) were produced using CNA and CRA as a coarse aggregate. For each of these two families, three different levels of FA (0%, 15%, and 30% by volume of replacement of cement) were used with three different volume-fractions of HSF (1%, 0.5%, and 0%). All aggregates are utilized in saturated-surface dried (SSD) conditions. Since the aggregates' absorption was already satisfied, effective water contents of both RC and NC families were kept the same and no additional-water was added. To prepare CRA in SSD-condition, first, it was presoaked in tap water for 1 h. After pre-soaking, CRA was dried in air for about 15 min. After air-drying, CRA was immediately used in the mixing process. After air-drying of CRA, WA of the CRA sample was also measured and it was found that due to the effect of the pre-soaking, CRA absorbed about 95% water of their 24-h absorption capacity. The slump of concretes reduced with the inclusion of HSF. Therefore, the amount of superplasticizer (SP) is also increased to achieve the desired-level of workability. SP was used in the whole mixes to maintain the target slump (80–110 mm). The quantity of SP required for each mix was pre-determined in the trial stage. Actual slump of all concrete mixes is presented in Table 4.

2.3. Mixing process

The mechanical mixer with adjustable rotation speed (rpm) was used to mix the concrete mixes. Firstly, aggregates with the binder (cement, FA) were dry mixed for two minutes at the speed of 60 rpm. Dry mixing was done at low speed of 60 rpm to avoid dust clouds of cement from the mechanical mixer. Then, 60% of the total-water is added and mixing continued for two more minutes at the same speed. After that the HSF is added and mixed for 4 minutes. After that, the remaining 40% of the water and the SP are added and mixed for 2 min at an increased speed of 100 rpm. When fibers were added to fresh mix, it was crucial to mix at a high speed to disperse the fibers throughout the binder matrix. Good dispersion was achieved at 100 rpm at both 0.5% and 1% HSF. After completion of mixing, the mechanical mixer is turned-off for two minutes to avoid overheating of electric motor. Then again, the mixing was carried on, at the slower speed of 60 rpm until the casting process of concrete specimens finished. Mixer containing fresh concrete should be kept running during the casting stage to keep the fibers and other ingredients properly dispersed.

2.4. Preparation of specimens for testing

2.4.1. Mechanical properties

Details of curing and testing of specimens for mechanical characteristics are given in Table 5. An overview of the testing procedure of mechanical properties is shown in Fig. 4. The compressive=and splitting tensile tests are conducted on 100×200 mm cylinders. Flexural=tests are carried out on prismatic-specimens of 100×100×500 mm within 3rd-point loading.

2.4.2. Durability properties

For *WA*, 100×100 mm-cylindrical specimens were tested in compliance with ASTM C948 (2016). *WA* capacity of all mixes was measured at 56-days. Specimens of similar size were also used for the measurement of *CP* and *AAR*. In this study, the actual *CP* in the specimens was measured using an immersion method proposed by Ali and Qureshi (2019a). Following this method, specimens were first cured in normal water for the duration of 28 days. After curing, specimens were air-conditioned for 30-days. Then these specimens were dipped in the 10% "sodium-chloride" (10% NaCl) solution for the period of 56 days. In this method, chloride ions (Cl^-) penetrated the material without any aid (or naturally). After 56-days, specimens were cut in two halves across the diameter (in the direction of height) and then the cut plane were mist-sprayed with 0.10 normality "silver nitrate" ($AgNO_3$) solution. White precipitates were formed when $AgNO_3$ reacted with the penetrated chlorides (Cl^-) ions. *CP* was recorded at 6 different points around the periphery of the samples and the average-result is given in this work. Serious care should be taken while spraying $AgNO_3$ solution on the

Table 1
Chemical composition of binders.

Type of binder	Al_2O_3	SiO_2	CaO	MgO	Fe_2O_3	Na_2O	K_2O	Loss in ignition
Type I cement	6.2%	23.5%	61.5%	1.2%	4.3%	0.5%	1.4%	3.1%
FA	27.7%	54.3%	4.5%	0.9%	3.7%	0.2%	2.4%	4.3%

Table 2
Physical characteristics of binders.

Type of binder	Particle density (kg/m^3) (ASTM C188, 2017)	Bulk density (kg/m^3)(ASTM D6683, 2019)	Specific surface area (m^2/kg) (ASTM C115, 2010)	Soundness(ASTM C151, 2018)	7-Days f_{CS}(MPa)(ASTM C109, 2016)
Type I cement	3.13	1440	265	0.1%	45
FA	2.34	1130	345	-	-

Fig. 1. Overview of CRA used in this study.

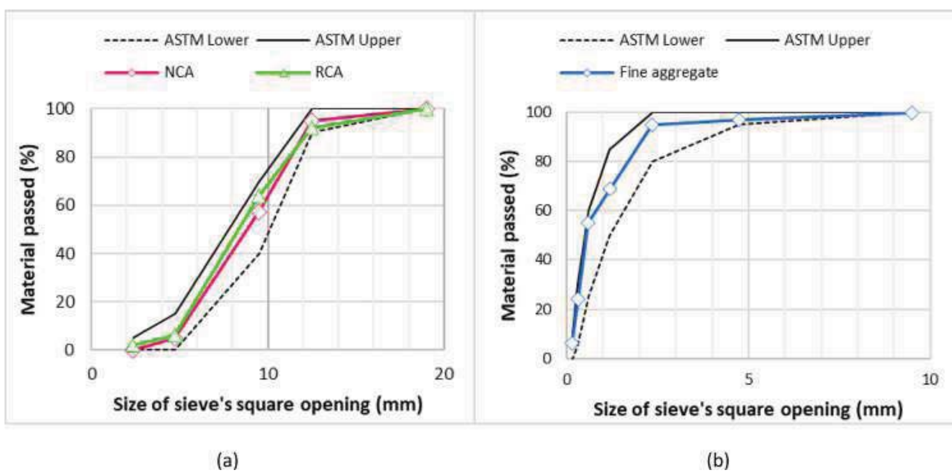

Fig. 2. Granulometry of **(a)** coarse aggregates i.e., CRA and CNA **(b)** fine aggregates.

Table 3
Properties of aggregates.

Aggregate	Water-absorption (%)	Bulk-density (kg/m^3)	Specific-gravity
Fine aggregate (ASTM C128, 2015)	0.78	1635	2.71
CNA (ASTM C127, 2015)	0.54	1572	2.67
CRA (ASTM C127, 2015)	7.53	1345	2.31

specimens. Generally, it takes 1-2 gentle sprays of $AgNO_3$ solution from a 500ml-Burkle bottle and a time of 2-3 sec to precipitate the penetrated chlorides. Split-surfaces should not be over sprayed to avoid smudging the boundary line between chloride-penetrated and chloride-free zones.

Specimens for the determination of *AAR* were first submerged in water-tank and cured at 24–30 °C for the 28 days. After that, the specimens are conditioned in the air for 30-days. Subsequently, samples are dipped in a 5% sulfuric-acid solution (5% H_2SO_4). The loss-in-the-mass of these samples was calculated after 56 and 90 days. The Loss-in-mass (%) was measured by noting the initial weight of the air-conditioned sample and acid-affected specimen after cleaning the eroded material at the required age.

The steel molds was used to cast all specimens. After casting, compaction was done on the vibrating table. All specimens were allowed to set in the molds for the duration of 24-h under waterproof covers. Subsequently, samples are cured in the "water-tank" at a temperature-of 27±3 °C up to the testing-day.

3. Results of mechanical testing and discussion

3.1. Compression strength

The compression test results of the mixes at 28–90 days are shown in Fig. 5. The results exhibit that combined incorporation of the HSF and 15% FA can considerably enhance the f_{CS} of RC. Moreover, interaction of FA and HSF improves the net-gain in f_{CS} because of the fibre inclusion in

Fig. 3. Overview of HSF used in the present study.

the binder matrix. RC with 15% FA and 1% HSF experiences a net gain of 23% in f_{CS} over plain RC. Further details are provided in the following sub-sections (§ 3.1.1-3.1.3).

3.1.1. *Influence of FA on f_{CS} results of NC and RC*

The influence of FA incorporation on the compressive test results of both RC and NC is shown in Fig. 6. These results exhibit that FA is beneficial to the f_{CS} at 15% incorporation level. For higher incorporation ratio, specifically at 30%, FA may significantly reduce the f_{CS} of both NC and RC, especially at 28 days. The results show that relative to NC, FA contributes more towards the f_{CS} development of RC due to the facts mentioned in the next paragraph.

The strength of NC was notably higher than that of the RC. The f_{CS} of RC was 18% lower than that of the NC. The lower-strength of RC can be generally ascribed to lower density and higher water-demand of CRA compared to that of the CNA, which increases the overall porosity of RC (Ali et al., 2020b; Kou et al., 2011). 15% FA increases the f_{CS} of RC by more than 4.2% and 12.7% at 28- and 90-days, respectively. 15% FA also improves the f_{CS} of NC by 2.1% and 6.5% at 28 and 90-days, respectively. These results confirm the fact that the f_{CS} development rate of the FA-NC was lower than that of the FA-RC. FA contributes to strength development in two different ways: (i) pozzolanic reaction between free calcium hydroxide (CH) and silica particles of FA produces strong and dense calcium silicate hydrates and (ii) filler effect of smaller particles of FA helps in reducing the pore-size in the binder matrix of the mixes. RC has more CH content than NC, therefore, RC offers more potential for pozzolanicity than NC. FA particles can also react across the binder matrix with CH exist in CRA, as explained by Kurda et al. (2017). Compared to the present study, Sujivorakul et al. (2011) reported a slightly higher net gain of 5-15% in f_{CS} of NC due to 10-20% FA incorporation. Boga and Topcu (2012) reported that up to 15% FA substitution, f_{CS} of NC was similar to that of the OPC-NC at 28-days. The FA on concrete vary significantly in literature due to a huge variation in the composition of FA content and its source and the type of coal. In this study, positive effect of 15% FA on f_{CS} might be because of a lower water-binder ratio (0.35) that helps in closing the spaces between the FA particles and OPC particles facilitating a quicker pozzolanic reaction.

Incorporation of 30% FA decreases the f_{CS} of NC by 12% and 5% at 28- and 90-days, respectively. At 30% FA, RC shows a slightly different behavior than that of the NC. RC shows a reduction of 8% at 28 days, but at longer ages (90 days), RC achieved 2.6% higher f_{CS} compared to that of the mix made without FA (i.e. R/FA0/HSF0). At 30% FA level, the main explanation for the reduction in 28-days' f_{CS} is the decrease in calcium oxide (CaO) content of binder. CaO in cement generates CH, when calcium silicates of clinker react with water. Thus, the amount of required CH reduces when the incorporation level of alumina-silica rich FA increases to the paste matrix. Consequently, it reduces the pozzolanicity potential of concrete. At 30% FA, strength development RC is

Table 5
Details of casting, curing days and testing methods for mechanical properties.

Test	Method/ Standard	Size of the specimen (mm)	Curing age (Days)
Compression test	ASTM C39 (2015)	100×200-cylinder	28, 90
Indirect tensile test	ASTM C496 (2017)	100×200-cylinder	28, 90
Flexural test	ASTM C78 (2018)	100×100×500-prism	28, 90

Table 4
Details of concrete mixes.

Mix No.	ConcreteFamilies	FA (%)	HSF (%)	Mix ID	Binder (kg) Cement	FA	Aggregates (kg) Fine aggregate	CNA	CRA	Water (kg)	HSF (kg)	SP (kg)	Slump (cm)
1	NC (Family I)	0	0	N/FA0/HSF0	510	0	895	905	0	180	0	2	9
2			0.5	N/FA0/HSF0.5	510	0	888	892	0	180	39	4	8
3			1	N/FA0/HSF1	510	0	882	878	0	180	78	5.5	9
4		15	0	N/FA15/HSF0	433	59	895	905	0	180	0	2	10
5			0.5	N/FA15/ HSF0.5	433	59	888	892	0	180	39	4	10
6			1	N/FA15/HSF1	433	59	882	878	0	180	78	5.5	8
7		30	0	N/FA30/HSF0	357	118	895	905	0	180	0	2	11
8			0.5	N/FA30/ HSF0.5	357	118	888	892	0	180	39	4	10
9			1	N/FA30/HSF1	357	118	882	878	0	180	78	5.5	9
10	RC (Family II)	0	0	R/FA0/HSF0	510	0	895	-	835	180	0	2	10
11			0.5	R/FA0/HSF0.5	510	0	888	-	822	180	39	4	8
12			1	R/FA0/HSF1	510	0	882	-	808	180	78	5.5	10
13		15	0	R/FA15/HSF0	433	59	895	-	835	180	0	2	10
14			0.5	R/FA15/ HSF0.5	433	59	888	-	822	180	39	4	9
15			1	N/FA15/HSF1	433	59	882	-	808	180	78	5.5	9
16		30	0	R/FA30/HSF0	357	118	895	-	835	180	0	2	11
17			0.5	R/FA30/ HSF0.5	357	118	888	-	822	180	39	4	10
18			1	R/FA30/HSF1	357	118	882	-	808	180	78	5.5	8

(a) (b) (c)

Fig. 4. Overview of mechanical tests **(a)** compression test **(b)** splitting tensile test and **(c)** 3rd-point flexural test.

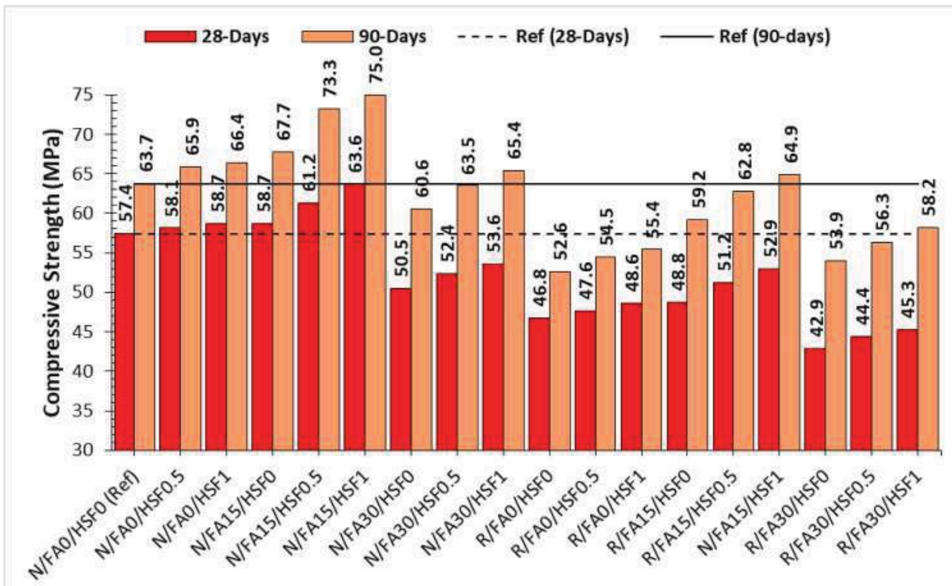

Fig. 5. Compression testing results of all mixes.

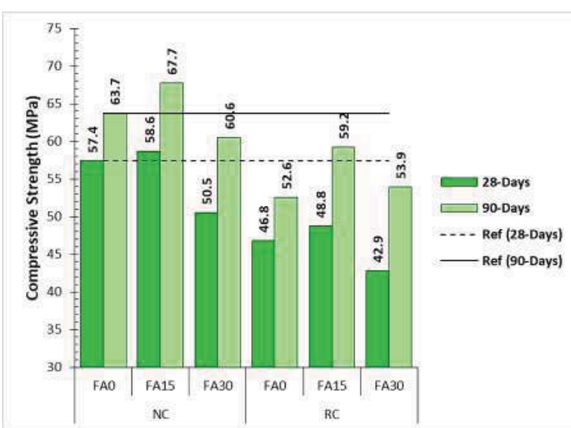

Fig. 6. Effect of FA on the f_{CS} of NC and RC.

more positively affected than that of the NC which can be credited to the presence of CH in CRA.

3.1.2. *Effect of HSF f_{CS} of RC and NC*

The effect of HSF incorporation on f_{CS} of RC and NC is shown in Fig. 7. A general-trend in shows that the f_{CS} of both RC and NC mixes increases gradually when the HSF amount is increased from 0% to 1%. At 28 days, f_{CS} of RC increases about 2% and 4% at 0.5% and 1% HSF, respectively. At 90-days, the f_{CS} of RC increases by 4% and 5% at 0.50% and 1.00% volume-fraction of HSF, respectively. Fibers can provide confinement effect to the binder matrix. This confinement effect increases the stiffness of concrete which consequently improves the f_{CS} of both RC and NC. Nevertheless, there are some studies (Afroughsabet

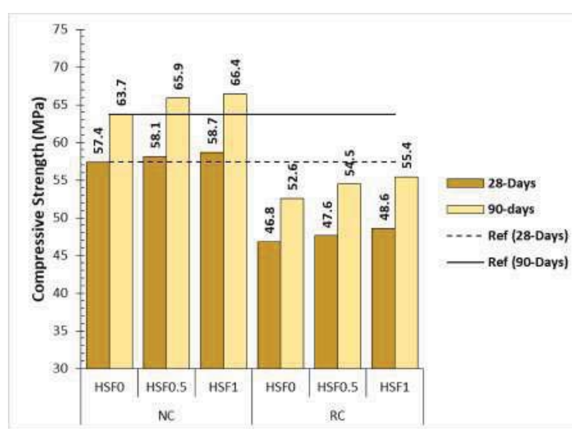

Fig. 7. Effect of HSF on f_{CS} of NC and RC.

et al., 2017; Karahan and Atiş, 2011; Xie et al., 2018b) that have reported inconsiderable or negative effects of fibers on the f_{CS} of concrete. Reduction in f_{CS} with the addition of plain fiber was blamed to the weak bond between fiber and binder-matrix [45]. Fiber inclusion slightly increases the porosity of concrete (Ali and Qureshi, 2019b; Atiş and Karahan, 2009) which also negatively affect its f_{CS}. In this study, no such decrease in f_{CS} was observed with the use of HSF. It may be due to better compaction factor achieved in this research by increasing the dosage of SP with a rising percentage of HSF. Better compaction can help in minimizing the porosity increased due to the addition of fibers. In other words, the difference between the porosity of concrete mixes with similar w/b ratio (0.365±0.015) may not be significant.

3.1.3. Coupling-effect of FA and HSF on f_{CS} of RC and NC

The combined-effect of FA and HSF incorporation on the f_{CS} of NC and RC is shown in Fig. 8. Overview of results indicates that 15% FA and HSF together can significantly recover the loss in strength due to CRA incorporation. Moreover, FA improved the net-gain in f_{CS} due to fibers inclusion, which indicates the FA enhanced the bond of HSF with binder-matrix.

The f_{CS} of NC-1%HSF-15%FA is 11% and 18% higher than that of the reference concrete at early and longer ages, respectively. Similarly to NC, RC-1%HSF-15%FA reaches 93% potential of reference mix at 28-days. At the age of 90-days, RC-1%HSF-15%FA outperforms the reference mix. At longer ages (90-days), RC-1%HSF-15%FA shows 23% improvement in f_{CS} over plain RC (i.e. R-0%HSF-0%FA). Maximum f_{CS} at 15% FA and 1% HSF is achieved because individually FA and HSF positively contribute to the strength and in addition to the individual effects, their synergistic effect is maximum in both RC and NC at 1% HSF and 15% FA, Fig. 9.

The estimated f_{CS} of RC and NC mixes with combined incorporation of HSF and FA is calculated using Eq. (1)-(3). Using Eq. (1), the difference between experimental-strength of concrete at a specific percentage of FA and reference concrete is calculated. Whereas using Eq. (2), the difference between experimental-strength of concrete at a specific percentage of HSF and reference concrete is calculated. Then the strength of mix with combined incorporation of FA and HSF is estimated using Eq. (3). The ratio between estimated and experimental f_{CS} for mixes with combined incorporation of FA and HSF is shown in Fig. 9. It is seen that net gains in f_{CS} due to combined-incorporation of HSF and FA are more than the total of net gains which are achieved due to individual-incorporation of HSF and FA (in the case of both NC and RC). It is because FA increased the efficiency of HSF in resisting compressive-stresses. Pozzolanic reaction with CH and filling effect of FA particles can strengthen the bond of the binder matrix with fibers. Xie et al. (2018b) reported that silica-fume as a supplementary cementitious-material enhanced the bond of binder matrix with steel fibers, and improved the efficiency of fiber-reinforced concrete mix. Similar behaviour can be expected from HSF and FA used in this study. In Fig. 9, it can be noticed that actual (experimental) net gains are higher than those of the estimated gains (calculated using individual effects of FA and HSF incorporation) in the mixes incorporating both FA and HSF. $f_{c.EXP}/f_{c.EST}$ values of RC-1%HSF-15%FA is 109% at 90-days which means that actual strength of the mix is 9% higher than its estimated strength. These results show the usefulness of interaction between HSF and FA towards f_{CS} of both NC and RC.

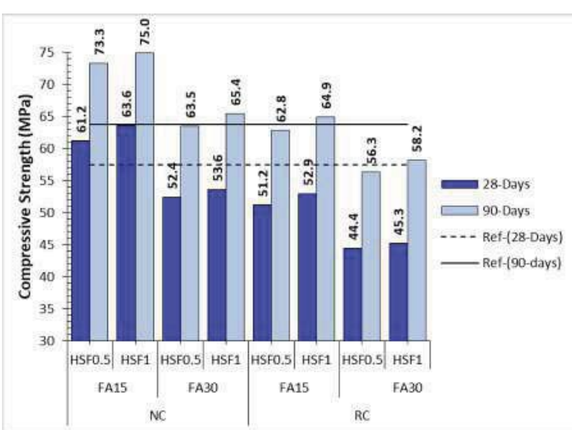

Fig. 8. Coupling effect of FA and HSF on the f_{CS} of NC and RC.

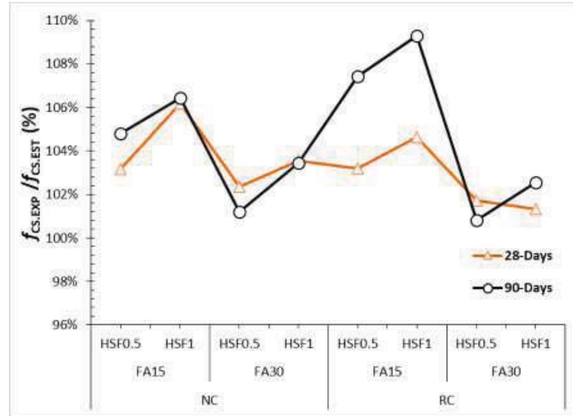

Fig. 9. Ratio between experimental f_{CS} ($f_{CS.EXP}$) and estimated f_{CS} ($f_{CS.EST}$) of NC and RC mixes incorporating both FA and HSF.

$$\Delta f_{FA(\%)} = f_{FA(\%)} - f_{REF} \tag{1}$$

$$\Delta f_{HESF(\%)} = f_{HESF(\%)} - f_{REF} \tag{2}$$

$$f_{EST} = f_{FA(\%)} + f_{HESF(\%)} + f_{REF} \tag{3}$$

Where, $\Delta f_{FA}(\%)$ = Net change in strength with the addition of specific % age of FA

$\Delta f_{HSF(\%)}$ = Net change in strength with the addition of a specific % age of HSF.
f_{EST} = Estimated-strength of concrete mix (MPa) with specific %age of FA and HSF.
$f_{FA(\%)}$ = experimental-strength of concrete with a specific %age of FA.
$f_{HSF(\%)}$ = experimental-strength of concrete with a specific %age of HSF.
f_{REF} = experimental-strength of reference concrete in MPa.

3.2. Splitting tensile strength

Results of all mixes in splitting=tensile testing are shown in Fig. 10. The general-trend of the results shows that HSF is extremely helpful in upgrading the f_{STS} of RC. 15% FA is also helpful in improving the performance of both plain and HSF reinforced RC. RC made with 15% FA and 1% HSF shows 50% more f_{STS} than that of the plain RC at 90 days. 15% FA improves the efficiency of HSF in the f_{STS} of both RC and NC. Further detail has been shown in the following sub-sections (§ 3.2.1-3.2.3).

3.2.1. Effect of FA on f_{STS} of NC and RC

The effect of varying FA percentage on f_{STS} of both RC and NC is shown in Fig. 11. As expected, f_{STS} of RC is notably lower than that of the NC. RC has 16% lower f_{STS} than that of the NC. 15% FA incorporation helps in upgrading the f_{STS} of RC by 6-12%. 15% FA incorporation improves the 28-days' f_{STS} of RC and NC by 3% and 6%, respectively. At longer ages (90 days), 15% FA incorporation enhanced the f_{STS} of NC

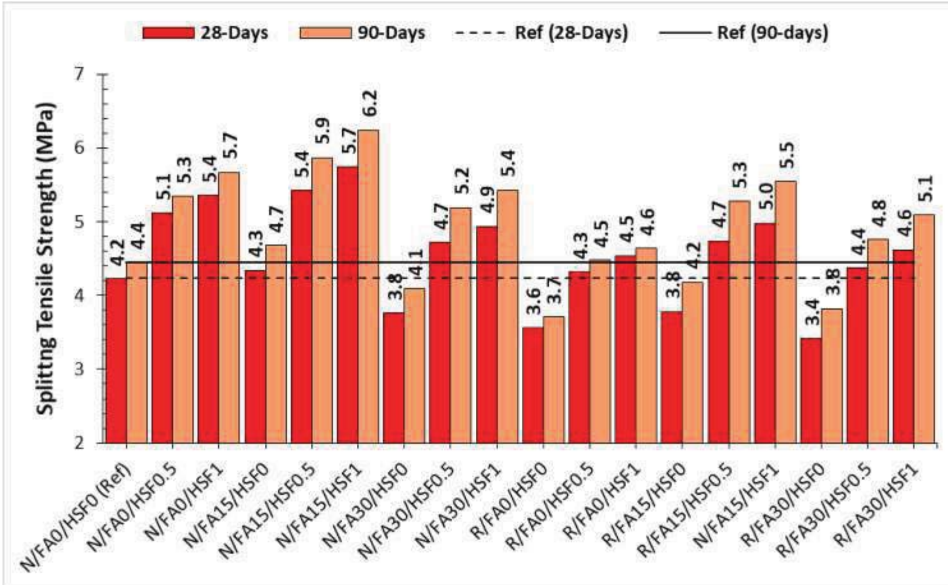

Fig. 10. Splitting tensile testing results of all mixes.

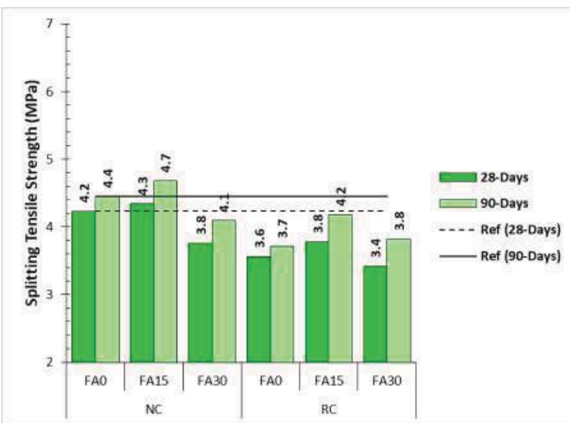

Fig. 11. Effect of FA on f_{STS} of NC and RC.

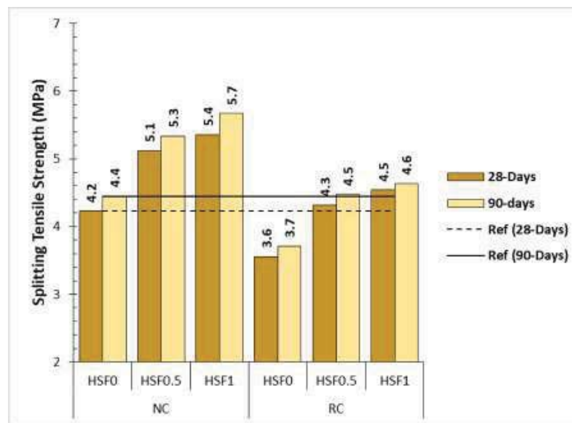

Fig. 12. Effect of HSF on f_{STS} of NC and RC.

and RC by 5.2% and 12.3%, respectively. These results clearly indicate that FA contributes more towards RC. As explained in Section 3.1, RC offers more pozzolanicity potential than NC, therefore, FA contributes more towards the strength-development of RC. Kou et al. (2011) stated that mineral admixtures enhanced the bond between the binder matrix and CRA, this strengthens the ITZs and leads to enhancement in f_{STS}. 30% FA decreases the f_{STS} of both RC and NC at 28 days. At longer ages (90-days), RC with 30% FA showed 2.6% higher-strength relative to that of plain RC. It can be concluded that 15% FA incorporation is most desirable if the recovery of f_{STS} of RC is desired. Furthermore, at 90-days RC with 15% FA can reach the 28 days' f_{STS} potential of reference mix (Fig. 11).

3.2.2. *Effect of HSF on f_{STS} of NC and RC*

The influence of HSF on f_{STS} of both RC and NC is shown in Fig. 12. HSF shows a positive-effect on f_{STS} of NC and RC at both ages of testing. Moreover, net gain in f_{STS} of concrete mixes (over corresponding plain mixes) increases with rising dosage of HSF.

The f_{STS} of NC increases by 21% and 27% at 0.50% and 1.00% HSF dosage, respectively. Similarly to NC, the f_{STS} of RC increases by 20 and 25% at 0.5% and 1% dosage of HSF, respectively. Fiber inclusion helps RC to outperform reference mix at both ages. Even 0.5% inclusion of HSF can help RAC to outperform reference mix in f_{STS}. Fiber inclusion is extremely beneficial in increasing the tensile#strength of cement-based composites owing to their very high tensile strength i.e. up to 1200 MPa. Fibers delay the initiation of cracks under tensile stresses, hence prevents the premature failure of specimens under splitting=tensile loads. There are many studies that have confirmed positive-influence of steel fibers (Atiş and Karahan, 2009; Koushkbaghi et al., 2019; Raza et al., 2020) on f_{STS} of cement-based composites. It is also well established (Ali et al., 2020c; Atiş and Karahan, 2009; Simões et al., 2018) that steel and other fibers are more efficient in enhancing the f_{STS} than f_{CS}.

3.2.3. *Coupling effect of FA and HSF on f_{STS} of NC and RC*

The coupling-effect of FA and HSF on f_{STS} values of both RC and NC is shown in Fig. 13. It can be said that together 15% FA and 0.5–1% HSF can enable RC to outperform reference mix by a distinguished margin.

NC with 15% FA and 0.5–1% HSF shows 31–40% higher f_{STS} than Ref mix at 90-days. On the other hand, RC-15%FA-1%HSF shows 17% and 21% higher f_{STS} than Ref mix at early and longer ages, respectively. At 28-days, enhancement in f_{STS} is dominantly caused by HSF inclusions. Whereas, at 90-days, enhancement in f_{STS} of both NC and RC is attributed to both 15% FA and HSF. At 90-days, 15% FA and 1% HSF contribute improvements of 13% and 27% respectively to f_{STS} of NC. Similarly, 15% FA and 1% HSF contributes of improvements of more than 20% each to RC. HSF inclusion also recovers the loss in f_{STS} due to

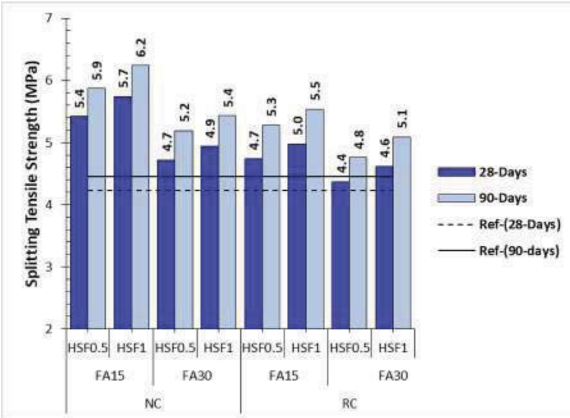

Fig. 13. Coupling effect of FA and HSF on f_{STS} of NC and RC.

30% FA incorporation. Fig. 13 shows that RC mixes with 30% FA and HSF outperformed the Ref mixes mainly because of improvement caused by HSF.

The efficiency of fiber-reinforcement improves with the inclusion of FA. FA containing RC and NC showed more enhancement in f_{STS} due to addition of HSF than those mixes having 0% FA. Actual net-improvement in f_{STS} due to the inclusion of both FA and HSF is also greater than the estimated net improvement calculated using improvements caused by individual incorporations of FA and HSF. This is illustrated in Fig. 14, where the ratio between experimental or actual f_{STS} ($f_{STS.EXP}$) and estimated f_{STS} ($f_{STS.EST}$) is presented for all mixes having both FA and HSF. The $f_{STS.EST}$ was calculated similar to $f_{CS.EST}$ using Eq. (1)-(3). All $f_{STS.EXP}/f_{STS.EST}$ ratios are greater than 100% for different combinations of FA and HSF. $F_{STS.EXP}/f_{STS.EST}$ above 100% shows the degree of usefulness of combination of FA and HSF. Higher $f_{STS.EXP}/f_{STS.EST}$ ratios are for RC and NC mixes having both 15% FA and HSF. This indicates that combined use of 15% FA and 0.5–1% HSF in RC can yield maximum benefits in terms of f_{STS}.

3.3. Flexural strength

Flexural strength (f_{FS}) also known as rupture-modulus is another widely used measure of tensile strength. Most of the theories used for the highway and air-field pavement design are based on the f_{FS}. Therefore, laboratory designed mixes on the basis of f_{FS} may be required. For plain concretes, it can be accurately estimated from f_{CS} but for the fiber-reinforced concrete mixes it is essential to evaluate the f_{FS} experimentally as the fiber addition does not affect f_{CS} and f_{STS} similarly. Fibers are

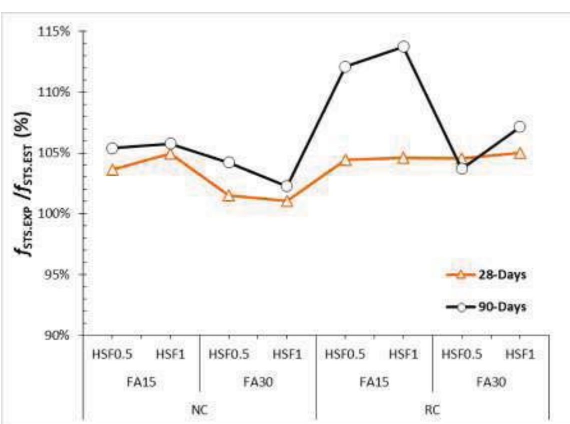

Fig. 14. Ratio between experimental f_{STS} ($f_{STS.EXP}$) and estimated f_{STS} ($f_{STS.EST}$) of NC and RC mixes incorporating both FA and HSF.

more useful in upgrading the tensile=strength capacity of concrete and less beneficial to f_{CS}. The results of f_{FS} testing are shown in Fig. 15.

Similarly to f_{STS}, f_{FS} of both RC and NC undergoes remarkable improvement due to HSF inclusion. RC with HSF shows very high f_{FS} than reference mix. 15% FA is also very helpful in upgrading the f_{FS} of RC, especially at the age of 90-days. RC with 15% FA and 1% HSF shows 73–77% and 57–63% higher f_{FS} than that of the plain RC (R/FA0/HSF0) and reference concrete, respectively.

In Fig. 16, a relationship is developed between the f_{STS} and f_{FS} for all plain and fiber-reinforced mix. A strong linear-correlation (i.e. R^2 = 0.81) exists between these two strength-parameters. It is because the loadcarrying capacity of specimens under flexural and splitting=tensile loads depends largely upon the ability of material to restrain the tensile cracking. Therefore, it can be concluded that f_{FS} of concrete can be predicted with a great accuracy using experimental f_{STS}. Relationship between f_{FS} and f_{CS} values of all plain and fiber-reinforced mixes is shown in Fig. 17. These results tell that f_{CS} cannot predict the f_{FS} of both plain and fiber-reinforced concretes using a generalized relationship. It is ascribed to the less sensitivity of f_{CS} to fiber-reinforcement unlike f_{FS}. Literature (Ali and Qureshi, 2019b; Thomas and Ramaswamy, 2007) has shown that accurate relationships between f_{CS} and f_{FS} can only be developed when the effect of fiber-dosage or reinforcement-index is considered. However, this study shows that f_{FS} can be estimated accurately from the f_{STS} of concrete without considering the effect of reinforcement-index.

4. Results of durability testing and discussion

4.1. Water absorption

WA capacity of all mixes at the age of 56-days is given in Fig. 18. Overview of results indicate that FA reduces *WA*, whereas, both CRA and HSF increase *WA* capacity of concrete. Further detail is shown in the next sub-sections.

4.1.1. Effect of FA incorporation on WA of NC and RC

Effect of FA on *WA* of NC and RC is shown in Fig. 19. RC shows 28% higher *WA* than NC. This is mainly because of low-density mortar present in CRA, which facilities the penetration of water into the matrix of concrete. FA incorporation leads to reduction in *WA* of both NC and RC. *WA* of NC reduces by 24% and 14% at 15% and 30% FA, respectively. Similarly to NC, *WA* of RC reduces by 31% and 20% at 15% and 30% FA, respectively. The main reason for reduction in *WA* the pozzolanic-reaction between CH and silica generating further C-S-H, this reduces the pore size and disconnect the total porosity of matrix of concrete (Ali and Qureshi, 2019b; Chindaprasirt and Rukzon, 2009; Kurda et al., 2019; Sujivorakul et al., 2011). On the other hand, filler effect of FA particles can also reduce the pore-size in binder matrix of both NC and RC. RC shows more reduction in *WA* due to inclusion of FA than that of the NC. FA particles can penetrate the pores of CRA, rendering the cracks already present inside CRA. Subsequently, FA particles may react with CH present inside CRA and binder matrix in case of RC, this this is one of the main reasons that FA reduces *WA* of RC more than that of the NC. This finding is in line with Kurda et al. (2019). Owing to FA, RC made with 15% FA shows lower *WA* than Ref mix. 15% FA is more useful than 30% FA because, with 15% FA more CH remains in the matrix of concrete offering good pozzolanicity potential.

4.1.2. Effect of HSF on WA of NC and RC

Effect of HSF of *WA* on NC and RC mixes is shown in Fig. 20. Inclusion of HSF is slightly harmful to *WA* of both NC and RC. *WA* of NC increases by 3% and 5% at 0.5% and 1.0% HSF, respectively. On the other hand, *WA* of RC increases by 2-4% when HSF varies 0.5-1.0%. Previous studies (Ali and Qureshi, 2019b; Koushkbaghi et al., 2019) have also shown that fiber-reinforcement can slightly increase the *WA* capacity of concrete. Frazao et al. (2015) stated that addition of

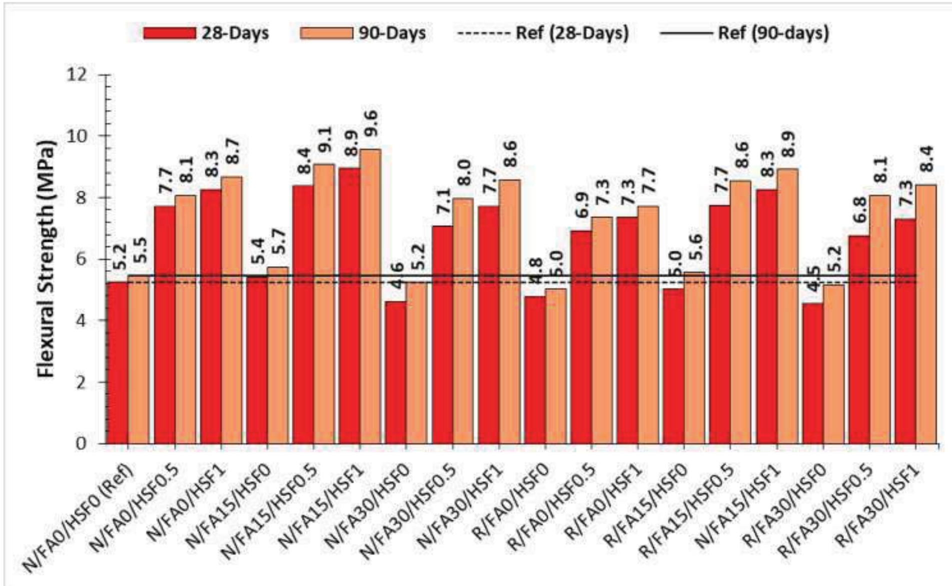

Fig. 15. Flexural testing results of all mixes.

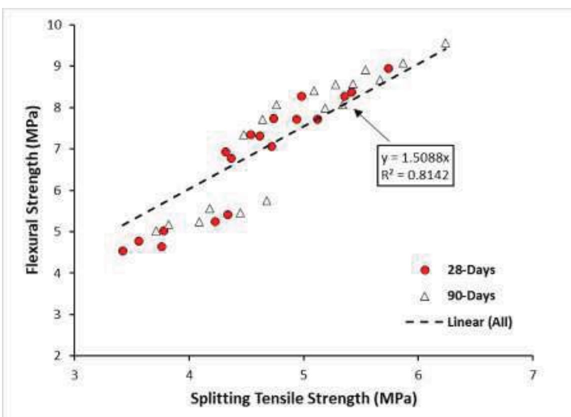

Fig. 16. Correlation b/w f_{STS} with f_{FS} values.

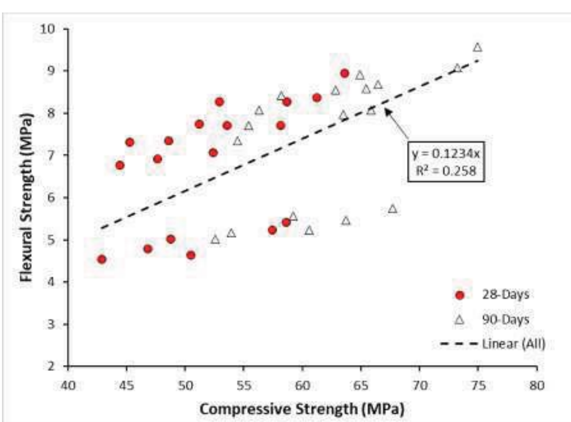

Fig. 17. Correlation b/w f_{CS} and f_{FS} values.

steel-fibers slightly increases the open porosity of concrete mix.

Furthermore, increase in open porosity can aid in the movement of moisture along the fibers from outer surface of the specimen into the matrix of concrete. Similar to previous researches (Ali and Qureshi, 2019c; Frazão et al., 2015; Koushkbaghi et al., 2019), in the present study no substantial increase in *WA* of NC or RC is observed due to fiber-reinforcement.

4.1.3. Coupling effect of FA and HSF on WA of NC and RC

The coupling-effect of FA and HSF on *WA* capacities of mixes is shown in Fig. 21. FA compensates the loss in imperviousness of concrete due to incorporation of both CRA and HSF. All HSF-reinforced mixes of NC family show lower *WA* than Ref mix mainly because of FA. At 0.5% HSF, RC made with 15% FA has *WA* capacity comparable to that of the Ref mix. RC with 15% FA has *WA* capacity comparable to that of the Ref mix at 1% HSF. These results show that with the help of 15% FA, RC incorporating 0.5–1% HSF can be prepared with porosity comparable to that of the NC. Durability of concrete largely depends upon its porosity. High porosity helps the penetration of harmful chemicals into the microstructure that may start the deterioration of cement-based materials. Therefore, *WA* is an indirect measure of durability and ensuring lower *WA* capacity guarantees good durability. Using fiber-reinforcements like HSF can increase the *WA* as noticed in the results of present study, therefore, to maintain the durability, FA can play a useful role in case of both NC and RC.

4.2. Chloride penetration

In this study, chloride ions penetrate test was made without any external-aid of electrical charge. As steel fibers increase the conductivity (or decrease electrical resistivity) of concrete specimens (Afroughsabet et al., 2017), which accelerates the *CP* if an external aid of electrical charge is used. Therefore, *CP* is determined using immersion technique instead of rapid *CP*. The immersion method is adopted to avoid false interpretations of *CP* resistance of HSF-reinforced concretes. Further detail regarding the set-up of the test described in study of Chindaprasirt et al. (2007). *CP* of each mix is shown in Fig. 22. Owing to high porosity or permeability, RC shows 34% higher *CP* compared to that of the Ref mix. Incorporation of HSF slightly increases the *CP* of both NC and RC mixes. FA improves the *CP* resistance of concretes and compensates for the loss in *CP* resistance because of the incorporation of HSF and CRA.

4.2.1. Effect of FA on CP resistance of NC and RC

The effect of FA on *CP* resistance of NC and RC is shown in Fig. 23. FA plays a useful role in enhancing the *CP* resistance of NC and RC. Lower