Effect of Hybrid Fiber Reinforcements on the Mechanical and Ductility Performance of HPC Incorporating Micro Silica and Alccofine-1203 Prabath, N V N a , and Ramadoss, P b

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Effect of Hybrid Fiber Reinforcements on the Mechanical and Ductility Performance of HPC Incorporating Micro Silica and Alccofine-1203

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Abstract

This study investigates the effect of fiber volume fractions of single and hybrid fibers on the mechanical and ductility performance of high-performance concrete (HPC) with w/b ratios of 0.38 and 0.28, and 20% silica fume replacement. Macro steel fiber volume fractions (V_f = 0.5, 1 & 1.5%) and micro polypropylene fiber volume fractions (V_f = 0.25, 0.5 & 1%) and alccofine-1203 as an additive were used in this study. For high performance fiber reinforced concrete (HPFRC) and high performance hybrid fiber reinforced concrete (HP-HyFRC) mixes, compressive strength, modulus of rupture (MOR) and elastic modulus were evaluated. Test results of HPSFRC show improvement in 28-day compressive strength by 15.4% and in MOR by 44.66% at steel fiber volume fraction, for HPPFRC, improvement in compressive strength and in MOR the improvement is moderate at polypropylene fiber volume fraction, V_f = 1%. Stress-strain behavior of HPFRC and HP-HyFRC was studied and modulus of elasticity was obtained in the range of 33.72 - 44.26 GPa and 33.72 - 45.21 GPa, respectively. Engineering properties were improved as a result of synergetic effect between steel and polypropylene fibers. Effect of addition of alccofine-1203 on the mechanical performance of HPC was examined, and the optimum dosage as 8% was observed. HPSFRC improved the compressive toughness and ductility considerably, which is evidenced from stress-stain behavior, and in HP-HyFRC, this improvement is high due to the synergetic effect between both the fibers. Statistical models for the estimation of compressive strength ratios/ flexural strength ratios of HPSFRC/ HPPFRC were developed. The predicted values are in good agreement with the experimental values of earlier researchers. Relationship between 28-day flexural and compressive strengths of HPSFRC/ HPPFRC was developed with AAE= 4.32%. Multiple linear regression model with R= 0.98 was developed by Response surface method for the prediction of compressive strength of HP-HyFRC mixes and validated.

Key words: High-performance concrete; micro silica; steel fibers; polypropylene fibers; hybrid fiber reinforced concrete; alccofine; strength; ductility; response surface method.

1. Introduction

High performance concrete (HPC) and ultra-high performance concrete (UHPC) contain supplementary cementitious materials (SCM), which enhance the mechanical properties and improves the durability of the matrix and also have financial and environmental benefits (Ezheldin & Balaguru, 1992; Handong et al., 1999; Bhanja & Sengupta, 2000; Ramadoss & Nagamani, 2008; Mahmoud Nili & Afroughsabet, 2010; Savino et al., 2017). The addition of discrete steel fibers in HPC/ HSC/ UHPC transforms it from a brittle to a more ductile form and enhances the mechanical properties, and improves the ductility, toughness, impact strength and post-peak response of concrete (Hsu & Hsu, 1994; Mansur et al., 1999; Mohammadi & Kaushik, 2003; Poon et al., 2004; Ramadoss & Nagamani, 2008; Mahmoud Nili & Afroughsabet, 2010; Kuder & Shah, 2010; Ismail et al., 2011; Vogel & Svecova, 2012; Ramadoss & Nagamani, 2014). The properties of the fiber, volume of fiber, type and geometry of fiber and orientation of fiber influence the efficiency of the concrete matrix. Among the polymer fibers, polypropylene fibers are mostly used as an additive in concrete matrix to enhance the mechanical properties, shrinkage cracking characteristics, toughness and impact resistance of concrete (Qian & Stroeven, 2000; Song et al., 2005; Banthia & Gupta, 2006; Bagherzadeh et al., 2011).

Fibers can be useful in enhancing the mechanical performance and preventing cracks in FRC. The majority of FRC used today is single fiber type. Concrete reinforced with mono type of fiber would improve desirable qualities. For an optimal response of the concrete composites, different types of fibers can be rationally combined to produce hybrid fiber reinforced concrete (HyFRC). Hybrid in a composite derives benefits from each of the fibers and exhibits a synergetic response. 28-day compressive strength, flexural strength and flexural toughness of hybrid composite mixes were investigated, and the effects of addition of fibers on these mechanical properties were described. (Banthia & soleimani, 2005).

High-strength concrete containing polyethylene, steel, carbon and polypropylene fibers showed enhanced flexural strength and ductility while reducing crack width (Banthia et al., 2005; Abbas et al., 2018). Hybrid fiber reinforced concrete containing PP fibers with two different aspect ratios has improved the mechanical properties, toughness and reduced the drying shrinkage (Hsie et al., 2008). They have observed that the use of two or more types of fibers in a suitable combination has the potential to improve the mechanical properties of concrete. In all of the hybrid (hooked end steel and double deformed steel and cellulose) composites tested in flexure, there was a positive interaction between steel and cellulose fibers (Banthia et al., 2014).

Most of the researchers have investigated on the mechanical performance and a few researchers on flexural behavior of normal strength/ high-strength HyFRC; a limited studies on the ductility and toughness of HyFRC composites. Thus, this study aimed to investigate the effect of fiber volume fractions (single and hybrid fibers) on the mechanical and ductility performance of high-performance concrete. The stress-strain behavior of high-performance concrete with hybrid fibers in compression was investigated and fiber synergetic effects in composites was examined.

(Ezheldin & Balaguru, 1992; Thomas & Ramasamy, 2007; Ramadoss & Nagamani, 2008; Xu & shi, 2009; Permual, 2015) have investigated the HSSFRC/ HPSFRC with varying w/cm ratios and steel fiber volume fractions (V_f = 0 -1.5%). They observed significant improvements in flexural and splitting tensile strengths at V_f = 1.5% and also developed empirical expressions for the prediction of compressive strength, flexural and splitting tensile strengths of HSFRC/ HP-SFRC, as a function of V_f or RI. Ramadoss & Nagamani (2012) have investigated the compressive strength of high-performance steel fiber reinforced concrete with fiber volume fraction, V_f = 0- 1.5% and silica fume replacement = 5 to 15%, and developed a MLR model for compressive strength. The proposed model was found to predict the values quite accurately. Savino et al. (2017) have investigated on the mechanical properties of high performance fiber reinforced concrete (HPFRC) as the steel fiber content and type changes, and developed a simple and effective empirical equation to account for the effect of fibers and change of aspect ratio on the compressive and tensile strengths of HPFRC. The empirical expressions/ models developed by the earlier researchers have their own limitations/ constraints in practice and therefore, could not be applied for all types of specimen parameters and varying w/b ratios.

Alccofine has unique properties that improves the concrete strength in both the fresh and hardened state and leads to optimized particle size distribution. The effect of alccofines-1203 addition by weight of binder on the mechanical performance of HPC incorporating micro silica was also investigated and optimum dosage was arrived.

Because of complex mixture proportions, and lack of relationships between the mix proportions and measured properties of HSFRC/ HPFRC, properties are often described using empirical equations (Wafa & Ashour, 1992; Choi & Yuan, 2005; Thomas & Ramasamy, 2007; Ramadoss & Nagamani, 2008; Xu & Shi, 2009; Ramadoss Perumal, 2015; Sardemir, 2016; Savino et al., 2017). Concrete strength is influenced by many factors and determination of 28-day strength of mix proportions used at construction site is a difficult task and therefore, numerical modeling of strength of the HPFRC/ Hybrid FRC based on the data of mixtures is becoming a necessary task. Numerical modeling of compressive strength/ flexural strength of HPFRC/ HyFRC by using Response surface method (RSM) based on the influencing input variables in mix proportions, was developed. Multiple linear regression (MLR) model developed by RSM, was found to predict the values with high efficacy.

2. Materials and Methods

2.1 Materials and Mixture Proportions

Ordinary Portland cement (OPC-53 grade) with a 28-day compressive strength of 54.5 MPa and specific gravity of 3.15 was used in this study. Micro silica as SCM with Blennies' specific surface area of 23000 m^2/kg and alccofine-1203 (an additive to binder) with a specific surface area of 1200 m^2/kg were used. Micro silica complying the requirements of ACI 234R-1996 was used. The fibers used in this investigation are: macro steel fibers (V_f = 0.5, 1, and 1.5%) and micro polypropylene fibers (V_f = 0.25, 0.5, and 1%). The physical properties of macro and micro fibers are given in Table 1.

River sand passing through a 4.75mm IS sieve, conforming to IS: 383-1978 with grading zone-II was used. Coarse aggregates of granite stones with a maximum size of 12.5mm was used. Sulphonated naphthalene formaldehyde condensate having specific gravity of 1.20 as HRWR admixture was used.

Mixtures were proportioned as per the guidelines of IS: 10262-2019 and recommended guidelines of ACI 544.3R-93. Mix proportions used in this experimental investigation are listed in Table 2. For each water-binder ratio (w/b), one HPC mix and 6 FRC mixes containing steel fiber volume fraction, V_f = 0.5, 1.0 and 1.5 % (39, 78 and 117.5 kg/m^3), polypropylene fiber volume fraction, V_f = 0.25, 0.5 and 1.0 %, and 9 mixes of HP-HyFRC containing combinations of both the fibers were prepared. A super-plasticizer (TEC MIX -550) in the range of 1.75 to 2.5 % by weight of binder was used. 14 series of HPSFRC and HPPFRC mixes were used in this investigation. For each mix, 3 no. of 150 mm cubes, 3 no. of 100 x 100 x 500 mm prisms and 3 no. of 150 dia x 300 mm high cylinders were produced. Specimens were casted and water curing at 27^{o}C until the age of testing at 28-days.

2.2 Tests on hardened concrete

Compressive strength tests were carried out in accordance with IS: 516-1959 (2004) specifications using 150 mm cubes and ASTM C 39-92 (2004) standards using uniaxially loaded 150 mm diameter cylinders. The tests were carried out in a servo-controlled 3000 kN capacity compression testing machine with a loading rate of 14 MPa/min. The average compressive strength was determined by testing three specimens.

Flexural strength tests were carried out complying the ASTM C 78- 94 standards using 100 x 100 x 500 mm beams with simply supported span of 400 mm applied under third-point loading. The tests were conducted in a 100 kN capacity hydraulically operated flexural testing machine with a deformation rate of 0.1 mm/min. The average flexural strength was determined by testing three specimens

Split tensile strength tests was conducted on cylinder specimens 100 mm dia. x 200 mm height in accordance with ASTM C496-1990 standards. The tests were carried out in a 2000 kN capacity closed loop hydraulically operated CTM. The average Split tensile strength was determined by testing three specimens.

3. Results, Analysis and Discussion

3.1 Mechanical Properties

Compressive Strength

Compressive strength of high performance concrete (HPC or HPFRC-0) with w/b = 0.38 at SF = 20% (replacement) obtained is 105% of that of HPC at SF = 15% (replacement). Table 3 presents the variation in the compressive strengths, (f_{cf}), obtained for cube specimens as a result of the influence of steel fiber volume fraction, polypropylene fiber volume fraction and hybrid fibers. Maximum 28-day compressive strength values obtained for HPC with 20% silica fume replacement, steel fiber reinforced concrete (SFRC) at volume fraction, V_f = 1.5%, polypropylene fiber reinforced concrete (PFRC) at volume fraction, V_f = 1% and hybrid fiber reinforced concrete HP-HyFRC*(S1.5, P1) with w/b ratio = 0.28, are 87.30 MPa, 98.70 MPa, 92.10 MPa and 104.30 MPa, respectively shown in Table 3. For HP-HyFRC (S1.5, P-1) with w/b = 0.28, the maximum improvement in compressive strength obtained is 19.47%. Comparing the sum of individual strength improvement of HPSFRC(S-1.5) and HPPFRC(P-1), there is an additional improvement of 1.01% for HP-HyFRC with w/b = 0.28. This increase in strength revealed the fibers' positive interaction and the ensuring hybrid performance. The strength ratios between (HPFRC) and HPC (f_{cf}/f_c) are presented in Table 4. These strength ratios can be used to develop the generalized empirical expression independent of w/b ratios or specimen characteristics. The performance of compressive strength of HPSFRC/ HPPFRC as a function of fiber volume fraction (steel / polypropylene fibers) volume fraction (V_f) is shown in Figs. 1 and 2. The influence of hybrid fiber composition on the compressive strength of HPC with w/b ratio = 0.38 and 0.28 is shown by bar chart in Fig. 3. The failure patter of specimens under compression is shown in Fig. 7.

Flexural Strength

Flexural strength or modulus of rupture, f_{rf} obtained for HPSFRC and HPPFRC (with w/b ratio = 0.38 and 0.28) are in the range of 8.12 to 12.40 MPa, and 8.12 to 9.89 MPa, respectively are shown in Table 3. The maximum improvement in flexural strength at steel fibers volume fraction, V_f = 1.5% in HPC was found to be about 44.66%, which indicates significant improvement in strength and also depends on the fibers pull out effect is shown in Fig. 4. It was observed from the experimental results that failure state was prolonged after ultimate load, which indicates the considerable improvement in ductility and flexural toughness of HPSFRC. All the specimens are shown deflection- hardening behavior due to addition of steel/ polypropylene fibers, resulting in higher load-carrying capacity after the first crack. The maximum improvement in MOR at 1.5% of steel fiber volume fraction suggests that fiber volume fraction has significant impact on the post-cracking behavior of HPFRC. The post cracking response is significantly improved due to the fiber-matrix bond effects. The maximum increase in flexural strength due to the incorporation of polypropylene fibers (V_f = 1%) in HPC was found to be about 14.87%, which indicates moderate improvement in strength and also depends on the pull out effect of fibers is shown in Fig. 5. The effect of hybrid fiber volume fractions on flexural strength of HPC with w/b ratio = 0.38 and 0.28 is shown by bar chart in Fig. 6. It is observed from the test that failure state was prolonged after ultimate load that indicates the considerable improvement in ductility and flexural toughness of HP-HyFRC. The failure patter of specimens under flexure is shown by bar chart in Fig. 7.

3.2 Synergetic Effect - Hybrids Containing Macro and Micro Fibers

Addition of steel (S) fiber and micro polypropylene (P) fiber to silica fume concrete (HPC) improved significantly the flexural strength of the HPFRC containing steel fibers (S) and moderately for the concrete containing polypropylene fibers (P). For HP-HyFRC (S1.5, P-1) with w/b = 0.28, the maximum improvement in flexural strength obtained, is 61.44%. Comparing the sum of individual strength improvement of [HPSRFC(S-1.5) and HPPFRC(P-1)], there is an additional improvement of 1.91% for HP-HyFRC with w/b = 0.28. This improvement in strength showed the favourable interaction between the fibers (ie. fiber synergy) and resulting hybrid performance. HP-HyFRC(S-1, P-1) containing volume fraction of S and P fibers (each 1% by volume) showed an improvement in flexural strength (modulus of rupture).

3.3 Relationship between Compressive Strength Ratio and Fiber Volume Fraction (%)

Table 4 shows compressive strength ratios (f_{cf} /f_c) of HPSFRC as a function of proportion of fiber volume fraction, V_f (%). The strength ratios (dimensionless) of axial compressive strengths of HPSFRC has a linear relationship with the fiber volume fraction, V_f (%). Based on the experimental data, an empirical equation for predicting the compressive strength ratios (f_{cf} /f_c) of HPSFRC as a function of fiber volume fraction ,V_f (%) for w/b ratios of 0.28 and 0.38, using regression analysis has been obtained (refer Fig. 8) as:

$$f_{cf} / f_c = 1 + 0.092\, V_f \qquad R^2 = 0.96 \qquad (1)$$

Where, f_c = Compressive strength of HPC, MPa

f_{cf} = Compressive strength of HPSFRC, MPa and

V_f = Steel fiber volume fraction, %.

The coefficient of determination, R^2 = 0.96, which indicates that 96 % of the variation in strength is explained by the reinforcement parameter, taking in to account the sample size and number of independent variable.

The value of correlation coefficient (R) = 0.98, and the average absolute error (AAE) and integral absolute error (IAE) have been obtained as 0.70% and 0.72%, respectively. Eq. 1, if expanded for f_{cf} (the compressive strength of HPSFRC), the second term with coefficient (= 0.092 * f_c* V_f) is the contribution of matrix strength and fiber interaction explicitly which is dependent on fiber-matrix bond characteristics. The proposed model Eq. (1), was also verified with the test results of 150 dia. cylinder specimens of HPSFRC (fiber aspect ratio (l/d) = 80), with AAE and IAE as 1.31 % and 1.37%, respectively.

The general equation for predicting the Compressive strength of HPSFRC is written from the Eq. (1) as.

$$f_{cf} = f_c + (0.092\, V_f) f_c \qquad (2)$$

The proposed prediction model Eq. (2) was examined for the validation of data of earlier researchers. It was found that the predictions (strengths) given by the model is in good agreement with the experimental values. A comparison of experimental values obtained by (Song & Hwang, 2004; Thomas & Ramasamy, 2007; Koksal & Altum et al., 2008) with the predictions of the suggested model [Eq. (2)], is shown in Fig. 9. The resulting IAE and AAE value obtained are 3.80, 5.75, 2.19 and 3.46, 5.70, 2.14 %, respectively.

The integral absolute error (IAE) used to evaluate the difference between the actual observation and predicted value, is given as:

$$IAE = \frac{\Sigma(Q-P)}{\Sigma Q} x100\ \% \tag{3}$$

Where Q, is the actual strength and P is the predicted value.

Table 4 Shows compressive strength ratios, (f_{cf} /f_c) of HPPFRC as a function of the proportion of fiber volume fraction, V_f (%). The strength ratios (dimensionless) of axial compressive strengths of HPPFRC has a linear relationship with the fiber volume fraction, V_f (%). Based on the experimental data, an empirical equation for predicting the compressive strength ratios (f_{cf} /f_c) of HPPFRC in relation to the volume fraction, V_f (%) for w/b ratios of 0.28 and 0.38, using regression analysis has been obtained (refer Fig. 10) as:

$$f_{cf} / f_c = 1 + 0.051 V_f \qquad R^2 = 0.91 \tag{4}$$

Where, f_c = Compressive strength of HPC, MPa

f_{cf} = Compressive strength of HPPFRC, MPa and

V_f = Polypropylene fiber volume fraction, %.

The coefficient of determination, R^2 = 0.91, which indicates that 91 % of the variation in strength is explained by the reinforcement parameter, taking in to account the sample size and the independent variable.

The proposed prediction model Eq. (4) was examined for the validation of data of earlier researchers. It was observed that the predictions (strengths) provided by the model were found to be in good agreement with the experimental results. A comparison of experimental values obtained by (Afringhsabet & Ozbakkalogle, 2015; Ahmed, 2020; Banthia & Soleimani, 2005) with the predictions of the suggested model [Eq. (4)], is shown in Fig. 11. The resulting IAE and AAE value obtained are 3.59, 5.49, 2.58 and 3.51, 5.33, 2.56 %, respectively.

3.4 Relationship between flexural strength ratio and fiber volume fraction (%)

Table 5 shows flexural strength ratios (f_{rf}/f_r) (dimensionless) of HPSFRC, has a linear relationship with the fiber volume fraction, V_f (%). Based on the experimental data, an empirical equation for predicting the flexural strength ratios (f_{rf}/f_r), using regression analysis has been obtained with R^2 = 0. 92 (refer Fig. 12) as:

$$f_{rf}/f_r = 1 + 0.253\,V_f \qquad R^2 = 0.924 \tag{5}$$

Where, f_r = Flexural strength of HPC (MPa)

f_{rf} = Flexural strength of HPSFRC (MPa)

V_f = Steel fiber volume fraction (%).

The values of correlation coefficient (R) and the AAE and integral absolute error (IAE) have been obtained as 0.96, 2.57 and 2.79%, respectively. The above statistical parameters indicate the significance of the model in predicting the test data quite accurately.

The proposed model's validity was tested using experimental data from previous researchers (Song & Hwang, 2004; Thomas & Ramasamy, 2007; Koksal & Altum et al., 2008). The IAE and AAE value obtained are 8.70, 1.47, 8.16 and 8.66, 1.38, 7.44 %, respectively. It was found from Fig. 13 that the proposed empirical Eq. 5 performance very well.

Table 5, shows the flexural strength ratios (f_{rf}/f_r) of HPPFRC, has a linear relationship with the fiber volume fraction, V_f (%). Based on the experimental data, an empirical equation for predicting the flexural strength ratios (f_{rf}/f_r), using regression analysis has been obtained with R^2 = 0. 92 (refer Fig. 14) as:

$$f_{rf}/f_r = 1 + 0.119\,V_f \qquad R^2 = 0.91 \tag{6}$$

Where, f_r = Flexural strength of HPC (MPa)

f_{rf} = Flexural strength of HPPFRC (MPa)

V_f = Polypropylene fiber volume fraction (%)

The values of correlation coefficient (R), the AAE and integral absolute error (IAE) have been obtained as 0.96, 1.72 and 1.79, respectively. The above statistical parameters indicate the significance of the model in predicting the test data quite accurately.

The proposed model's validity was tested using experimental data from previous researchers (Banthia & Soleimani, 2005; Afringhsabet & Ozbakkalogle, 2015; Ahmed, 2020). The IAE and AAE value obtained are 4.93, 5.22, 4.66 and 3.66, 4.99, 4.32%, respectively. It was found from Fig. 15, and the proposed model [Eq. (6)], is in accordance with the experimental values.

3.5 Relationship between flexural strength and compressive strength

The flexural strength and compressive strength ratio is one of the main indicators to reflect the brittleness of concrete. For concrete, the greater the tension and compression ratio is, the smaller the brittleness, and the greater the toughness and ductility. In this investigation, the flexural and compressive strength ratio of HPSFRC varies from 0.099 to 0.126.

Based on the experimental data, a nonlinear equation for predicting the flexural strength of HPSFRC using regression analysis by least-square method has been obtained with $R^2 = 0.87$ (refer Fig. 16) as:

$$f_{rf} = 0.026 f_{cf}^{\,1.134} \qquad R^2 = 0.87 \tag{7}$$

Where, f_{rf} = flexural strength of HPSFRC (MPa)

f_{cf} = compressive strength of HPSFRC (MPa)

The coefficient of correlation (R) and the average absolute error (AAE) have been obtained as 0.93 and 4.32% respectively.

The proposed prediction model Eq. (7) was testified for the validation of data of earlier researchers. A comparison of experimental values obtained by (Song & Hwang 2004, Banthia & Mohamad, 2005; Thomas & Ramasamy, 2012; Ramadoss & Nagamai, 2012) with the predictions by the proposed model Eq. (7) is shown in Fig. 17. The AAE values obtained are 6.26, 3.79, 4.95 and 5.26 respectively. It was observed that the suggested model performs very well with the experimental data.

Based on the experimental results, a nonlinear equation for predicting the flexural strength of HPPFRC using regression analysis has been obtained with $R^2 = 0.69$ (refer Fig. 18) as:

$$f_{rf} = 0.592 f_{cf}^{\ 0.613} \qquad R^2 = 0.69 \qquad (8)$$

Where, f_{rf} = Flexural strength of HPPFRC (MPa)

f_{cf} = Compressive strength of HPPFRC (MPa)

The coefficient of correlation (R) and the AAE values obtained, are 0.883 and 2.85%, respectively.

The proposed prediction model Eq. (8) was testified for the validation of data of earlier researchers. A comparison of experimental values obtained by (Banthia and Mohamad 2006, Afroughsabet and Ozbakkaloglu 2015 and Ahmeed at el 2020) with the predictions of the proposed model Eq. (8) is shown in Fig. 19. The AAE values obtained are 5.29, 5.48 and 6.68 respectively. It was observed that proposed model performs very well with the experimental data.

3.6 Stress-strain behavior in compression

The stress-strain response of HPSFRC, HPPFRC and HP-HyFRC with compressive strength ranging from 60.79 - 80.44 MPa/ 60.79 - 75.52 MPa and 70.68 - 82.12 MPa, respectively, with w/b ratio = 0.38 and 0.28, and SF replacement = 20% with varying fiber volume fractions is shown in Fig. 20. The variation of modulus of elasticity values (E_c) of HPFRC/ HP-HyFRC by the effect of fiber volume fraction (V_f) is presented in Table 6. Modulus of elasticity, E_c for the HPFRC and HPHyFRC obtained in the range of 33.72 - 44.26 GPa and 33.72 - 45.21 GPa, respectively, are given in Table 6. Based on the experimental data, an empirical equation for the modulus of elasticity (E_c) of HP-HyFRC has been obtained as:

$$E_c = 0.789 f'_{cf}{}^{0.910} \qquad R^2 = 0.96 \qquad (9)$$

Where, f'_{cf} = cylinder compressive strength (MPa)

The stress-strain relationship of fiber reinforced concrete has two different branches: an ascending branch up to peak stress, followed by a descending branch till the concrete fails is shown in Fig. 20. The ascending branch of the curve is characterized by the compressive strength, the initial tangent modulus and strain at peak stress. It is observed from the stress-strain curves that the post-peak behavior of HPSFRC/ HP-

HyFRC is greatly influenced as fiber volume fraction (V_f) increases, which is evidenced from the larger area of stress-strain curve. From the post-peak stress-strain relation, it is seen that descending portion of the curve changes remarkably and ductility/ toughness of SFRC/ PFRC/ HyFRC are comparatively increased as the fibers are more effective in providing post-peak response and restraining the cracks. The ductility factor for HPSFRC (S-1), HPPFRC (P-0.5) and HP-HyFRC (S-1, P-0.5) mixes obtained, are 2.57, 1.21 and 3.93 respectively, are given in Table 7. The maximum ductility factor achieved for the HyFRC (S-1, P-0.5) mix is 3.93 which is 103% of the sum of the ductility factor of SFRC (S-1) and PPFRC (P-0.5) mixes. This improvement is due to the synergy effect between the fibers, and resulting hybrid performance.

3.7 Effect of alccofine-1203 on mechanical performance of high performance concrete (HPC)

Compressive strength of high performance concrete (HPC) with 20% silica fume replacement by varying the addition of dosage of alccofine-1203 from 0 to10 % by weight of binder was studied. The maximum improvement in 28-day compressive strength obtained is 2.13% at 8% of alccofine-1203 addition and at 10% of alccofine-1203 addition, no improvement in strength was observed. The similar trend was seen in flexural strength developments.

Flexural strength of high performance concrete (HPC) at 8% of alccofine-1203 addition, was improved to 5.54% compared to that of reference HPC and at 10% of alccofine-1203 addition no improvement in strength was obtained.

Figs. 21 and 22 show the effect of addition of alccofine-1203 on the mechanical properties of high performance concrete (compressive and flexural strengths). From the test results shown in Tables 8 and 9, it is found that optimum dosage of alccofine-1203 is 8% by weight of binder with margination improvement in compressive and flexural strengths.

4. Numerical modeling of Strength

The results of this investigations reports on the numerical analysis by using Response surface method (RSM) on data sets (mixture proportions and 28-day compressive strength of HPFRC/ HP-HyFRC) produced by the authors. For the purpose of numerical modeling of compressive strength of HP-HyFRC, the following 5 influencing input variables are used.

(1) w/b ratio (2) Cement (C), kg

(3) Micro silica (MS), kg (4) Steel fiber (SF), kg

(5) Polypropylene fiber (PF), kg

4.1 Numerical Modeling of compressive Strength by Response surface method (RSM)

Multiple linear regression (MLR) determines the coefficients of a linear equation that best predict the value of dependent variable. The MLR model was developed by utilizing RSM to analyses experimental data sets with five input parameters. MLR model [Eq. (10)] developed by RSM for 28-day compressive strength of HPHyFRC with coefficient of determination (R^2) = 0.99, is expressed as:

$$\begin{aligned} y = 134.84 - 138.9\,(w/b) + 0.0287\,C - 0.0371\,Micro\,Silica + 0.0783\,SF \\ - 0.66\,PF + 0.000056\,C*SF + 0.0013\,C*PF \qquad (R = 0.99) \end{aligned} \tag{10}$$

where, y = estimated compressive strength or dependent variable and n = 5 (no. of independent parameters or variables) and corresponding regression coefficients.

The AAE (%) for the estimated compression strength was observed to be 1.24, indicating accuracy in the established relationship. Predicted compressive strength of HP-HyFRC by MLRM and their absolute variations are shown in Table 10. Surface plots for compressive strength of HP-HyFRC with the influence of variable in the concrete mix is shown in Fig. 23.

The predicted values of the numerical model (MLR model), values obtained is within 1.4%. It is observed that proposed model is good arrangement with experimental values and also the model predicts the strength of HP-HyFRC mixes quite accurately.

6. Conclusions

Based on the experimental and numerical investigations on HPFRC/ HP-HyFRC with micro silica as SCM, the following conclusions are drawn.

- Significant improvement in flexural tensile strength for HPSFRC at V_f = 1.5% obtained, is 44.66%; for HP-HyFRC(S-1.5%, P-1%) the improvement is 61.44% and for HPPFRC at V_f = 1% the moderate improvement in strength is obtained.
- Empirical equations for predicting the compressive strength ratios and flexural strength ratios of HPSFRC / HPPFRC as a function of fiber volume fraction were developed, and the AAE values computed are 0.7and 2.57 / 0.28 and 1.72, respectively.
- It was observed that the proposed models perform very well for different types of fibers and aspect ratios and on the results of evaluation of strengths, models show better reliability in estimation the strengths.
- The empirical equation involved the non-dimensional variables (ie. independent of specimen parameters) is suitable for wide range of w/b ratios and all types of specimens.
- Micro steel fibers were found to contribute to strength, ductility, and toughness, whereas polypropylene fibers were found to be effective in crack control.
- Relationship between flexural strength and compressive strength of HPSFRC has been proposed with correlation coefficient (R) = 0.93 and AAE = 4.32%, and predicted the strengths with high accuracy.
- Relationship between flexural strength and compressive strength of HPPFRC has been proposed with correlation coefficient (R) = 0.95 and AAE = 2.85%, and predicted the strengths with high accuracy.
- Numerical models (MLR models) were developed by using response surface method for the prediction of compressive and flexural strengths of HP-HyFRC mixes and AAE values obtained are 1.24 and 1.73%, respectively, indicate the reliability of the models.
- On predicting the 28-day compressive strength of HP-HyFRC mixes of earlier researchers by MLR model, the average absolute error (AAE) obtained for the experimental data is 5.53%. It is observed that the MLR model performs exceptionally well in predicting the strengths of HP-HyFRC mixes.
- Static modulus of elasticity of HPFRC and HP-HyFRC obtained is in the range of 33.72 - 44.21 GPa.
- Ductility factor achieved for HP-HyFRC is 103% of sum of ductility factor of HPSFRC and HPPFRC, which indicates the synergistic effect between the steel and polypropylene fibers.

- Addition of 8% (optimum value) of alccofine-1203 in HPC, improved the compressive and flexural strengths marginally.

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Figures

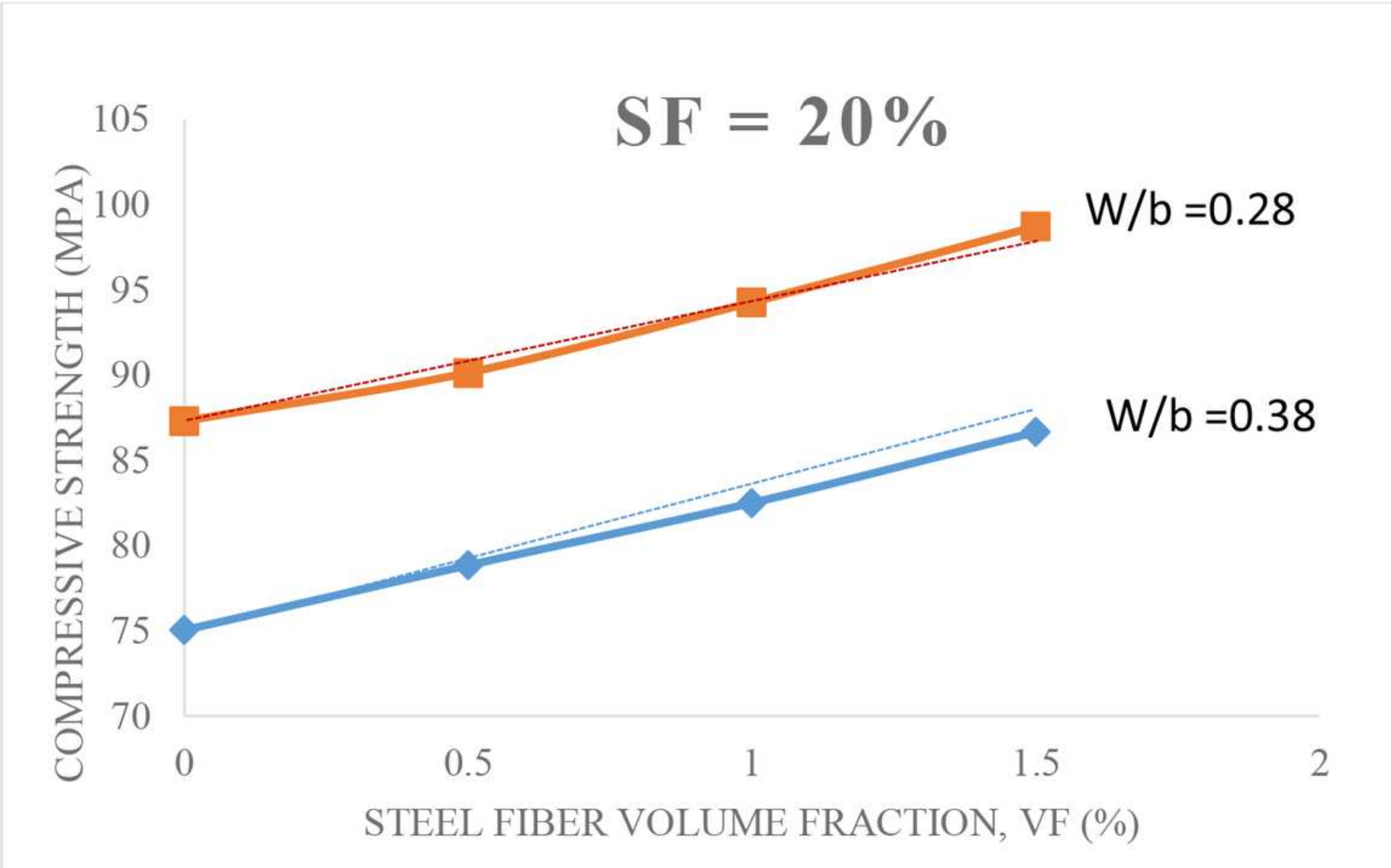

Figure 1

Effect of Steel fiber volume fraction (Vf) on compressive strength of HPC

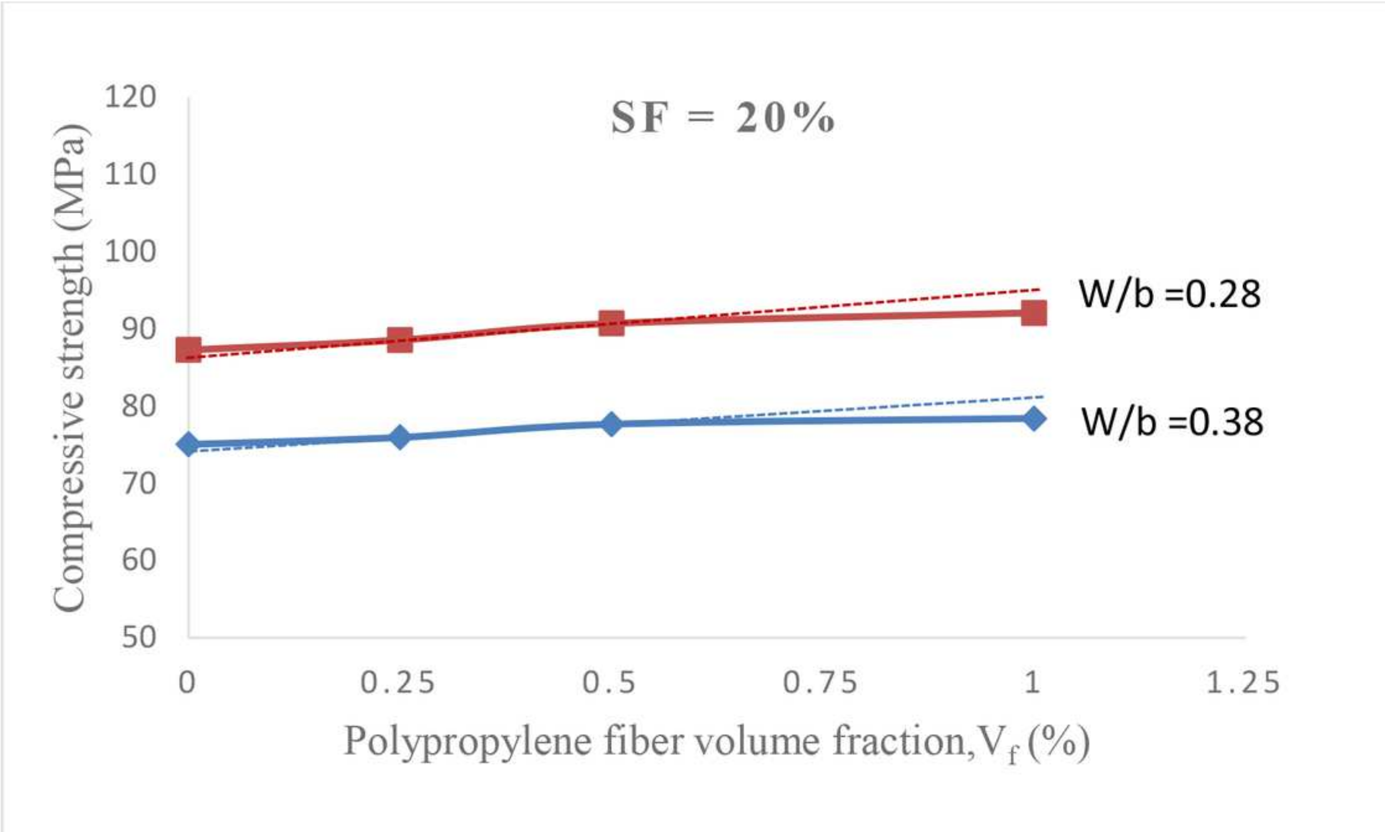

Figure 2

Effect of Polypropylene fiber volume fraction (Vf) on compressive strength

of HPC

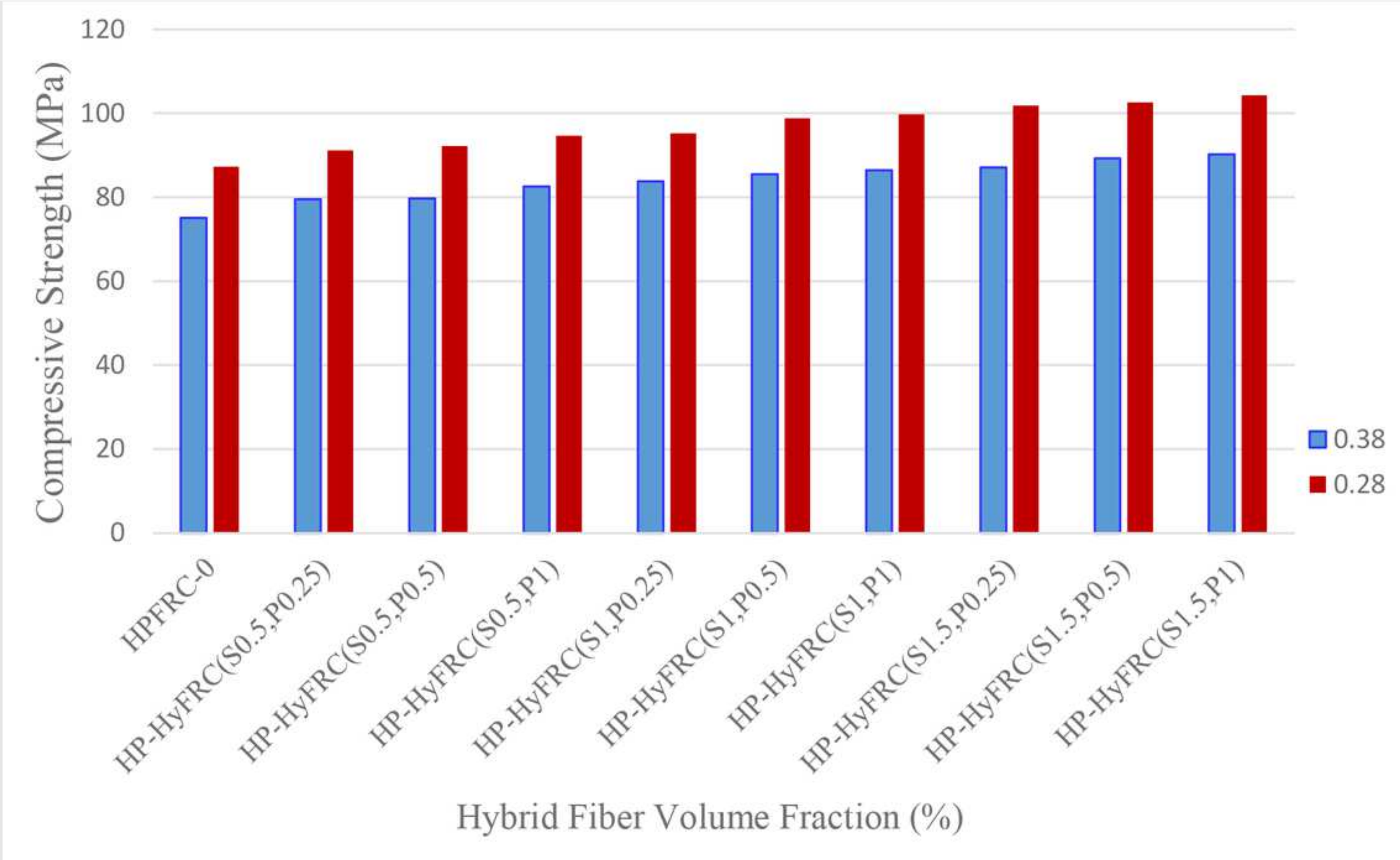

Figure 3

Compressive Strength of HP-HyFRC Vs Hybrid Fiber Volume Fractions

(Vf)

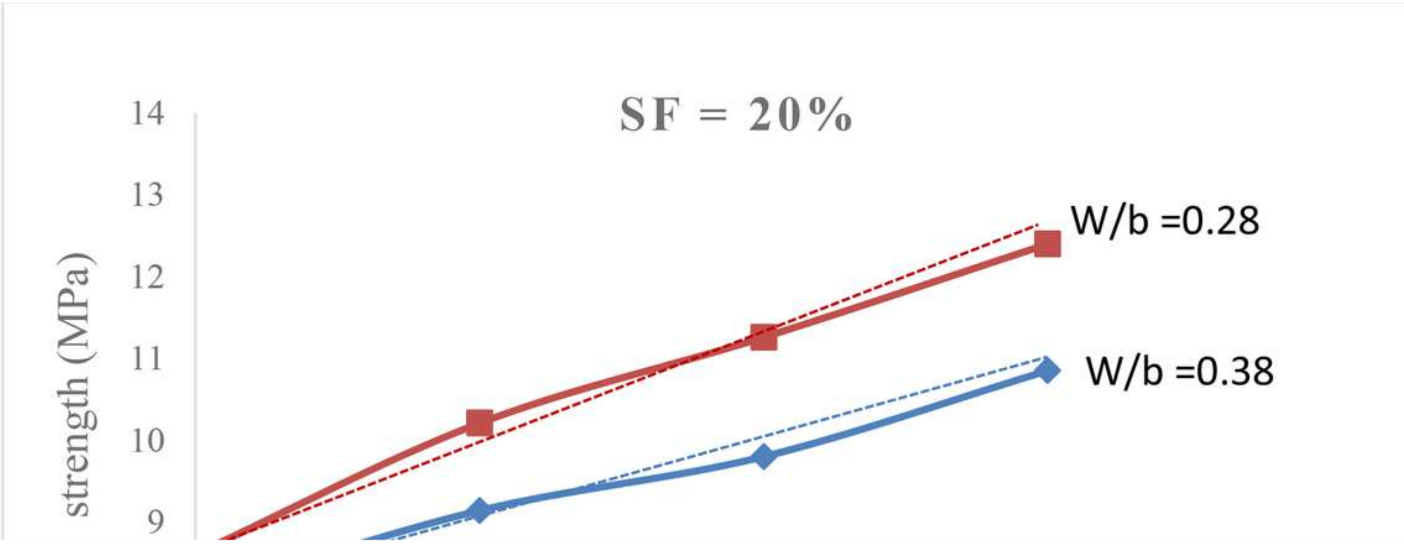

Figure 4

Effect of Steel fiber volume fraction (Vf) on flexural strength of HPC

Figure 5

Effect of Polypropylene fiber volume fraction (Vf) on flexural strength of HPC

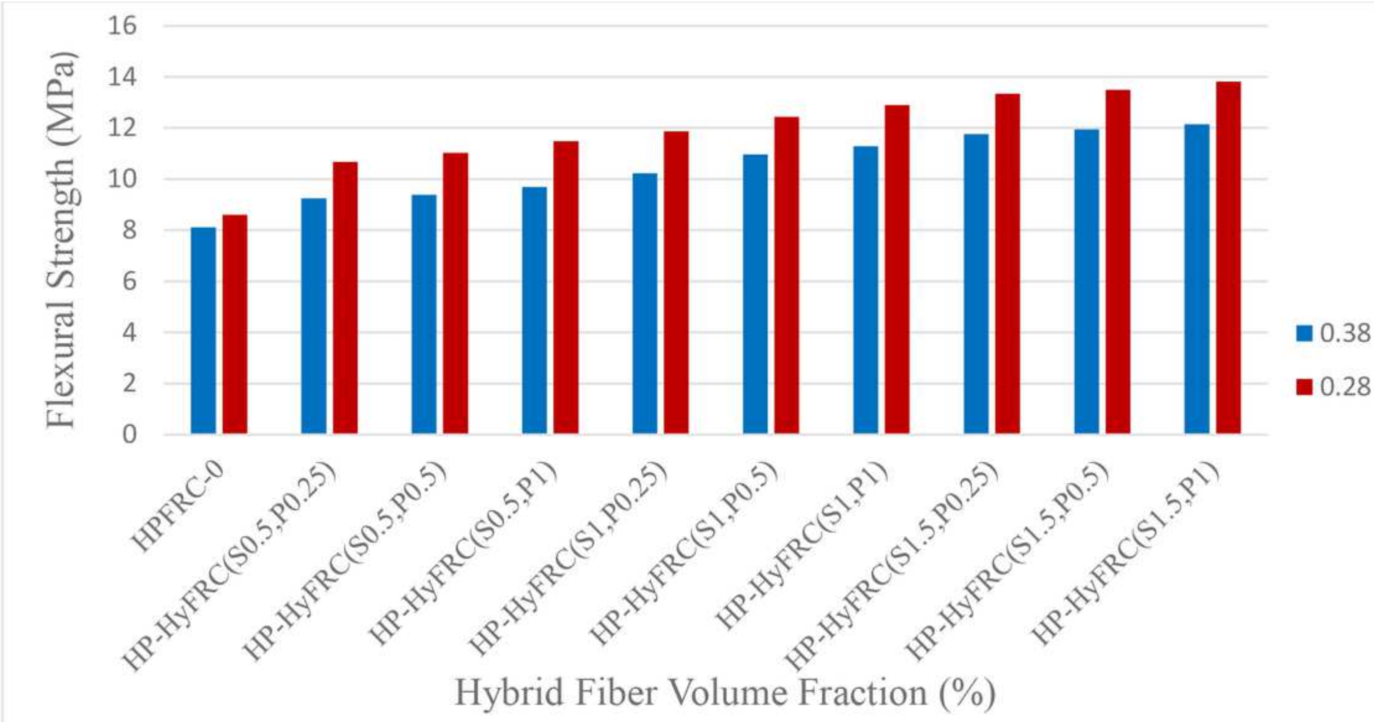

Figure 6

Flexural Strength (MOR) of HP-HyFRC Vs Hybrid Fiber Volume Fractions (Vf)

Figure 7

Experimental setup and failure mechanism fiber reinforced cube and prism specimens

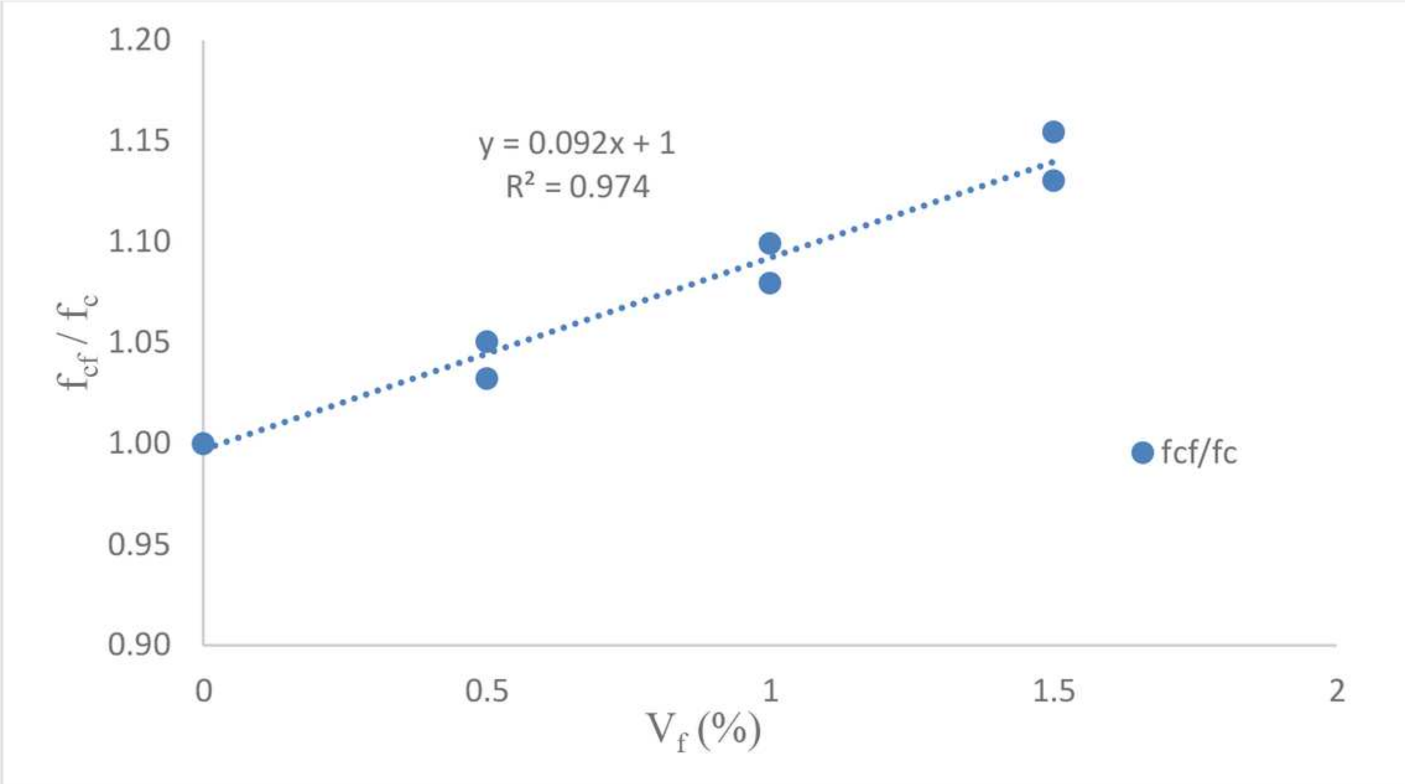

Figure 8

Compressive strength ratios of HPSFRC and HPC Vs Steel fiber volume fraction, Vf (%)

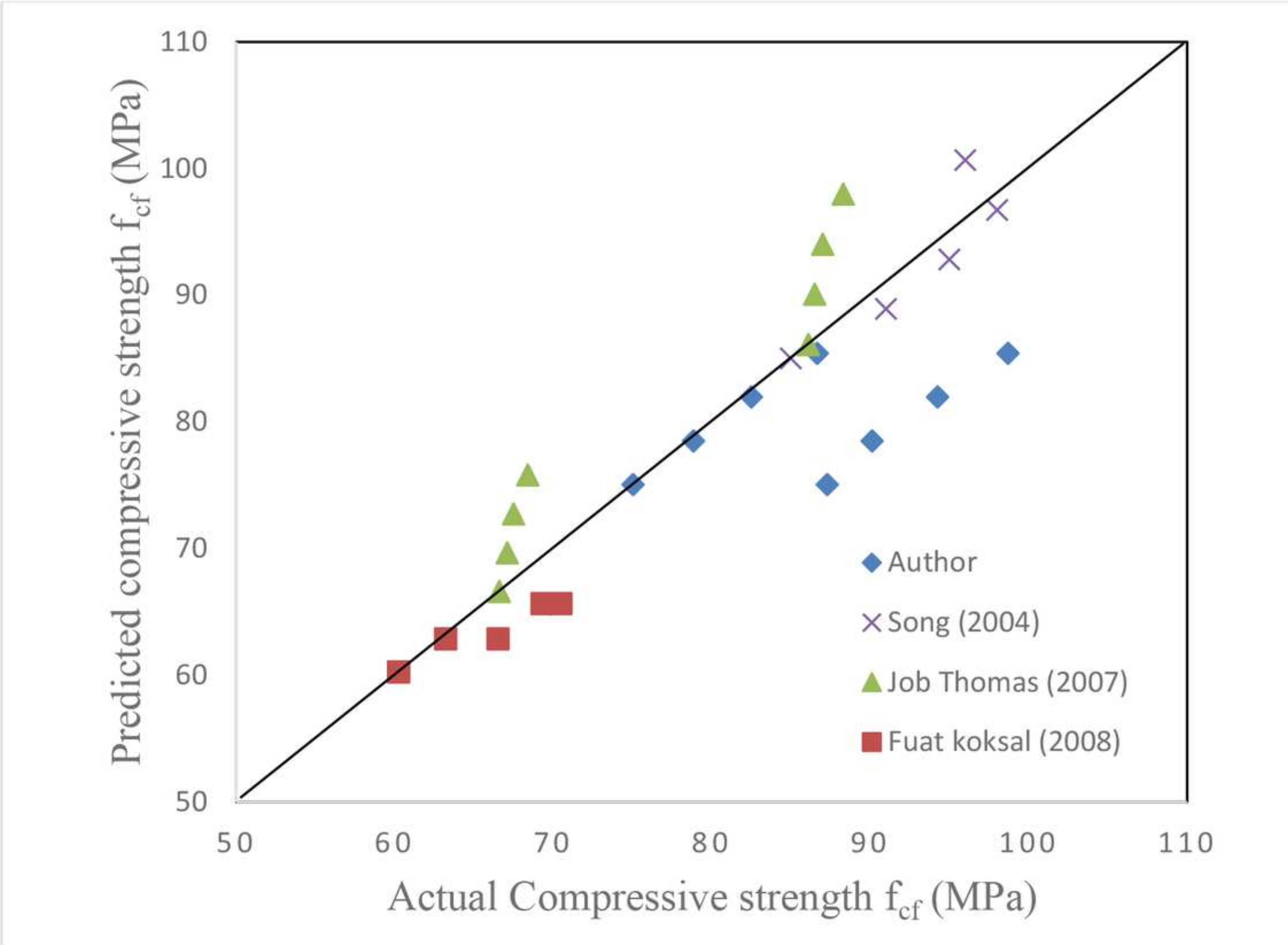

Figure 9

Comparison of experimental values of compressive strength (MPa) of HPSFRC with the predications by the model

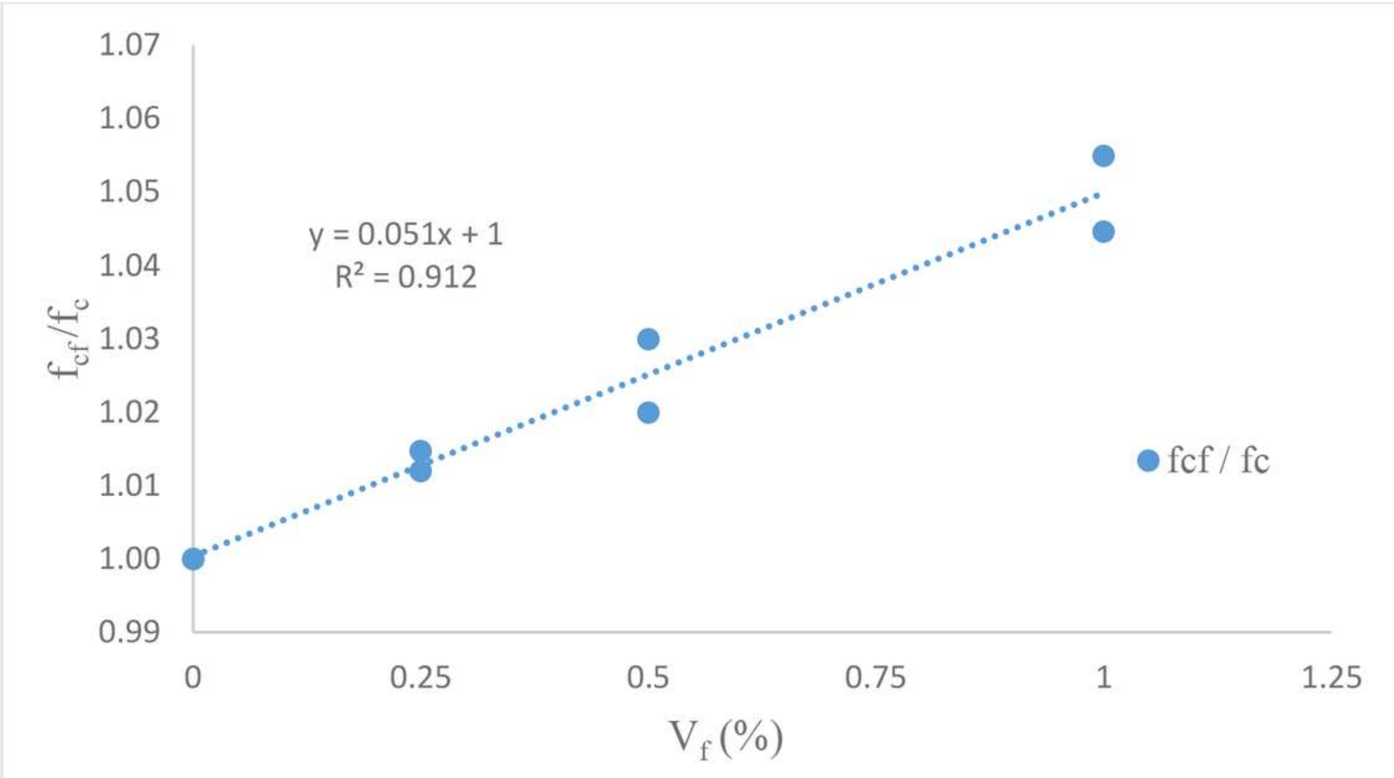

Figure 10

Compressive strength ratios of HPPFRC and HPC Vs Polypropylene fiber volume fraction, Vf (%)

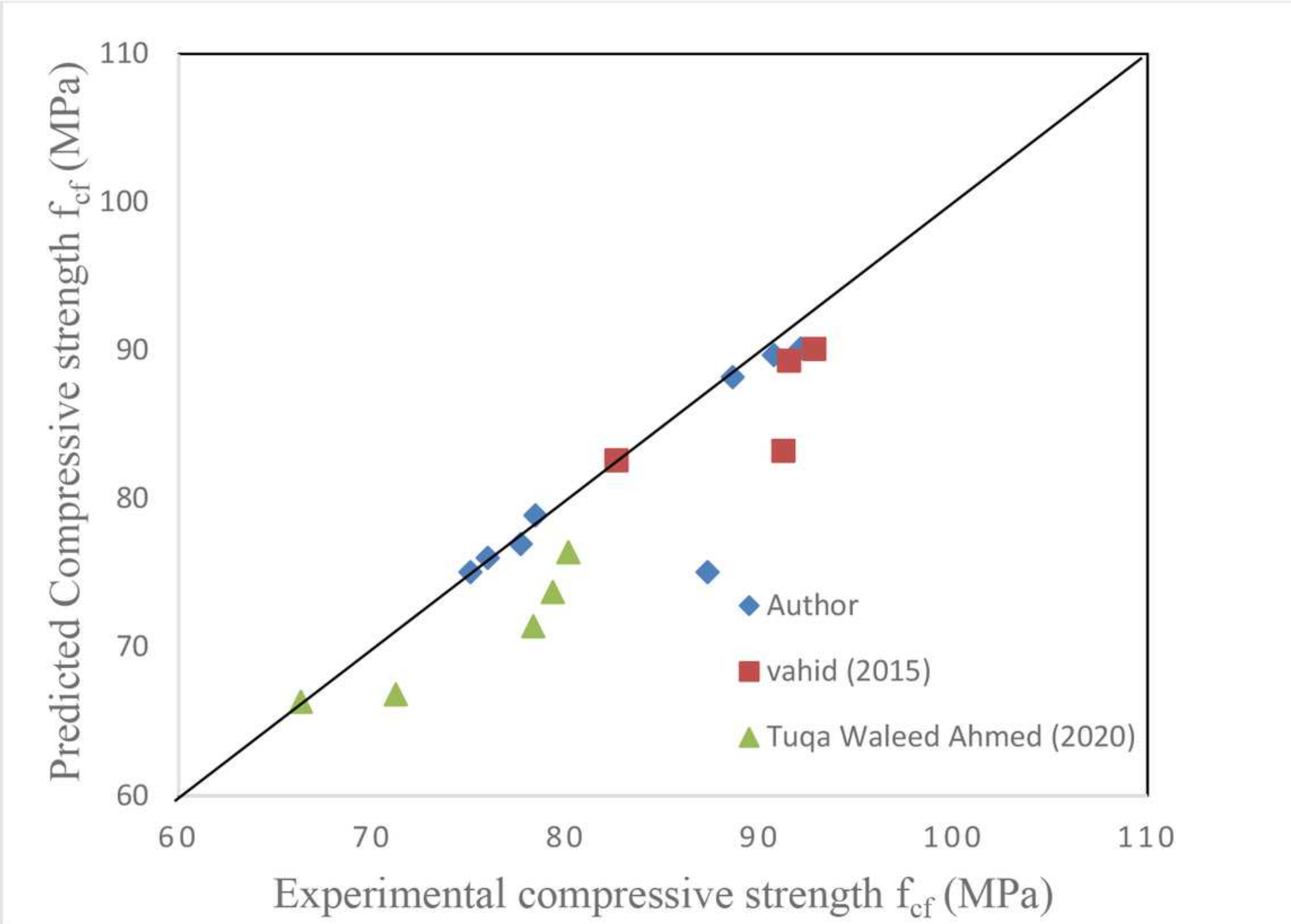

Figure 11

Comparison of experimental values of compressive strength (MPa) of HPPFRC with the predications by the model

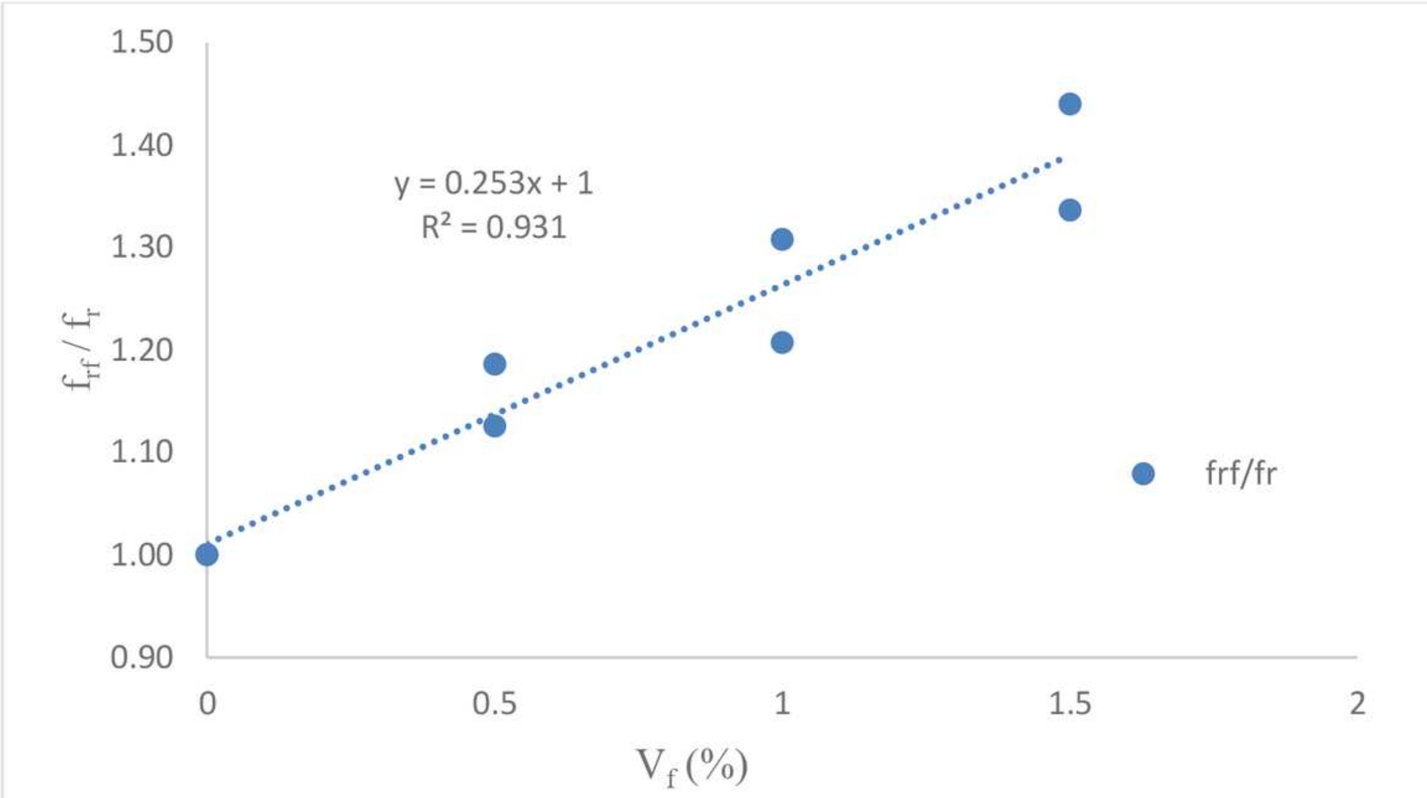

Figure 12

Flexural strength ratios of HPSFRC and HPC Vs Steel fiber volume fraction,

Vf (%)

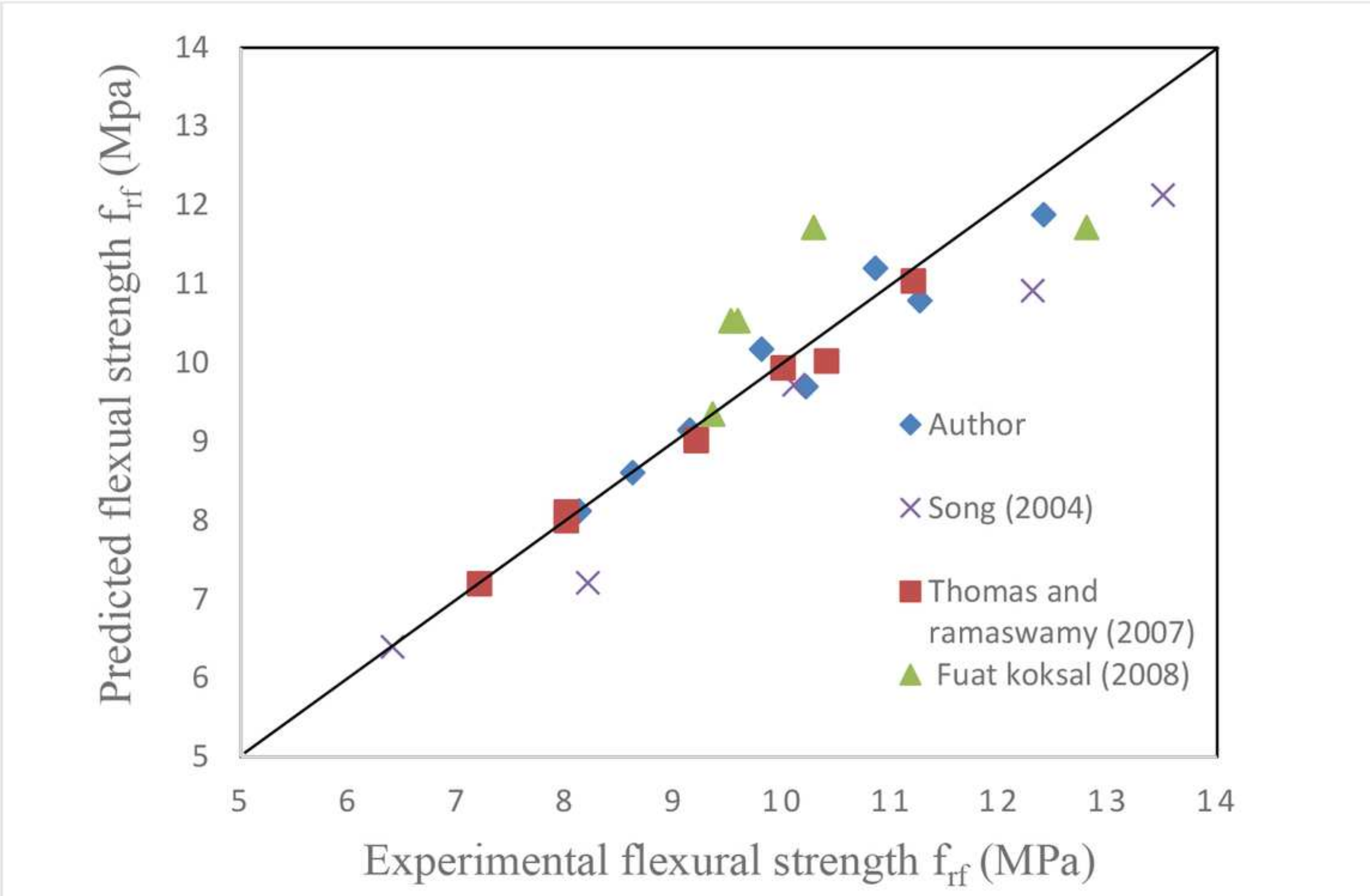

Figure 13

Comparison of experimental values of flexural strength (MPa) of HPSFRC

with the predications by the model

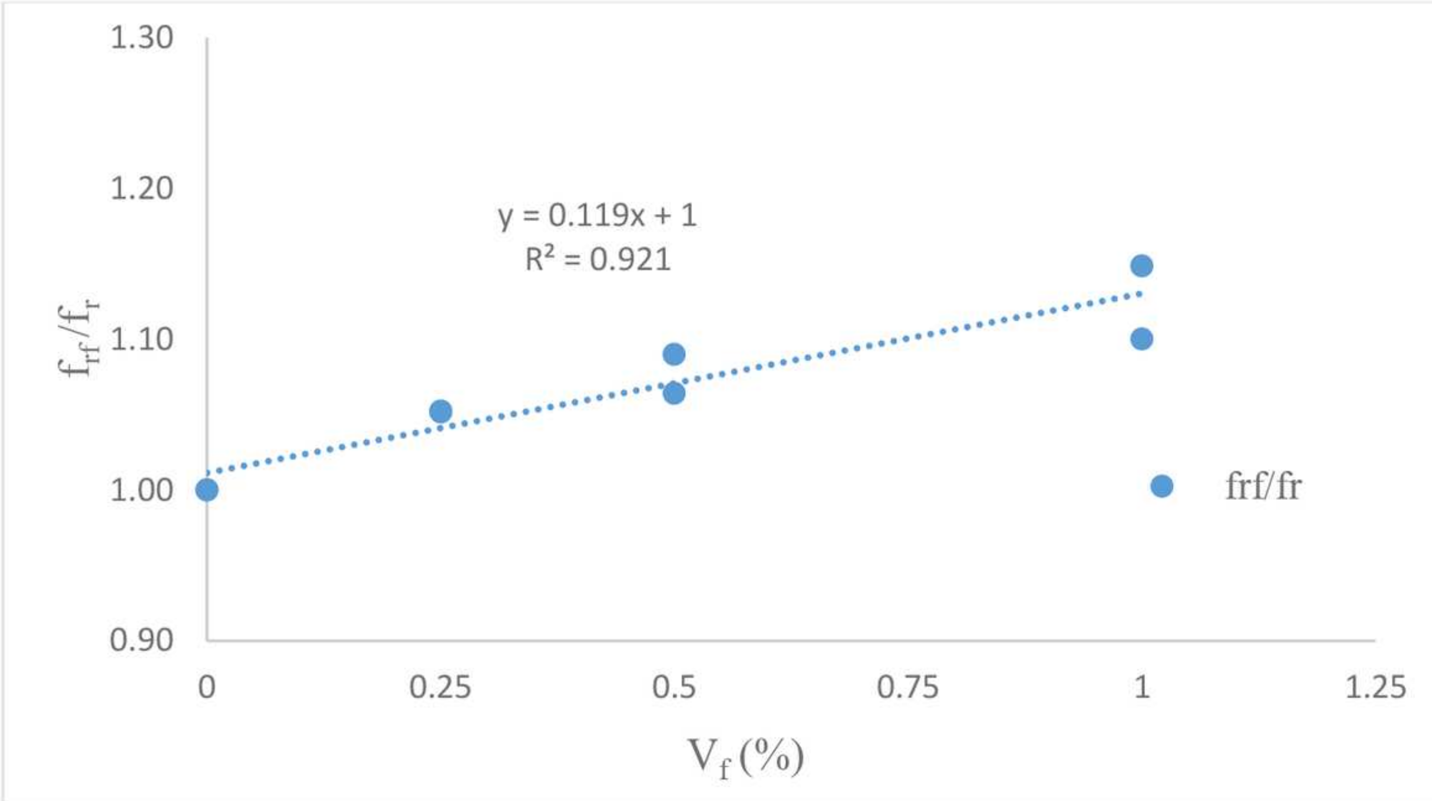

Figure 14

Flexural strength ratios of HPPFRC and HPC Vs Polypropylene fiber volume fraction, Vf (%)

Figure 15

Comparison of experimental values of flexural strength (MPa) of HPPFRC with the predications by the model

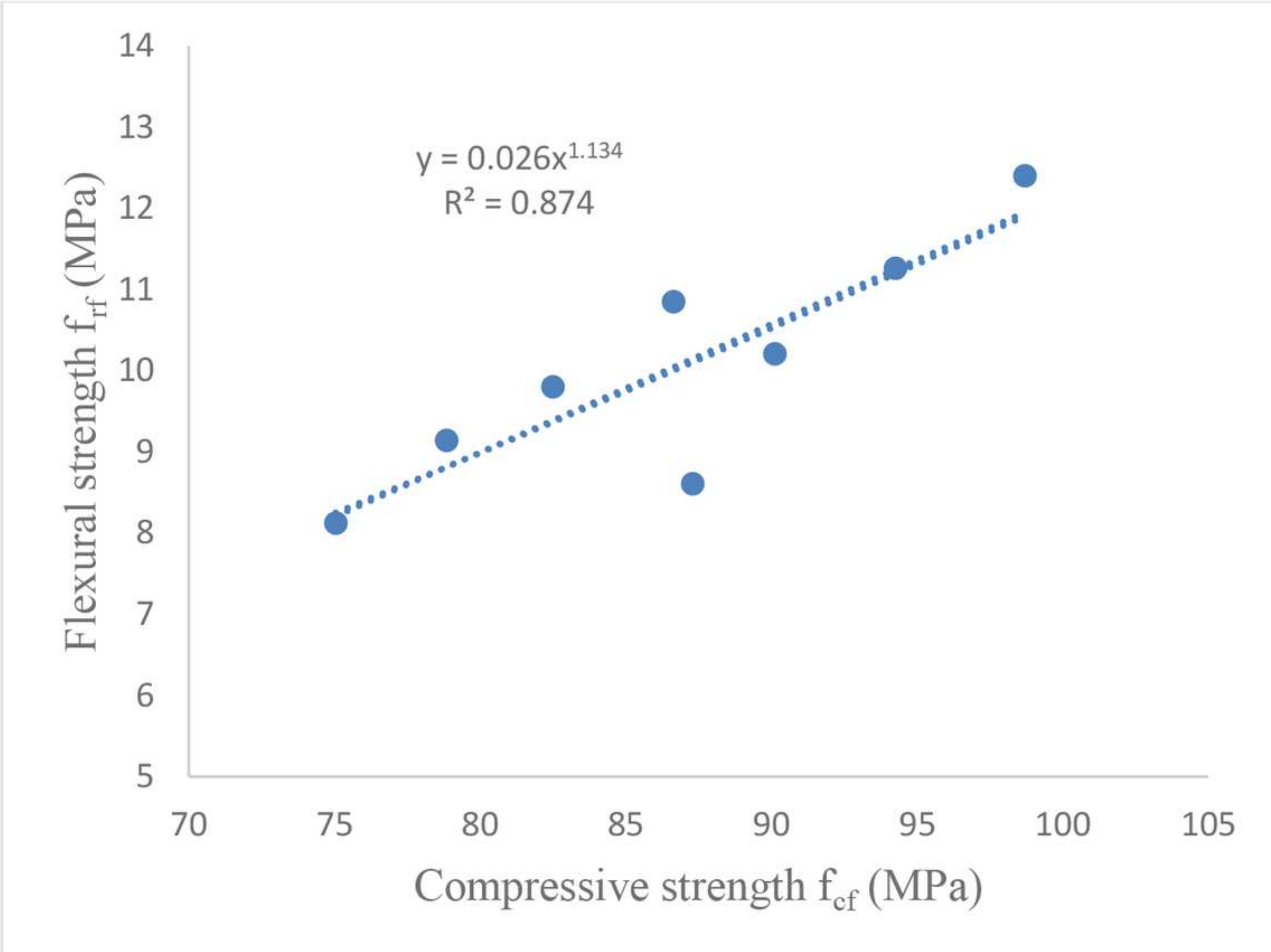

Figure 16

Relationship between flexural strength and compressive strength (MPa) of

HPSFRC

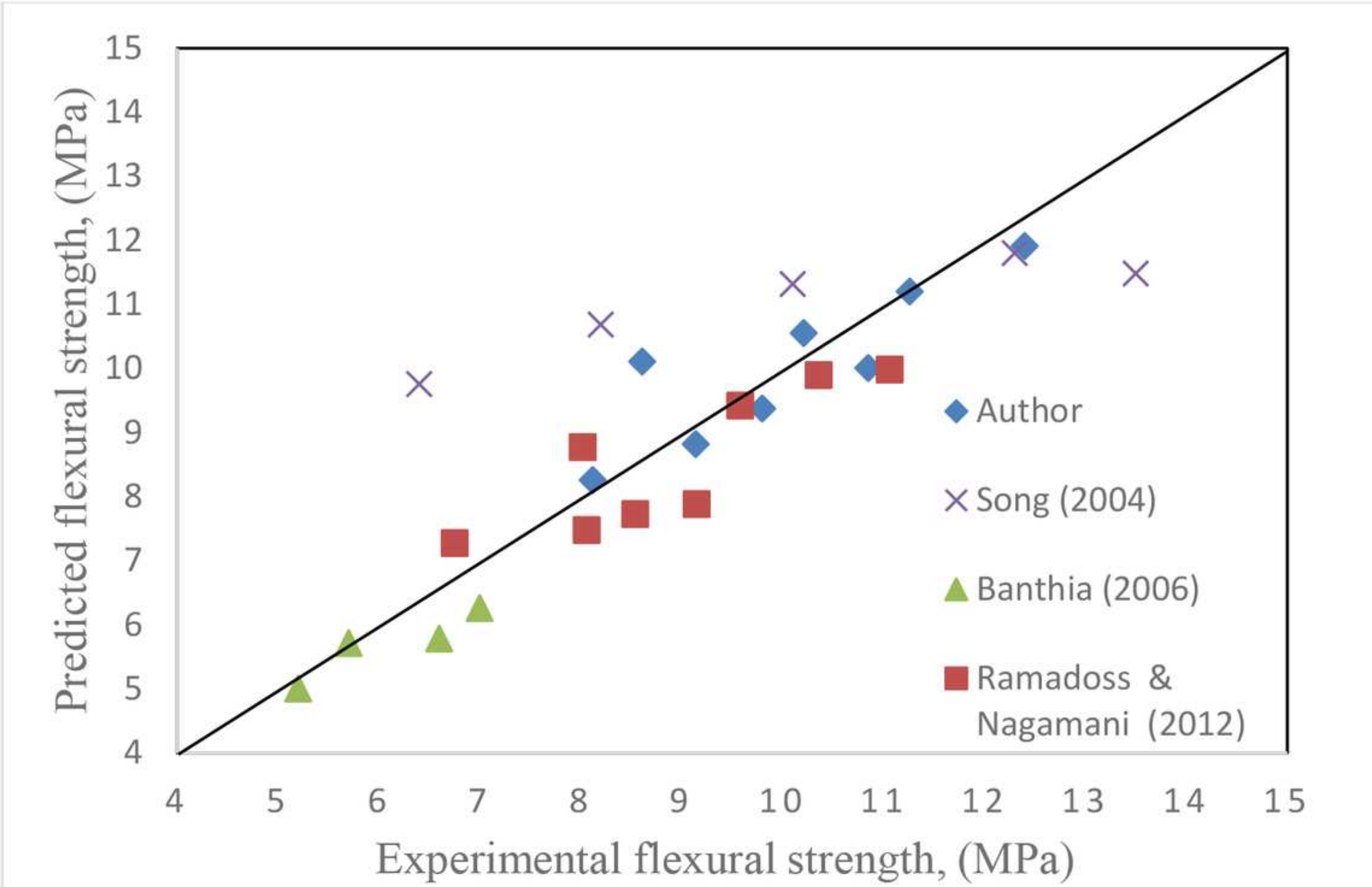

Figure 17

Comparison of experimental values of flexural strength (MPa) of HPSFRC with the predications by the model

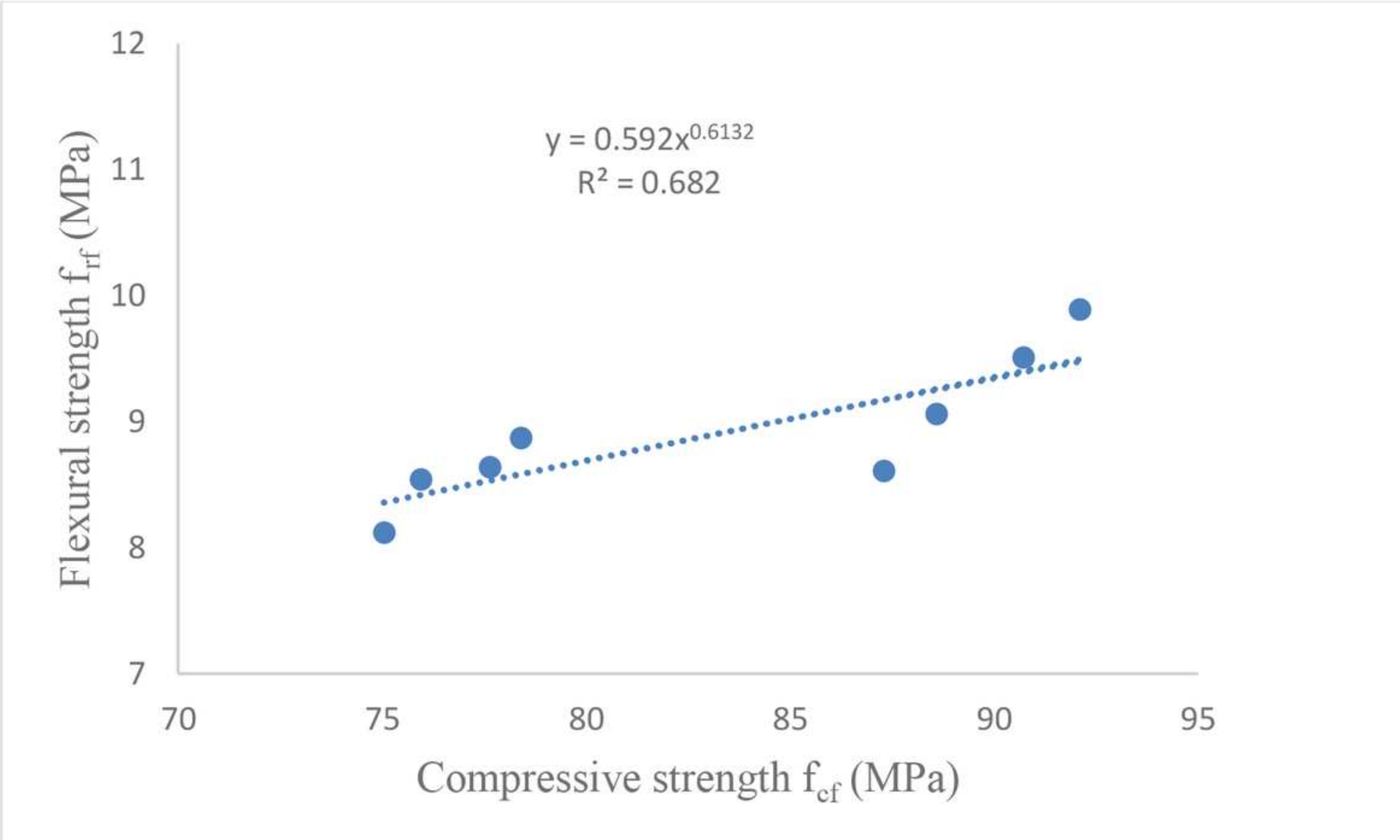

Figure 18

Relationship between flexural strength and compressive strength (MPa) of HPPFRC

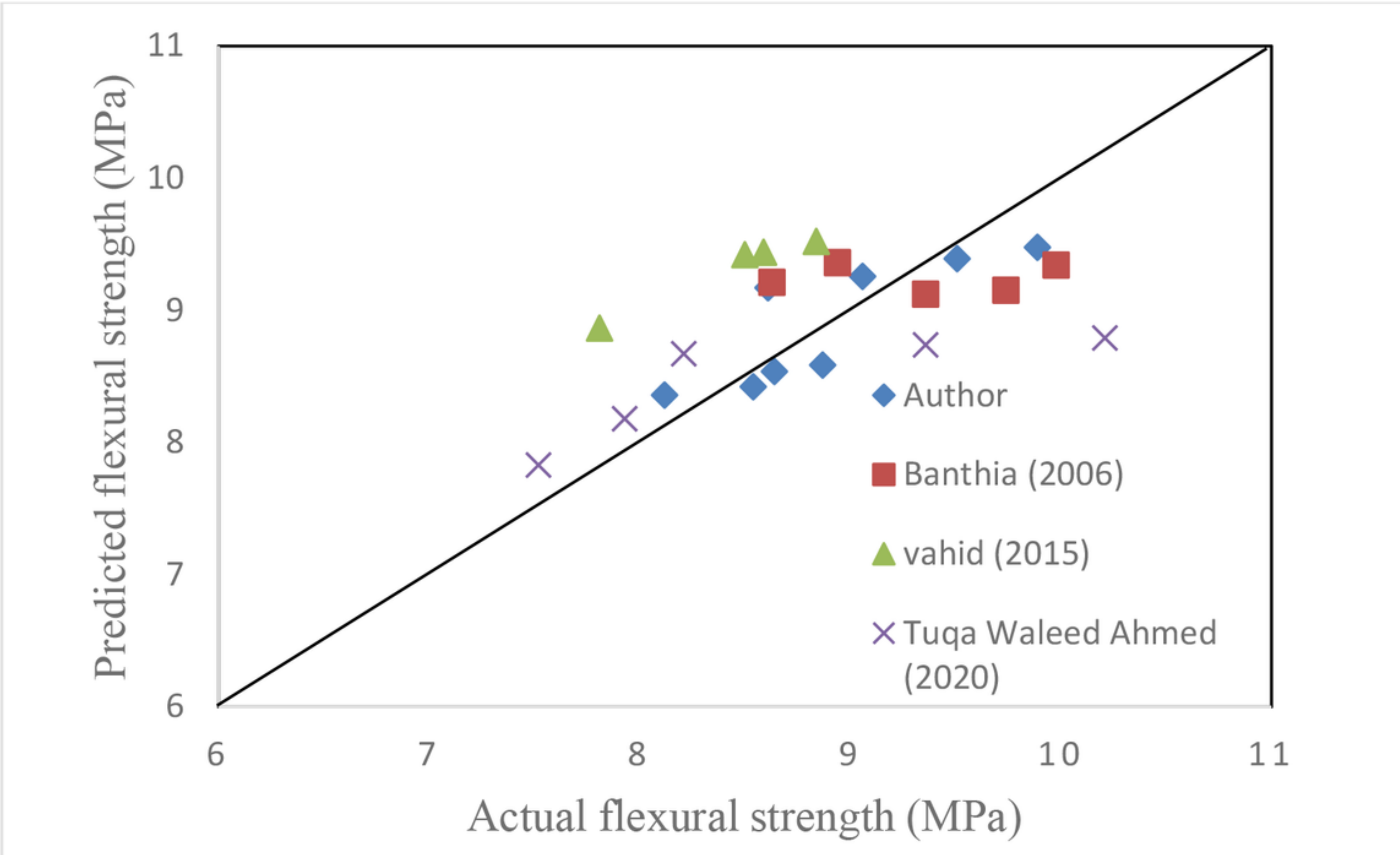

Figure 19

Comparison of experimental values of flexural strength (MPa) of HPPFRC with the predications by the model

Figure 20

Effect of volume fraction of steel, polypropylene and hybrid fibers on the stress-strain behavior (w/b = 0.38, SF replacement = 20%)

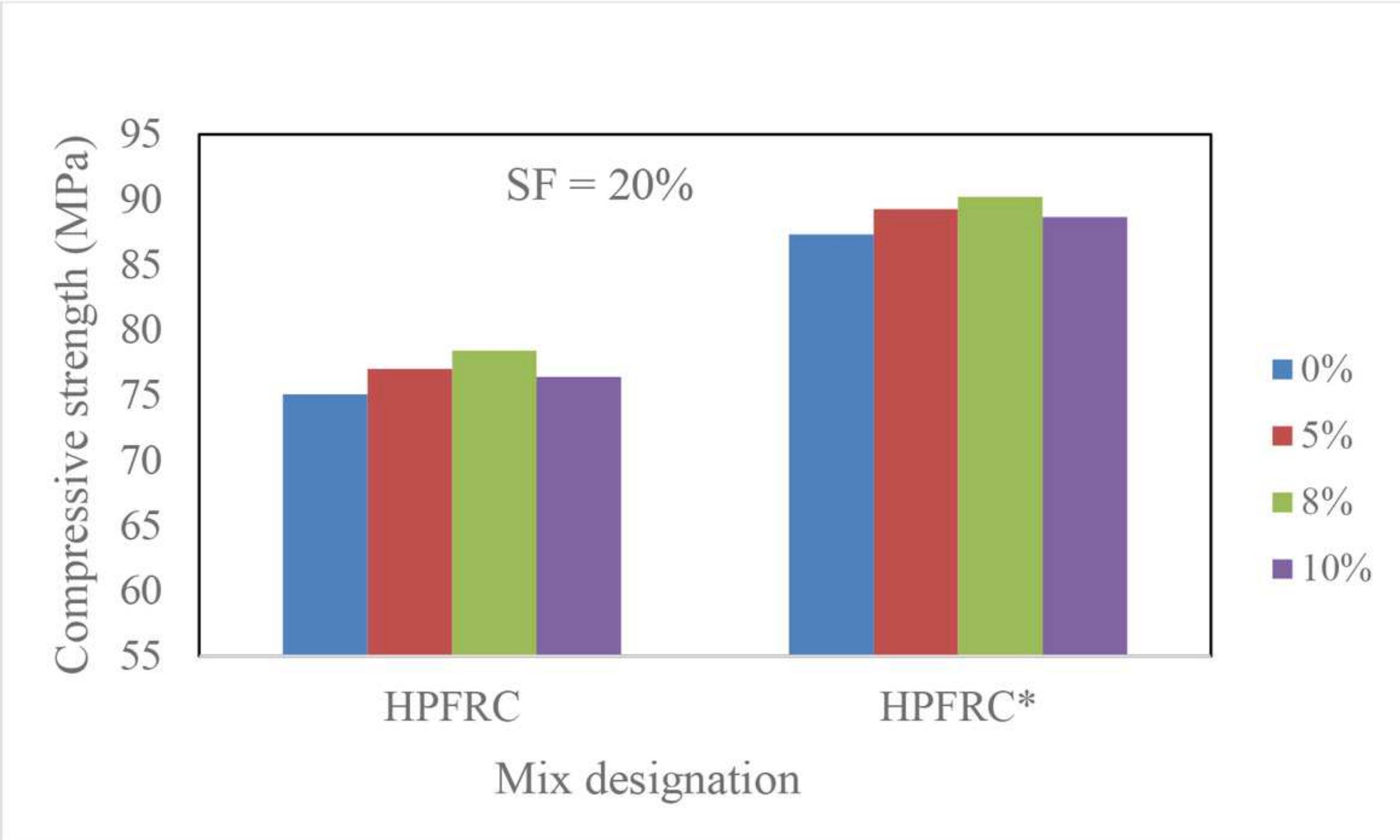

Figure 21

Compressive strength (MPa) Vs alccofine content (%) in high performance concrete

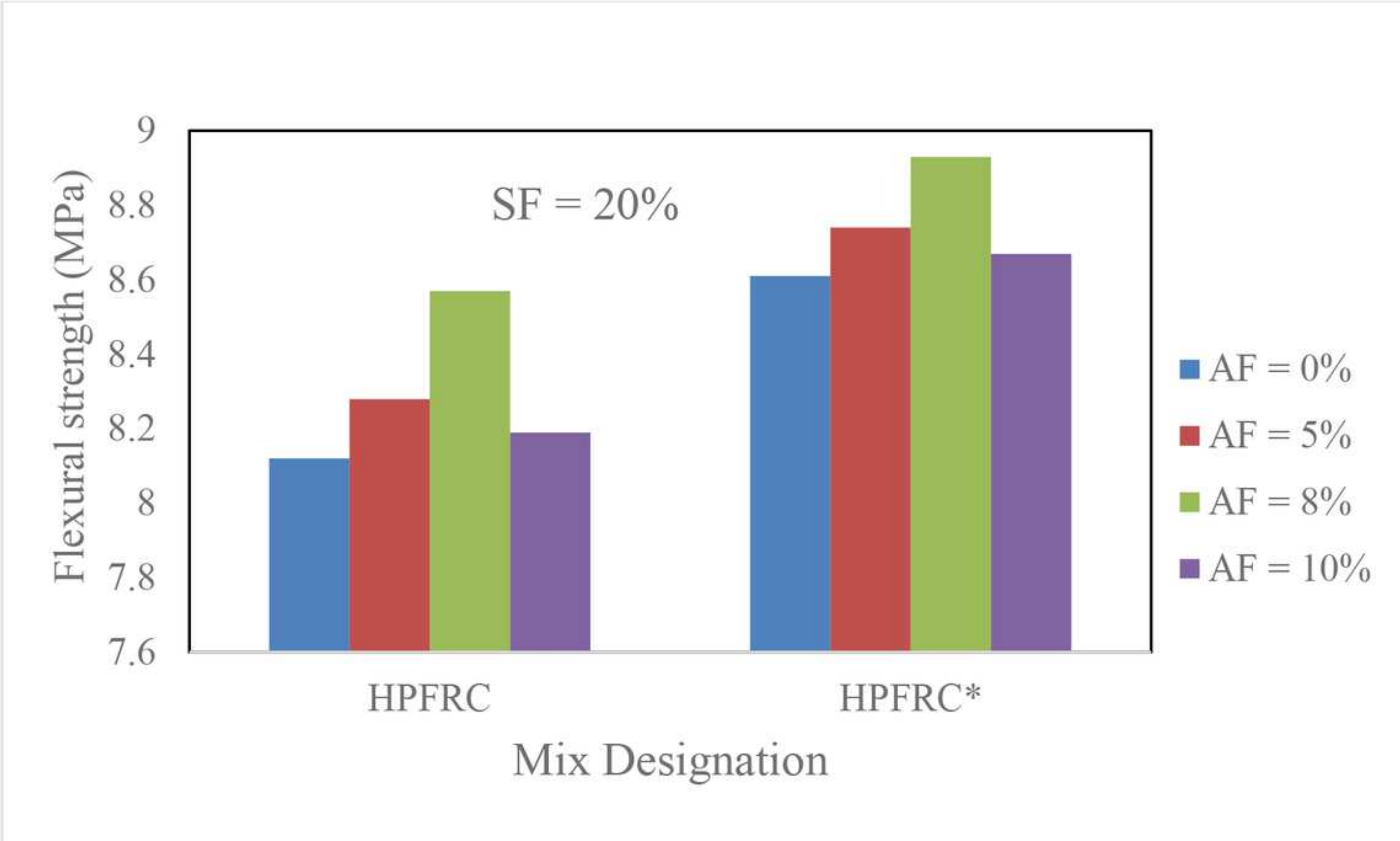

Figure 22

Flexural strength (MPa) Vs alccofine content (%) in high performance

concrete

Figure 23

Surface plots for compressive strength Vs influencing variables in and HPHyFRC mixes

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 5.SymbolsHPHyFRC.pdf
- 3.TablesHPHyFRC.pdf