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The Characterization and Modeling the Mechanical Properties of High Strength Concrete (HSC) Modified with Fly Ash (FA)

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K E Y W O R D S

Compressive strength; curing time; Fly ash; Modeling; Normal and high strength concrete; Statistical analysis.

A B S T R A C T

*One of the main challenges facing Civil Engineering community is to modify cement quantity in the mix design by admixtures to enhance the mechanical properties. According to more than 1000 data from literature, mechanical characteristics of concrete modified with FA were discussed. The statistical variation with modeling were achieved by set of data. The cement was replaced up to 70% with FA (weight of dry cement) and by cube of concrete testing up to 90 days of curing time and different w/c ratio. The compressive strength of concrete varied from 18-67 MPa, while, for modified concrete with FA, compressive strength ranged from 21-94 MPa, tensile strength ranged from 1-9 MPa and flexural strengths ranged from 3 - 10 MPa. The w/c ratio of concrete modified with FA varied from 0.24-0.53, also the FA content varied from 0-50 %. Vipulanandan correlation model was effective by connecting mechanical properties and compare with Hoek-Brown model. The nonlinear model was used to investigate the effect of FA on properties of normal and high strength concrete. Study results presented a worthy correlation between compressive strength and curing time, w/c ratio and FA content. By using the interactive linked (model) for compressive, tensile, and flexural strengths of concrete quantified well as a function of w/c ratio, curing time and FA content by using a nonlinear relationship***.**

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1. Introduction

Concrete is defined as a mixture of Portland cement (OPC), fine and coarse aggregate, water and admixture that is used as a material for construction [1]. For years, researchers have tried to find more effective materials and ways for decreasing the disadvantages of concrete and making the use of concrete more effective by using admixtures for improving the properties of concrete in structural design [2]. Several experimental researches have shown that the different percent of FA is active to enhancing concrete properties, which decrease the cement content to reduce the costs, enhances the performance, mechanical properties, and durability of normal (NSC) and high strength concrete (HSC) in the hardened state [3 -5].

Concrete was evaluated from mechanical properties such as compressive (fc`), tensile (ft) and flexural (ff) strengths while, compressive strength of NSC and HSC were the utmost vital specific [6].

Research and development on HSC have been done for more than 40 years. In recent years, it has been observed that HSC has been usually used in construction. Based on ACI 363R [7], high strength concrete that has particular compressive strength of at greater than 55 MPa at 28 days [8-9]. HSC can be achieved by using super plasticizers and classical chemical additives like fly ash (FA), silica fume (SF), natural pozzolan and granulated blast furnace slag [10] also by lower water to cementitious materials ratio, w/c ratio principals of higher strength concrete (HSC) and durability, while make the mix difficult to work [11,12]. Workability can be regulated by the use of high-range water reducers [13-14].

In this study, many methodical forms (models) from literature for more understand FA influence on properties (mechanical) of NSC and HSC (Table 1).

Based on the literature data the influence of w/c ratio, percent of FA (%FA) and curing time (t) on mechanical properties of NSC and HSC modified with FA were calculated by Nonlinear modeling.

Objectives:

Particularly objectives were as below:

(i) Implement a statistical analysis for w/c ratio, percent of FA and mechanical properties of NSC and HSC modified with FA.

(ii) To evaluate and analyze the relations of compressive strength with both tensile strength and flexural strength for normal (NSC) and high strength concrete (HSC) modified with FA.

(iii) To establish correlation for the effect of water to cement ratio (w/c), percent of FA (%FA) and curing time (t) on most of mechanical properties of normal NSC and HSC.

Table 1: Properties of normal (NSC) and high strength concrete (HSC) modified with FA collected from literature

Reference	Fly ash, FA (%)	w/c (%)	Curing time, t (Day)	Compressive strength, f_c` (MPa)	Tensile strength, ft (MPa)	Flexural strength, f_f (MPa)	Test(s)
[15]	0-10	0.3	1,7,14,28,90	6 - 50	-	-	Compressive strength
[16]	0-60	0.3	1,7,28,60	16 - 105	-	-	Compressive strength
[17]	0-50	0.4	7,28,90	14 - 40	-	-	Compressive strength
[18]	0-30	0.4	2,7,28,90	18 - 60	3 - 4	3 -4	Compressive, split tensile and flexural strengths
[19]	0-30	0.35	1,7,28,90	15 - 59	-	-	Compressive strength
[20]	0-75	0.42	7,14,28	40 - 66	2 - 6	9 - 10	Compressive, split tensile and flexural strengths
[21]	0-25	0.3	28	71 - 96	-	-	Compressive strength
Remarks	Ranged from 0-75%	Ranged from 0.3-0.42%	Up to 90 days of curing	Ranged from 6-105 MPa	Range from 2-6 MPa	Ranged from 3-10 MPa	Compressive, split tensile and flexural strengths were used

2. Methodology

I. Collection Data

Research was concentrated on variation of statically also relationships of mechanical properties such as compressive, tensile and flexural strengths with w/c ratio, normal and high strength concrete modified with FA and curing time up to 90 days, according to literature data.

II. Modeling

1. Vipulanandan correlation model
Non-linear correlation of normal and high strength concrete properties such as compressive and tensile strengths also compressive and flexural strengths were analyzed using Vipulanandan model [22-25] of concrete modified with FA. According on the analysis of set of data collected from literature, using a relationship as below:

$$Y=Y_0+[X/(A+B*X)] \quad (1)$$

Y = Concrete properties like Compressive (f_c\`), tensile (f_t) and flexural (f_f) strengths (dependent variable)
Y_o, A and B = factors from model, Table 2.
X = Concrete properties like curing time (t) also compressive strength (f_c\`) (independent variable).

2. Hoek-Brown Model
Vipulanandan correlation and Hoek-Brown correlation models were compared for each other [26] by using set of data collected from literature, using an equation as below:

$$Y=X+C * [D*(X/E) +1] \quad (2)$$

Where: C, D and E are Hoek-Brown parameters, which are shown in Table 3.

3. Non-linear model parameters (NLM)
Mechanical properties such as compressive strength (f_c\`), tensile strength (f_t) and flexural strength (f_f) of normal and high strength concrete with and without FA as a function for w/c ratio, percentage of FA (%FA) and curing time separate and all together them in one equation [27], by using non-linear relationship (NLM) as below:
(i) Concrete without fly ash (FA) of NSC and HSC:

$$\left.\begin{array}{l} f_c` \\ f_t \\ f_f \end{array}\right\} = a\,[(w/c)^{b}]*(t)^{c} \quad 3(a),\ 4(a),\ 5(a)$$

Concrete modified with FA of NSC and HSC:

$$\left.\begin{array}{l} f_c` \\ f_t \\ f_f \end{array}\right\} = a\,[(w/c)^{b}]*(t)^{c}+d(w/c)^{e}*(t)^{f}*(FA)^{g} \quad 3(b),\ 4(b),\ 5(b)$$

Where a, b, c, d, e, f and g were relationship factors achieved by analysis of multiple regression with method of least squares as illustrated in Table 4.

III. Comparison model predictions
Root Mean Square Error (RMSE) also Coefficient of determination (R^2) were quantified and applied as below:

$$R^2=[\Sigma i(Yi-\bar{Y})*(Xi-\bar{X})]/[\sqrt{\Sigma(Yi-\bar{Y})^2}*\sqrt{\Sigma(Xi-\bar{X})^2}] \quad (6)$$

$$RMSE = \sqrt{[(\Sigma i(Yi-Xi)/N]} \quad (7)$$

Where: Y_i: value of experimental observation; X_i: value of prediction (model); $\bar{Y}$: value of experimental (mean); $\bar{X}$: value of premeditated (mean) and N: number points of data.

Table 2: Model parameters for physical and mechanical properties relationship of concrete modified with fly ash

Vipulanandan correlation model (Eq. 1)										
Depended Variable (Y-axis)	**In depended Variable (X-axis)**	**Type of concrete**	**Y_o**	**A**	**B**	**RMSE** (MPa)	**R^2**	**No. of Data**	**Eq. No.**	**Fig. No**
Tensile strength, f_t (MPa)	Compressive strength, f_c\` (MPa)	Concrete modified with fly ash	0.8	14.2	-0.04	1	0.89	154	11(a)	8
Flexural strength, f_f (MPa)		Concrete modified with fly ash	2.6	30	-0.12	0.2	0.91	20	12(a)	9
Compressive strength, f_c\` (MPa)	Curing time, t (day)	Concrete modified with fly ash	15.6	0.3	-0.2	4.6	0.85	431	8	4

Table 2: Statistical variation of concrete modified with fly ash properties

	Statistical parameters	**w/c**	**Compressive Strength, f_c\` (MPa) (up to 90 days of curing)**	**Tensile strength, f_t (MPa)(up to 28 days of curing)**	**Flexural strength, f_f (MPa) (up to 28 days of curing)**
Concrete	No. of Data	96	292	36	25
	Range	0.25-0.55	6 – 114	1 - 9	3 - 9
	Mean (μ)	0.35	48.4	4.6	5
	Std. Deviation (σ)	0.053	23.05	1.8	1.5
	COV (%)	15.2	47.6	39.1	29.5
Concrete modified with fly ash	No. of Data	329	1001	120	58
	Range	0.24–0.53	6–115	1 - 9	3 - 10
	Mean (μ)	0.34	45.3	4.5	4.5
	Std. Deviation (σ)	0.05	23	1.8	1.5
	COV (%)	19	53.7	46	40.2

Table 3: Hoek-Brown correlation model parameters

Hoek-Brown correlation model parameters (Eq. 2)									
Depended variables (Y-axis)	In-depended variable (X-axis)	Type of concrete	C	D	E	F	RMSE (MPa)	R^2	No. of data
Tensile strength, f_t (MPa)	Compressive strength, f_c\` (MPa)	Concrete modified with fly ash	12	-0.89	0.0007	1	0.52	0.93	118
Flexural strength, f_f (MPa)		Concrete modified with fly ash	4.41	-0.94	0.51	1	0.86	0.85	37

Table 4: Statistical variation of Concrete modified with fly ash properties

	Model parameters	**Concrete type**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**RMSE (MPa)**	**R^2**	**No. of data**	**Eq. No.**	**Fig. No**
f_c\`	Concrete (FA = 0%)	NSC	9.8	-1.2	0.11	-	-	-	-	3	0.90	76	9(a)	6(a)
		HSC	13	-0.95	0.13	-	-	-	-	2.9	0.91	30	9(b)	6(a)
	Concrete modified with fly ash	NSC	10.1	-1.1	0.18	0.9	-0.32	0.48	0.16	3.6	0.83	251	10(a)	6(b)
		HSC	11.9	-0.8	0.15	0.8	-2.1	0.1	0.1	3.8	0.82	103	10(b)	6(b)

3. Results and Analysis

I: Water to cement ratio, (w/c)

1. Concrete without fly ash (FA)

According to the data from literature of w/c ratio of 96 for normal and high strength concrete (Table 1), for concrete the w/c ratio ranged of 0.25 - 0.5, mean of 0.35, standard deviation (SD) of 0.035 and coefficient of variation (COV) of 15.2 % which illustrated at Table 3 and Figure 1(a). More than 65 % of the total of w/c ratio was ranged between 0.3 and 0.4.

2. Concrete modified with fly ash (FA)

According to the data from literature of w/c ratio of 329 for normal and high strength concrete modified with FA (Table 1), for the concrete modified with FA the w/c ratio ranged of 0.24 –0.53, mean 0.34, SD of 0.07 and COV of 19% which illustrated at Table 3 and Figure 1(b).

II: Fly ash, FA (%)

Based on the overall of 425 data of FA content used to modify concrete, which collected from literature (Table 1), FA content ranged between 0 to 70 %, mean of 19 %, SD of 17 and COV of 93.2 %. In addition, Figure 2 shown histogram which was analyzed and presented practically 60% of the total of %FA ranged between 10 - 30 %.

III: Compressive strength (f_c`)

1. Concrete without fly ash (FA)

a) Normal strength concrete (NSC)

According to the compressive strength (f_c`) of 188 data from literature of normal and high strength concrete (without FA) of curing time up to 90 days (Table 1), $f_c$` data of concrete ranged of 6.8 - 55 MPa, mean 34 MPa, SD 12.1 MPa and COV 35.5% which illustrated at Table 3 and Figure 3(a).

b) High strength concrete (HSC)

According to the compressive strength (f_c`) of 104 data from literature for normal and high strength concrete (without FA) of up to 90 days of curing time (t) (Table 1), $f_c$` data of concrete ranged between 55 - 115 MPa, mean of 74.1 MPa, SD of 14.3 MPa and COV of 19.2% which illustrated at Table 3 and Figure 3(a).

2. Concrete modified with fly ash (FA)

a) Normal strength concrete(NSC)

According to the compressive strength (f_c`) of 688 data from literature of normal and high strength concrete modified with FA of curing time up to 90 days (Table 1), $f_c$` data for concrete modified with FA ranged 7-54 MPa, mean 31.5 MPa, SD 13.3 MPa and COV 42.1% which illustrated at Table 3 and Figure 3(b).

b) High strength concrete (HSC)

According to the compressive strength (f_c`) of 313 data from literature of normal and high strength concrete modified with FA of curing time up to 90 days (Table 1), $f_c$` data for concrete modified with FA ranged of 55-124.5 MPa, mean 75 MPa, SD 14.4 MPa and COV 19.2% which illustrated at Table 3 and Figure 3(b).

IV: Tensile strength (f_t)

1. Concrete without fly ash (FA)

a) Normal strength concrete (NSC)

According to the tensile strength (f_t) of 24 data from literature of normal and high strength concrete (without FA) of curing time up to 90 days (Table 1), f_t data for concrete ranged between 1.6-5.4 MPa, mean 3.6 MPa, SD of 1.2 MPa and COV of 29.5% which illustrated at Table 3.

b) High strength concrete (HSC)

According to the tensile strength (f_t) of 12 data from literature of normal and high strength concrete (without FA) of curing time up to 90 days (Table 1), f_t data for concrete varied from 5.5 to 9 MPa, mean 6.6 MPa, SD 1.1 MPa and COV 17.2% which illustrated at Table 3.

2. Concrete modified with fly ash (FA)

a) Normal strength concrete (NSC)

According to the tensile strength (f_t) of 92 data from literature of normal and high strength concrete modified with FA of curing time up to 90 days (Table 1), f_t data for concrete modified with FA varied from 1 to 5.3 MPa, mean 3.7 MPa, SD 2.6 MPa and COV 43.6% which illustrated at Table 3.

b) High strength concrete (HSC)

According to the tensile strength (f_t) of 28 data from literature of normal and high strength concrete modified with FA of curing time up to 90 days (Table 1), f_t data for concrete modified with FA ranged of 5.6 - 9.1 MPa, mean 7 MPa, SD 1.4 MPa and COV 17.1% which illustrated at Table 3.

V. Flexural strength (f_f)

1. Concrete without fly ash (FA)

According to the tensile strength (f_f) of 25 data from literature of normal and high strength concrete of curing time up to 90 days (Tables 1), f_f data for concrete ranged of 3-9 MPa, mean 5.0 MPa, SD 1.5 MPa and COV 29.5% which illustrated at Table 3.

2. Concrete modified with fly ash (FA)

According to the tensile strength (f_f) of 58 data from literature of normal and high strength concrete modified with FA of curing time up to 90 days (Table 1), f_f data for concrete modified with FA ranged of 3 to 10 MPa, mean 4.5 MPa, SD 1.8 MPa and COV 40.2% which illustrated at Table 3.

4. Suggested Relationships

I: Relationship between compressive strength (f_c\`) and curing time (t), for normal and high strength concrete

More than 430 data m literature of NSC and HSC modified with FA of curing time (t) up to 90 days, to investigate the correlation between f_c\` and t by using model of Vipulanandan (Eq.1) which explain at Figure 4.

f_c\` = 15.6+t/(0.3-0.2t) (8)

(R^2=0.85, Number of data = 431)

The model factors Y0, A, B, R^2 and RMSE were 15.6, 0.3, 0.2, 0.85 and 4.6 MPa respectively, which illustrated at Table 4.

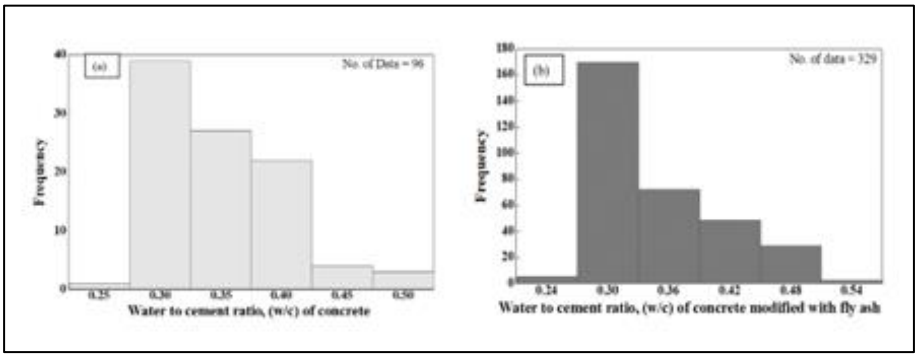

Figure 1: Histogram for (w/c) ratio of (a) concrete and (b) concrete with fly ash

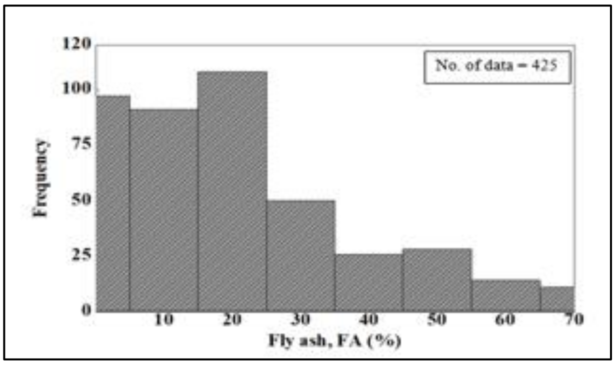

Figure 2: Histogram of percent of fly ash, FA (%) added to the concrete

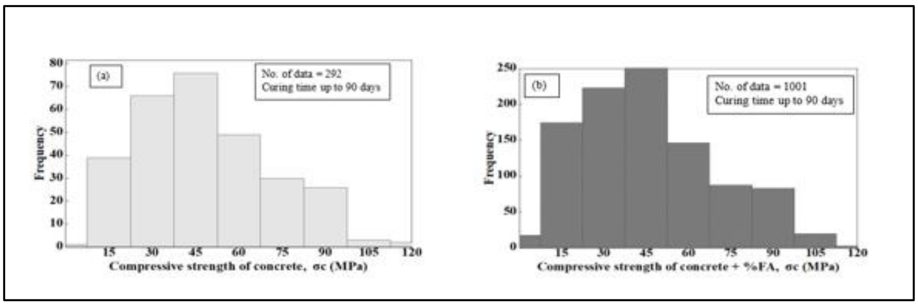

Figure 3: Histogram of compressive strength (f_c\`) of (a1) concrete and (b) concrete modified with FA

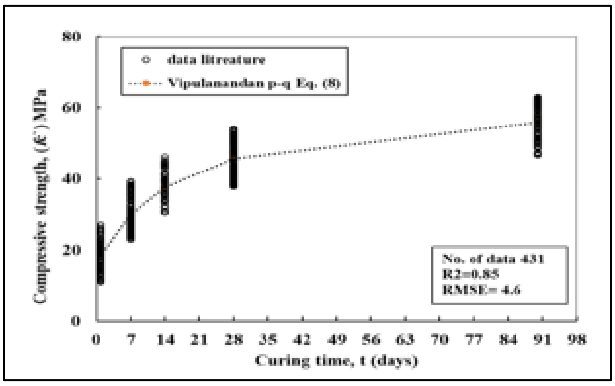

Figure 4: Relationship between the compressive strength and curing time of concrete modified with fly ash (FA)

II: Relationship between compressive strength (f_c\`) and water to cement ratio (w/c) for normal and high strength concrete modified with fly ash

More than 420 data from literature of NSC and HSC modified with FA of curing time (t) up to 90 days. There were weak relationships between the f_c\` and w/c ratio, up to 90 days of curing which explained at Figure 5.

III: Relationship between measured and predicted compressive strength (f_c\`)

1. Concrete without fly ash (FA)

Correlation between f_c\`, w/c ratio and up to 90 days of curing time was slightly practical, $f_c$\` was related to variables (independent) such as curing time (t) and w/c ratio by apply of non-linear (NLM) Eq. 3(a). Factors model was obtaining by analysis of multiple regression applying method of least square which illustrated at Table 4.

According on nonlinear model parameter (NLM) (Eq. 5(a)) f_c\` of concrete was influenced by w/c ratio more than t because the power of w/c ratio was more than the power of curing time as shown at Eq. 9 (a and b). The model parameters of NSC and HSC, R^2 and RMSE are illustrated at Table 4 and Figure 6(a).

For NSC

$$f_c`=9.8(t)^{0.11}/[(w/c)^{1.2}] \quad 9(a)$$

(R^2= 0.90, Number of data = 76)

For HSC

$$f_c`=13(t)^{0.13}/[(w/c)^{0.95}] \quad 9(b)$$

(R^2= 0.91, Number of data = 30)

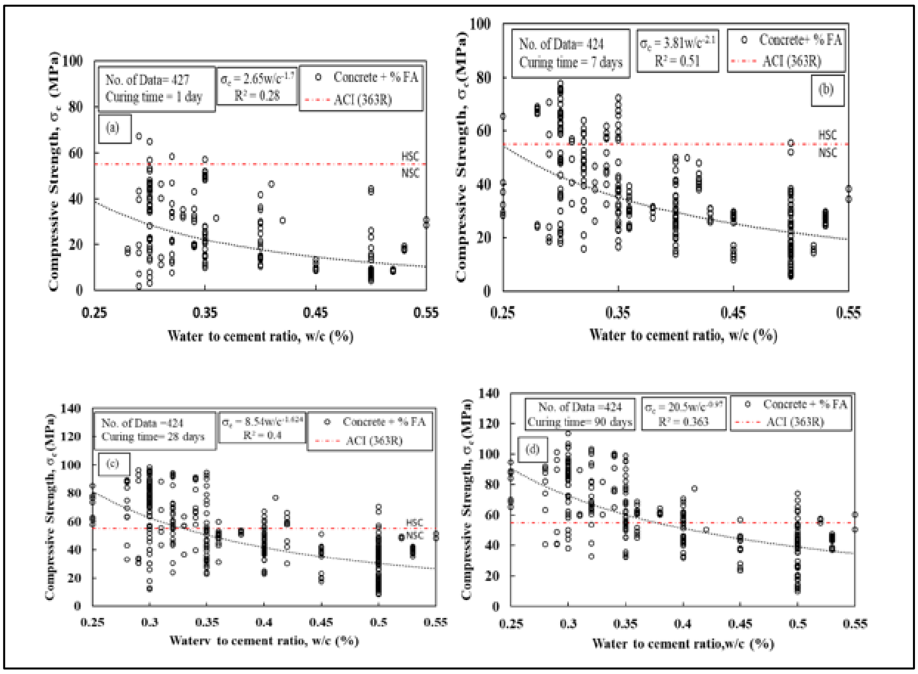

Figure 5: Correlation of compressive strength (f_c\`) and water- cement ratio (w/c) for concrete modified with FA at curing time (a)1, (b) 7, (c) 28 and (d)90 days

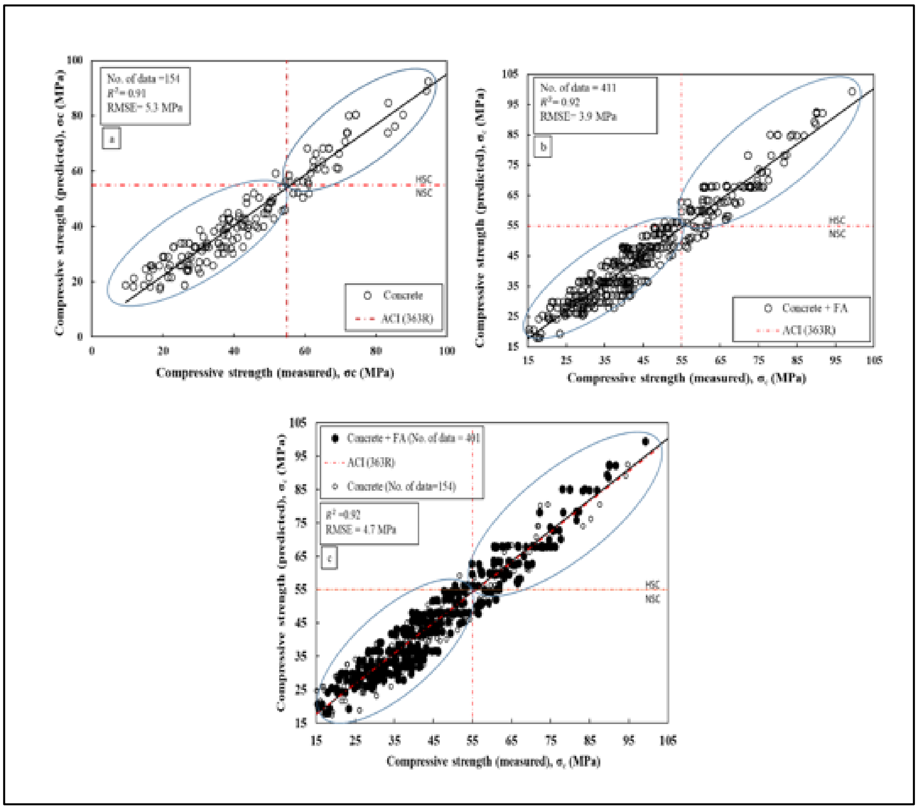

Figure 6: Relationship of predicted and measured the compressive strength (f_c\`) of NSC) and HSC (a) concrete (b) concrete modified with FA and (c) concrete + concrete modified with FA

IV: Relationship of compressive strength (f_c\`) and percent of FA (%FA)

Further than 400 data from literature of concrete modified with FA of curing time (t) up to 90 days. There were slightly correlations of f_c\`, w/c ratio and %FA for up to 90 days of curing time which explain in Figure 7.

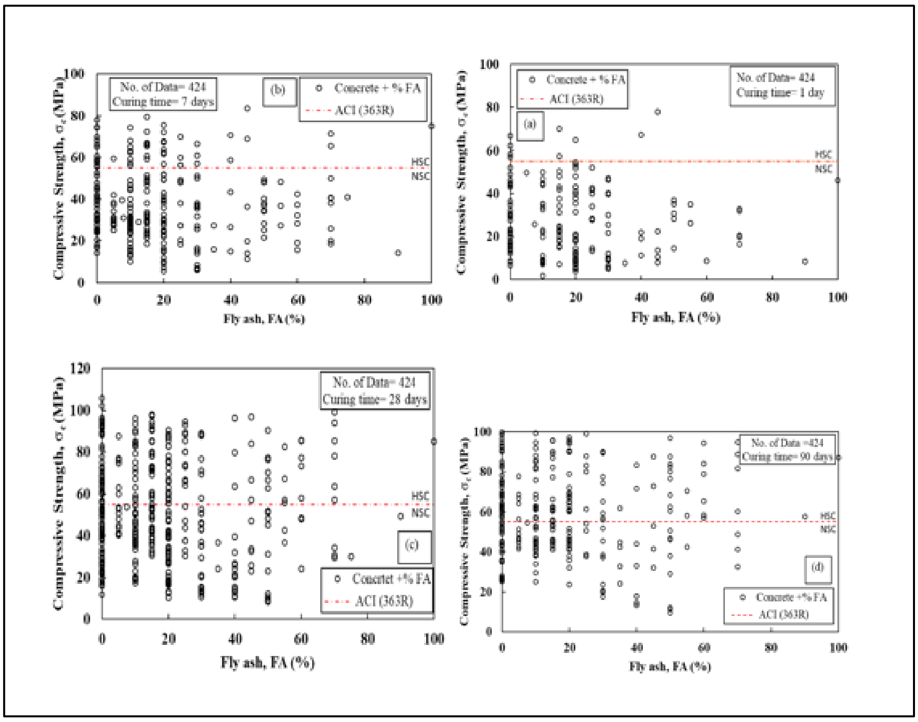

Figure 7: Relationship of compressive strength (f_c\`) of concrete modified with FA and percent of FA at different curing time (a) 1day, (b) 7 days, (c) 28 days and (d) 90 days

V: Relationship of compressive strength (f_c\`) and tensile strength (f_t)

Further than 150 data from literature of concrete modified with FA of curing time (t) up to 90 days (Table 2) to inspect the relationship of f_c\` and $f_t$ by applied Eq. 1 which explained in Figure 8. Vipulanandan correlation model, model factors Yo, A, B, $R^2$ and RMSE were 0.8, 14.2, 0.04, 0.96 and 0.2 MPa, respectively which illustrated at Table 2. According to $R^2$ also RMSE, Vipulanandan model predicted the correlation of $f_c$\` and ft of concrete modified with FA actual close to model of Hoek-Brown which shown at Figure 8.

Vipulanandan correlation:

f_t=0.8+ f_c\` / (14.2 - 0.04 $f_c$\`) 11(a)

(R^2= 0.96, Number of data = 154)

Hoek-Brown:

f_t=f_c\` -12* [(-0.9/-12) $f_c$\`+0.0007] 11(b)

(R^2= 0.93, Number of data = 118)

VI: Correlation between compressive strength (f_c\`) and flexural strength (f_f)

Further than 46 concrete modified with FA data were collected from literature. To inspect relationship of f_c\` and f_f was denoted by applying Vipulanandan correlation Eq.1 with Hoek-Brown models Eq.2 and compared to each other which explained at Figure 9. Vipulanandan correlation and the factors modelsY_o, A, B, R2 and RMSE were 2.7, 29.8, -0.1, 0.91 and 0.2 MPa respectively, which illustrated at Table 2. f_f of concrete modified with FA improved between 4 - 8 MPa when the f_c\` improved between 20 - 50 MPa for concrete modified with FA. According to $R^2$ also RMSE, Vipulanandan model predicted the correlation of $f_c$\` and f_f of the concrete modified with FA actual close to the Hoek-Brown model Figure 9.

Vipulanandan correlation:

f_f=2.6+ f_c\` / (30 - 0.12 $f_c$\`) 12(a)

(R^2=0.95, Number of data= 46)

Hoek-Brown:

f_f =f_c\` +4.41* [(-0.94/-4.41) $f_c$\` +0.51] 12(b)

(R^2= 0.85, Number of data = 37)

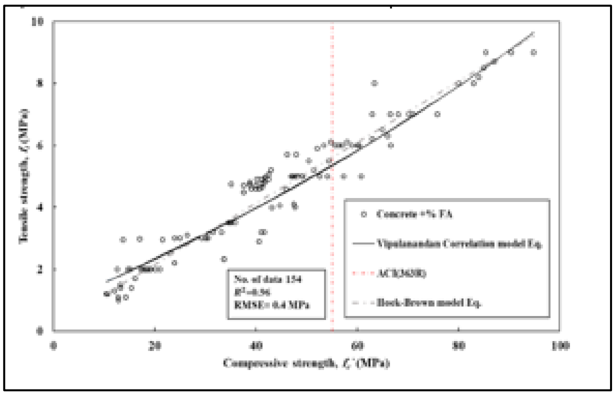

Figure 8: Relationship between tensile and compressive strength of concrete modified with fly ash

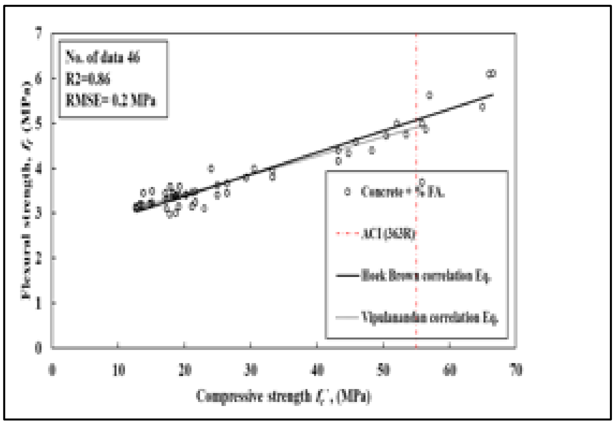

Figure 9: Relationship between flexural and compressive strength of concrete modified with fly ash

4. Conclusions

Based on further than one thousands of data were collected from literature and models, are observed:

1. The statistical analyses obviously explain the difference between concrete and concrete modified with FA for both NSC and HSC, water to cement ratio, compressive strength, tensile strength and flexural strength were investigated. The variation in the properties was quantified based on the coefficient of variation.
2. Based on modeling and statistical analysis the content of FA ranged of (3-70) % by w cement weight (dry). Farther more, further of FA had slightly affected much for increasing compressive (f_c`), tensile (f_t) and flexural (f_f) strengths of NSC and HSC modify with FA.
3. There was a good correlation of the f_c` and w/c ratio, curing time up to 90 days for concrete by applying Vipulanandan correlation model while, there were no correlations between the compression strength and water to cement ratio (w/c) ratio, curing time up to 90 days for concrete modified with FA.
4. There was a worthy correlations detected of measured and predicted compressive strength which influenced by w/c ratio, %FA and curing time up to 90 days by applying Vipulanandan model.
5. There was a worthy relationship between the compression strength (f_c`) with both tensile (f_t) and flexural (f_f) strengths by using Vipulanandan correlation model and Hoek-Brown model.
6. No relation was obtained between fly ash content with early age of compressive strength of normal and high strength concrete.
7. Compressive strength can be calculated by applying the models constructed with this methodology. There is useful and easy to apply these models for numerical experiments to predict the effects all variable together or separate such as w/c ratio, t and %FA.

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