Research Article

# Experimental Investigation and Prediction of Compressive Strength of HPC with SCMs

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## Abstract

Due to environmental concern, the use of supplementary cementitious materials (SCMs) is increasing at a high rate in construction industry. In this study, an experimental investigation has been carried out to assess the compressive strength of high performance ternary mix concrete with judicious replacement of cement with (SCMs), which include industrial waste products such as fly ash (FA), ground granulated blast furnace slag (GGBS) and micro silica. Replacement of cement was done up to 40%, 45%, 50%, by incorporating P100 fly ash as an ultrafine material with GGBS as SCMs. Each replacement was further divided into three sub parts (40%F. A-60%GGBS), (45%F.A-55%GGBS) and (50%FA-50%GGBS). Experimental results showed that Mix T3 (60%Cement-20%F.A-20%GGBS) produced maximum strength of 89.4 MPa and 100 MPa at 14 days' and 28 days' curing respectively. Experimentally generated data in the laboratory was used for the development of the multiple linear regression models.

**Keywords:** Cement; P100 fly ash; FA; GGBS; HPC; Compressive Strength

## Introduction

In construction industry, concrete is considered as the most widely used building material due to its immense benefits in various applications and different forms, (Ramezanianpour and Esmailpour 1991).Therefore, a necessary action for minimizing the harmful effects of cement and concrete production as well as its consumption is very much important, (Ramezanianpour 1998, ACI1992).The judicious use of common Supplementary Cementitious Materials (SCMs) like Fly Ash (FA), Silica Fumes (SF), and Ground Granulated Blast Furnace Slag(GGBS)which are industrial by products of thermal power station, electric arc furnaces and steel plant respectively, plays vital role in the production of concrete. Use of these materials with Ordinary Portland Cement (OPC) reduces cost of concrete, improves early age strength and durability of concrete. Also the use of Silica flumes reduces the maintenance cost of concrete structure and its service life. Therefore, many researchers, (Bull and Acker 1985, Nasser and Al-Manaseer 1986,Banthia 1988, Banthia *et al.* 1992, Al-Khaja 1994, Mokhtarzadeh and French 2000, Huo *et al.* 2001, Langan *et al.* 2002, Mozloom *et al.* 2004, Pala *et al.* 2007, Kovler and Roussel 2011, Deschner *et al.* 2012), have worked on this complex problem to find an appropriate concrete mix using different alternative cementitious materials.

Further, the use of these SCMs also reduces the influence of shrinkage, creep, and improves the durability and other properties of HPC at both the mechanical and at the micro structure level. Furthermore, use of such SCMs in concrete helps in preventing environmental degradation by reducing emissions of carbon dioxide $CO_2$, (Langan *et al.* 2002,Kovler and Roussel 2011, Deschner *et al.*2012).

As per an estimate of Fly Ash Utilization Program (FAUP) and Technology Information Forecasting and Assessment Council (TIFAC, India), the annual fly ash generation figures were 170million tons till 2012 andexpected to reach about 225

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million tons by 2017. In order to reduce the effects of these superfluous sources on the environment, it is necessary to study its physical, chemical and engineering properties and put to proper use so thatit becomes a resource rather than undesirable waste material, Rai *et al.* (2010).It is also observed that, useof FA for partial replacement of cement is limited up to 30% of total cementitious materials, (Dual and Kadri 1988, ACI 2002).

The use of fly ash in concrete can reduce the consumption of natural resources and also diminish the effect of pollutant in environment, Harison *et al.*(2014). Fly ash improves the performance and quality of concrete. Fly ash affects the plastic properties of concrete by improving workability, reducing water demand and reducing heat of hydration. The quaternary blend concrete solves problem of bleeding with ultrafine slag and decreases workability with Micro Silica, Patel and Sheth (2014).

Similar work was carried out Jatale *et al.* (2013), where authors have studied, various properties of fly ash concrete to develop the mix design curves for concrete mix proportioning with various percentages of fly ash. Based on study, authors have concluded that the use of fly ash improves the workability of concrete, reduces the bleeding in concrete significantly and also improves other properties like cohesiveness, pumping characteristics and surface finish.

Various studies were carried out by researchers like (Dual and Kadri 1988, ACI 2001a) and they found that the higher content of FA (>30%) is not beneficial for long-term strength development in concrete. It was observed that, Haque (1996) more than 20% replacement of cement by FA or GGBS increased the shrinkage strain substantially. The use of GGBS produces initially lower heat of hydration than OPC cement therefore; additional OPC cement/alkali salt/lime is used to increase the heat of hydration in concrete, ACI (2008).The use of Ground Granulated Blast-Furnace (GGBF) Slag in the production of blended cements began in 1905 in the United States. Use of GGBF slag as a separate cementitious material along with Portland cement in the production of concrete was also reported, ACI (2000).The literature reports that, partial replacement of cement by GGBS may be as high as 40-50% without significant reduction in compressive strength of concrete, ACI (2002). However, the problems associated with higher dosage of GGBS in concrete mix may produce low heat of hydration thereby slowing the rate of gain of compressive strength, ACI (2001a). It was reviewedthat concrete (Hamling and Kriner 1992) with GGBS has lowered the early strengths because the rate of initial reaction of GGBS is slower than that of Portland cement. Therefore, GGBS is generally grounded to a finer state than Portland cement. Authors also reported that, as the fineness of GGBS increased from around 4000 $cm^2/g$ to 6000 $cm^2/g$, the 28 days' strength increased significantly. It was reported, Lane and Ozyildirum (1999) that the early strengths (up to 28 days) of concrete mixes (with 25%, 35%, 50%, and 60% GGBS replacements) were lower than that of Portland cement concrete mixes. But by 56 days, the strength of 50% and 60% GGBS mixes exceeded that of the Portland cement mix and also by one year, all the GGBS mixes were stronger than Portland cement mixes.

Gadpalliwar (2014) was partially replaced Cement by GGBS (10%, 20% and 30%) and it was concluded that, by adopting same critical mix and replacing cement by GGBS with the said percentages, workability increases but strength decreases. Anexperimental investigation was carried out by, Audinarayana *et al.* (2013) for the optimization of a Ternary Blended Cementitious system based on OPC / Fly Ash / Micro Silica for the development of high performance concrete and concluded that the combination of Micro Silica and Fly Ash is complimentary in which Micro Silica improves the early age performance of concrete and Fly Ash continuously refines the properties of hardened concrete as it matures.Recent study has been carried out, Mansur (2012) to evaluate compressive strength and sulphate resistance properties of concrete by partially replacing class C and class F fly ash.

Moreover, regardless of the type, the addition of fly ash significantly increases the resistance to sulphate attack. Experimental investigations have been carried out, Uysal (2012) on class C and class F Fly Ash and 39 different concrete mix designs were prepared. The results indicated that the use of class C and class F fly ash positively affected freezing and thawing resistance of concrete, class C fly ash also showed higher compressive strength than class F fly ash. In the recent study, Durham (2012) a method to optimize the cement and fly ash contents in concrete on the basis of the hardened concrete properties in which nine concrete mixtures with fly ash contents ranging from 15-60% and cementitious material contents from 338-391 $kg/m^3$ were investigated. The optimized concrete mixture exhibited excellent characteristics in compressive strength (32.0 MPa at 28 days).

An extensive experimental study has been carried out by Hassan and Sayed (2013) to develop a high-performance self-consolidating concrete containing high volumes of supplementary cementitious materials, which significantly lowered concrete permeability compared to that of the controlled mixture. The effect of high-calcium fly ash in combination with finely ground limestone as cement replacement on cement's hydration characteristic is studied, Thongsanitgarn *et al.* (2014) where in 28 days curing results showed that, the hydration reaction of cement containing fly ash accelerated when limestone powder was incorporated. It was observed that, Gedam *et al.* (2015) partial replacement of OPC by cementitious materials like FA and

GGBS better addresses the issue of sustainability, more environmental friendly construction, and better durability and thus significantly improves life-cycle performance of built infrastructure in HPC concrete.

Statistical compressive strength prediction model was developed by, Nipatsat and Tangtermsirikul (2000) which take into account the effect of CaO content in the mixture, water binder ratio and paste cement content to void content of the compacted aggregate phase for 28 days' compressive strength using fly ash with various chemical compositions. The relationship between two or more independent variables and a dependent variable has been established by, Li Chen (2010) by fitting a linear equation to observed data. Every value of the independent variable is associated with a value of the dependent variables.

Regression models were proposed by, Kazberuk and Lelusz (2006) to predict compressive strength of concrete with fly ash replacement percentages up to 30%. Also various regression equations were proposed, Namyong *et al.* (2006) for predicting compressive strength of in-situ concrete. Authors selected principal factors that influence compressive strength of concrete using correlation analysis. The regression equations are proposed for 7 days' and 28 days' compressive strength taking water-cement ratio, cement content and cement-aggregate ratio as independent variables. Authors investigated, Islam *et al.* (2015) the effect of time-dependent mineralogical changes on the unconfined compressive strength (UCS) behavior of lime–ground granulated blast furnace slag (GGBS) treated naturally occurring acid sulfate soils (ASS) containing various proportions of pyrite.

Rachna *et al.* (2015) has been developed, 18 linear and 18 quadratic models for predicting compressive strength of concrete. The data set that has been used in the development of these models was generated in controlled laboratory conditions. The best prediction with a coefficient of determination has been obtained for the case of 56 days' strength of concrete with zone A of aggregates with fly ash. Mathematical regression models were developed, Abd *et al.* (2008) for compressive strength of Portland cement for curing ages 7 and 28 days. Authors have also proposed the models for compressive strength prediction of all types of concrete, especially, foam concrete for curing ages of 28 days and 365 days and concluded that proposed model yielded good correlation coefficients for both sets of data in predicting compressive strength of foam concrete.

Numerical procedure was presented by, Wang and Park (2016) to evaluate the strength development and carbonation depth of High-Volume Fly Ash (HVFA) concrete in which hydration model was used to predict the reaction degree of fly ash, CH contents, phase volume fractions, and calcium silicate hydrate contents of hardening cement-fly ash blends.An effort was made, Ghazy *et al.* (2016) to develop Nano-modified fly ash concrete as a repair material for concrete pavements. The performance of the newly developed mixtures was compared to that of two commercial cementitious products. The results indicate that the Nano-modified fly ash concrete has balanced performance in terms of hardening time, strength development and bonding with the substrate concrete.

It is evident from past studies that significant amount of work has been carried out on ternary mix concrete, in which cement was replaced with Fly ash, GGBS, Micro silica, Alco fine, Rice Husk Ash etc. It is also observed from literature that in ternary mix concrete the level of replacement of cement with SCMs was restricted to 35%-40% only. No literature is available indicating the replacement by more than 40% cement with SCMs. Moreover, it is found that micro silica was used as ultra-fine material to achieve optimum packing density. But micro silica is the costliest material in ternary mix concrete. It retards workability appreciably and increases the dosage of super plasticizer (Patel and Sheth 2014, Audinarayana 2013, Manju 2014, Hariharan and Santhi 2011).

## Research Significance

Today, supplementary cementitious materials (SCMs) are widely used in concrete either in blended cements or added separately in the concrete mixer. The use of SCMs such as Fly Ash (FA) or Ground Granulated Blast Furnace Slag (GGBS) is a viable solution to partially substitute portland cement. The use of such materials, where no additional clinkering process is involved, leads to a significant reduction in $CO_2$ emissions per ton of cementitious materials. Most of the past studies on ternary blend concrete have been carried out in which cement was replaced with GGBS, FA or Micro Silica. But, Micro Silica is the costliest material in ternary blend concrete which is generally used as ultra-fine material to achieve optimum packing density. In this research, a new ultra-fine material P100 Fly Ash is used. It is nearly of the same size as Micro Silica. The replacement of cement is tried up to 50%. This P100 fly ash material has been introduced in recent times wherein very few literatures and experimental data are available on it.Systematic study has been carried out on replacement of cement with P100 fly ash and GGBS with their effect on compressive strength in ternary mix concrete and also to evaluate the influence of high volumes of SCMs on the properties of HPC.In this study, an attempt is also made to develop multiple regression models to predict compressive strength of concrete for various mixes and their performance is measured with performance measure indicators.

## Materials

In view of the proposed experimental study, the materials such as Fly Ash, GGBS, Superplasticizers, Ordinary Portland

Cement, Aggregates (Metal 10, Metal 20) and Crushed Sand were used.

### Fly Ash

The fly ash was procured from *Ambuja Cement Limited, Andheri*, Mumbai, Maharashtra (India) which was supplied to them by *Dirk India Private Limited, Eklahare Nasik Maharashtra (India)*. The fly ash used in the investigation is Ultra-fine (Pozzocrete P100) fly ash. The chemical composition and physical properties of the Ultra-fine fly ash obtained from the suppliers are shown in Table1.

**Table 1.Physical properties and Chemical composition of Ultra-fine fly ash**

| **Chemical composition** | | **Physical properties** | |
|---|---|---|---|
| Constituents | Weight % | Presentation | Finely divided dry powder |
| Silicon dioxide ($SiO_2$) | 50 | Colour | Greyish White |
| Calcium oxide (CaO) | 5.5 | Bulk Weight | 0.65 tonne/ $m^3$ |
| Magnesium oxide (MgO) | 4.5 | Specific Density | 2.3 |
| Sodium oxide ($Na_2O$) | 2 | Loss of Ignition | <2.5 % |
| Sulphur oxide ($SO_3$) | 1.5 | Particle Size | Zero retention on 45μ sieve, <0.25 % retained on 25μ sieve |
| | | Particle Shape | Spherical |

### GGBS

The GGBS was procured from *JSW Steel Pvt. Ltd.* The chemical composition and physical properties of the GGBS obtained from the suppliers are shown in Table 2.

**Table 2.Chemical composition of GGBS**

| **Constituents** | **Weight % GGBS** |
|---|---|
| CaO | 30-45 |
| $SiO_2$ | 30-38 |
| $Al_2O_3$ | 15-25 |
| $Fe_2O_3$ | 0.5-25 |
| MgO | 4-17 |
| Glass | 85-98 |
| Specific gravity | 2.9 |

### Ordinary Portland cement

The cement used in the said investigation comprised of Ordinary Portland Cement (Ultratech Cement of 53 Grade) which was made available by local supplier from Panvel (Maharashtra, India). The chemical composition and physical properties of the OPCobtained from the suppliers are shown in Table 3.

**Table 3.Characteristics of Cement**

| **Normal Consistency (IS:4031 Part IV)** | |
|---|---|
| Required Water for Normal Consistency | 110ml |
| % of Normal Consistency | 27.5% |
| Setting Time (IS:4031 Part V) | |
| Initial setting Time | 150 Min (Maximum 30 Min) |
| Final Setting Time | 225 Min (Maximum 600 Min) |
| Specific Gravity (IS:4031 Part II) | 3.14 |
| Specific Surface (Fineness) (IS:4031 Part II) | 310.83 (Maximum 225 cm2/gm) |
| Compressive Strength | |
| 3 Days | 27 MPa |
| 7 Days | 37 MPa |
| 28 Days | 53 MPa |

### Superplasticizers

The superplasticizer used, namely Master Glenium SKY8233, was procured from BASF Pvt. Ltd. Turbhe, Mumbai, Maharashtra (India). The superplasticizer used is Polycarboxylic based High Range Water Reducing (HRWR) Admixture.

### Coarse Aggregates

Coarse aggregates of 20 mm and 10 mm nominal size having specific gravity of 2.79, confirming to (IS: 383-1970) was used in this investigation.

### Fine Aggregates

Crushed sand of zone-II having specific gravity of 2.74, confirming to(IS: 383-1970) was used in this investigation.

## Methodology

The present study involves a series of various tests performed on different materials to arrive at certain physical properties. The various experimental tests that were conducted during the present study includespecific gravity of aggregates and crushed sand, water absorption of aggregates and crushed sand as well as compressive strength of concrete. Concrete mixes of grade M100 were made using OPC. The details of the concrete mix design are given in Table 4. Replacement of cement was made using SCMs, namely Fly Ash and GGBS at 40%, 45% and 50%. These replacements were further divided into ratios of (40:60), (45:55) and (50:50) for Fly ash and GGBS respectively. The concrete mixes were tested for compressive strength at 3 days, 7 days, 14 days and 28 days of curing. The concrete mixes for the present study comprised of ordinary portland cement concrete and nine mixes of fly ash and GGBS concrete mixes to investigate their effect on compressive strength. After several trials, cement content of 650 kg/m$^3$and water-binder ratio of 0.24 were finalized based on 28 days' compressive strength gain of HPC mix and desired workability properties (slump flow). Thus, for making HPC mixes the mix proportion was finalized as follows.

- Cement (Binder) content - 650 kg/m$^3$
- Water/Binder ratio- 0.24
- Fine aggregates- 695 kg/m$^3$
- 20 aggregates- 735 kg/m$^3$
- 10 aggregates- 246 kg/m$^3$
- Water- 156 kg/m$^3$
- Chemical admixture- 0.9%
- Aggregate/Binder ratio- 2.58

**Table 4.Mix proportions of concrete mixes**

| Mix No. | Proportions (%) | | | Cement(kg) | FA (kg) | GGBS (kg) | Water (kg) | w/c ratio |
|---|---|---|---|---|---|---|---|---|
| | OPC | FA | GGBS | | | | | |
| N1 | 100 | 0 | 0 | 650 | 0 | 0 | 156 | 0.24 |
| T1 | 60 | 16 | 24 | 390 | 104 | 156 | 130 | 0.2 |
| T2 | 60 | 18 | 22 | 390 | 117 | 143 | 130 | 0.2 |
| T3 | 60 | 20 | 20 | 390 | 130 | 130 | 130 | 0.2 |
| T4 | 55 | 18 | 27 | 357.5 | 117 | 175.50 | 130 | 0.2 |
| T5 | 55 | 20.25 | 24.75 | 357.5 | 131.63 | 160.87 | 130 | 0.2 |
| T6 | 55 | 22.5 | 22.5 | 357.5 | 146.25 | 146.25 | 130 | 0.2 |
| T7 | 50 | 20 | 30 | 325 | 130 | 195 | 130 | 0.2 |
| T8 | 50 | 22.5 | 27.5 | 325 | 146.25 | 178.75 | 130 | 0.2 |
| T9 | 50 | 25 | 25 | 325 | 162.5 | 162.5 | 130 | 0.2 |

## Preparation of HPC

The required quantities of all the ingredients were taken by weigh batching. Mixing of the ingredients was done in a pan mixer as per the standard procedure. A reference mix was prepared using a water-binder ratio of 0.24 and suitable super plasticizer content was added in order to get desired workability. The workability of the concrete was studied by conducting slump flow tests as per the standard procedure. Standard cube specimens of 150mm x 150mm x 150mm size were cast using the procedure described (IS: 516-1959). Cubes were immediately covered with plastic sheet and kept there for 24 hours and then placed in water tank for curing. All the HPC mixes were prepared using the same mix proportion and water-binder ratio and considered for study of workability and strength properties. For each of concrete mixes, 15 concrete cubes were cast for strength tests. All the concrete cubes were de-molded within 24 hours of casting. The cubes cast were stored in the same curing environments and for varying durations. The cubes were then removed from curing tank in accordance to their curing ages. They were surface dried by air drying. The cubes were then placed carefully in the Concrete Testing Machine (CTM) and tested at a pace rate of 5kN/sec.The compressive strength of the cubes was determined using CTM of 3000 KN capacity in accordance with the procedures laid down (IS: 516-1959). For each mix, sets of three cubes were cast and cured. These were then tested at each of the following test ages: 3 days, 7 days, 14 days and 28 days.

## Tests Conducted

The observations of the various tests that were conducted such as sieve analysis, dry loose bulk density (DLBD), water absorption test of sand and aggregates, determination of specific gravity of sand and aggregates and compressive test of concrete have been analyzed and the behavior is studied. The results of the analysis are discussed in the subsequent sections.

### Sieve Analysis

This is the mean given to the operation of dividing a sample of crushed sand into various fractions, each consisting of particle of the same size. The sieve analysis is conducted to determine the particle size distribution in a sample of crushed sand, which iscalled as gradation.The result of sieve analyses for the sand used in the present experimental investigation is given in Table 5. From the above results it has been observed that the fineness modulus of the sample lies between 2.6-2.9 (Zone II). The sand is medium sand (IS: 2386 Part I-1963).

**Table 5.IS Sieve Analysis of Crushed Sand**

| Sieve | Average Weight (gm) | Percentage retained | Cumulative % retained | Cumulative % passing |
|---|---|---|---|---|
| 4.75 mm | 15.18 | 1.518 | 1.518 | 98.482 |
| 2.36 mm | 219.1 | 21.91 | 23.428 | 76.572 |
| 1.18 mm | 238.2 | 23.82 | 47.248 | 52.752 |
| 600 µ | 137.2 | 13.72 | 60.968 | 39.032 |
| 300 µ | 90.7 | 9.07 | 70.038 | 29.962 |
| 150 µ | 84.6 | 8.46 | 78.498 | 21.502 |
| pan | 215.02 | 21.502 | 100 | 0 |

### Dry Loose Bulk Density (DLBD)

Dry loose bulk density is the ratio of weight of dry aggregate to the total aggregate volume. The result of the *DLBD* of the aggregate sample used in the present experimental investigation is given in Table 6. From the above observations, best combination is 75% of 20 mm aggregate and 25% of 10 mm aggregate and hence the same combination is applied throughout the whole experimental procedure.

**Table 6.DLBD for Coarse aggregate**

| Sample | Percentage of CA-I (20 mm) | Percentage of CA-II (10 mm) | DLBD (kg/m³) |
|---|---|---|---|
| 1 | 100 | 0 | 1487 |
| 2 | 75 | 25 | 1585 |
| 3 | 50 | 50 | 1533 |
| 4 | 25 | 75 | 1543 |
| 5 | 0 | 100 | 1500 |

## Multiple Regression Analysis

MLR is the simplest and well developed representation of a casual, time invariant relationship between an input function of time and corresponding output function Chau et al. (2005). Linear regression attempts to model the relationship between two variables by fitting a linear equation to observed data. One variable is considered to be an explanatory variable, and the other is considered to be a dependent variable.MLR attempts to model the relationship between two or more independent variables and dependent variables by fitting a linear regression equation to observed data. If it is assumed that the dependent variable y is affected by independent variables $X_1,X_2,....,X_m$ and a linear equation is selected for the relation among them, the regression equation of y can be written as:

$$y=a+b_1 x_1+b_2 x_2+...+b_m x_m \quad \textbf{(1)}$$

"y" In this equation shows the expected value of the variable y when the independent variables take the values;

$X_1= x_1$, $X_2 =x_2,....,X_m = x_m$.

The regression coefficients,$b_1,b_2,....,b_m$ are evaluated, similar to simple regression, by minimizing the sum of the distances of observation points from the $e_{yi}$ plane expressed by the regression equation (Bayazit and Oguz 1988).

$$\sum_{i=1}^{N} e_{yi}^{2}=\sum_{i=1}^{N}(y_i-a-b_1 x_{1i}-b_2 x_{2i}-b_m x_{mi})^2 \quad \textbf{(2)}$$

In this study, the coefficients, are determined using least squares method.

### Model Assessment

To examine and assess how close the experimental results and predicted compressive strength of HPC mixesare three performances indices i.e. Correlation Coefficient, Mean Square Error and Mean Absolute Error have been evaluated by using performance measures.

### Correlation coefficient (R)

The correlation coefficient, R, measures the degree of linear association between the target and the realized outcome and it is a measure to know how far the trends in forecasted values follow those in actual observed values and it is a number between. Higher the correlation coefficient better is the model fit. The following formula was used to find the correlation coefficient (R):

$$R = \frac{\sum_{t=1}^{N}[fc_{est}(t)-\overline{fc_{est}}][fc_{pred}(t)-\overline{fc_{pred}}]}{\sqrt{\sum_{t=1}^{N}[fc_{est}(t)-\overline{fc_{est}}]^2[fc_{pred}(t)-\overline{fc_{pred}}]^2}} \tag{3}$$

Where,

$\overline{fc_{est}}$ = Mean Estimated Strength, $\overline{fc_{pred}}$ = Mean Predicted Strength

The values of *R* close to 1.0 indicate good model performance.

$$MSE = \frac{\sum_{i=1}^{N}[fc_{pred}(t)-fc_{est}(t)]^2}{N} \tag{4}$$

### Mean square error (MSE)

Mean Square Error is defined as the average of the square of the difference between the actual observations and the response predicted by the model. MSE is a function of the quality of the actual observations and the response predicted by the model. It is a measure of the statistical dispersion of the predicted response with respect to the desired response. The value of MSE close to zero indicates better model performance.

### Mean absolute error (MAE)

The mean absolute error has the advantage that it does not distinguish between the over and underestimation and does not get too much influenced by higher values. It is generally engaged in addition to RMSE to get the average error without worrying about the positive or negative sign of the difference. Lower the value of MAE, better is the forecasting performance. The following formula is used to compute MAE:

$$MAE = \frac{\sum_{i=1}^{N}|fc_{pred}(t)-fc_{est}(t)|}{N} \tag{5}$$

## Results and Discussions

Table 7 shows mix proportions of SCMs and 3 days', 14 days' and 28 days' mean compressive strength for all the mixes. From Table 7, it has been observed that Mix T3 (60% cement-20% fly ash-20% GGBS) is producing maximum strength of 89.4 MPa and 100 MPa at 14days' and 28 days' curing respectively. The reason for producing higher strength may bedue tosmaller particle size and higher specific surface area of mineral admixtures, which are favorable to produce highly dense and impermeable concrete. However, to increase workability and reduce water demand, Master Glenium (Superplasticizer) is added. From Table 7, it can also be seen that, in case of mix T8, there is substantial saving of quantity of cement in 50% replacement (50% Cement-22.5% Fly Ash -27.5% GGBS), Strength achieved was 94 MPa.

**Table 7.Compressive Strength Results**

| Mix No. | Proportions (%) | | | Strength @3days (MPa) | Strength @7days (MPa) | Strength @14days (MPa) | Strength @28days (MPa) |
|---|---|---|---|---|---|---|---|
| | OPC | FA | GGBS | | | | |
| N1 | 100 | 0 | 0 | 69.36 | 81.27 | 88.20 | 99 |
| T1 | 60 | 16 | 24 | 56.34 | 61.97 | 75.72 | 93.13 |
| T2 | 60 | 18 | 22 | 58.70 | 67.90 | 80.90 | 96.70 |
| T3 | 60 | 20 | 20 | 61.06 | 76.6 | 89.4 | 100 |
| T4 | 55 | 18 | 27 | 52.03 | 65.06 | 78.33 | 91.25 |
| T5 | 55 | 20.25 | 24.75 | 55.33 | 67.9 | 79.73 | 90.45 |
| T6 | 55 | 22.5 | 22.5 | 58.63 | 76.53 | 87.53 | 96.23 |
| T7 | 50 | 20 | 30 | 54.33 | 66.28 | 82.38 | 95.15 |
| T8 | 50 | 22.5 | 27.5 | 54.53 | 69.16 | 82.46 | 94 |
| T9 | 50 | 25 | 25 | 54.73 | 72.06 | 82.26 | 89.13 |

It was observed that the strength of T3mix was more than N1mix (100% cement) at 14 days' and 28 days 'curing. Mix N1 (100% cement) produced maximum strength of 69.36 MPa and 81.27 MPa at 3 days' and 7days' curing respectively.

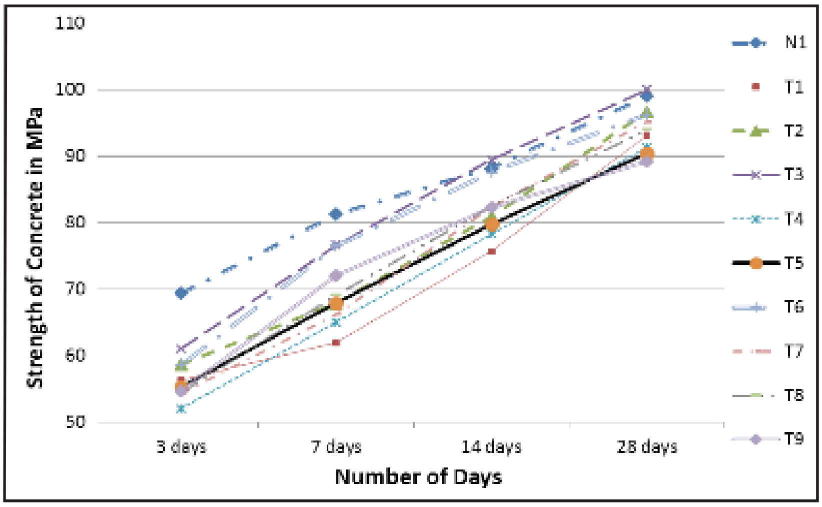

Figure 1.Comparison of increase of rate of strength of different concrete mixes

Fig.1shows curing period in number of days and respective compressive strength of various mixes in MPa. From Fig. 1, it has been observed that the strength of Mixes T1, T2, and T3 (40% Cement replacement) was consistently increasing because the replacement of both FA and GGBS resulted in a systematic decrease in early compressive strength. This may be because of variations in chemical composition and reactivity of FA which affect early stage properties and the rheology of concrete. This shows that calcium hydroxide (lime) depletes with time and its reaction affects the long-term gain of strength. This was essentially expected as the total heat of hydration is much lower in FA and GGBS than that of cement. Long term results however, indicated that the compressive strength of concrete prepared using both FA and GGBS increases with time and hence the compressive strength of concrete prepared using SCMsis either equivalent or more than the compressive strength of concrete prepared using cement solely.

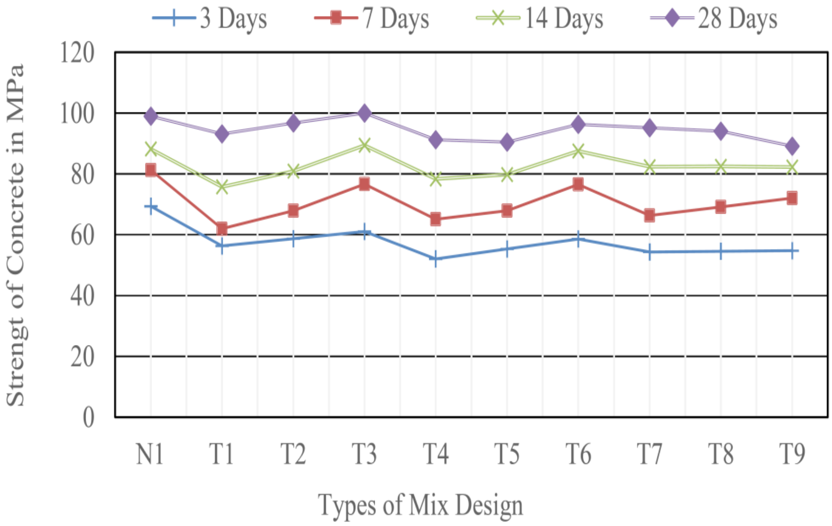

Figure 2.Compressive strength of concrete on 3 days, 7 days, 14 days and 28days

Fig.2shows a graphical presentation of mix numbers and compressive strength at various ages of concrete. From Fig.2, it has been observed that without any replacement of cement with SCMs the higher compressive strength was obtained at early age. Further, it is seen that Nominal mix (N1) gives higher compressive strength than ternary blend concrete. But it consumes more amount of cement as compared to other mixes. Replacement of cement with T3 (60%-cement, 20%-fly ash, 20%-GGBS) shows that compressive strength increases at later ages. It is also observed that there is substantial saving of quantity of cement in 50% replacement of it. The strength given by mix

T7 (50%-cement, 20%-fly ash, 30%-GGBS) was 95.15 MPa.

Based on laboratory results and using SPSS 16.0 statistic program, multiple linear regression models were developed corresponding to 3 days', 7days', 14days' and 28 days' curing which include four independent variables such as cement (*CEM*), fly ash (*FA*), *GGBS* and water cement ratio (*W/C*). The formula derived from the multiple regression analysis in respect of various stabilized mixes comprising different combinations of the ingredients and having been cured for different curing periods (3 days, 7days, 14 days and 28 days) are given below:

$$f_{c3} = 5.059 \times 10^{-4} \times CEM + 0.0057 \times FA - 0.121 \times GGBS - 139.79 \times \left(\frac{W}{C}\right) + 102.90 (6) \qquad (6)$$

$$f_{c7} = -6.63 \times 10^{-3} \times CEM + 0.19 \times FA - 0.1518 \times GGBS + 338.546 \times \left(\frac{W}{C}\right) + 0.0188 (7) \qquad (7)$$

$$f_{c14} = -1.02 \times 10^{-6} \times CEM + 0.13 \times FA - 0.102 \times GGBS + 193.531 \times \left(\frac{W}{C}\right) + 41.75 (8) \qquad (8)$$

$$f_{c28} = 9.89 \times 10^{-6} \times CEM - 0.031 \times FA - 0.081 \times GGBS - 308.235 \times \left(\frac{W}{C}\right) + 172.97 (9) \qquad (9)$$

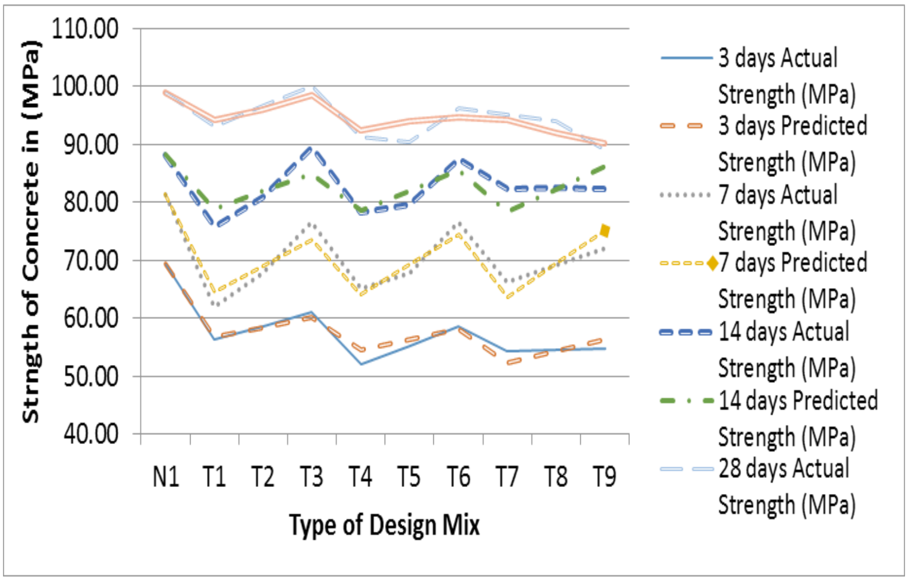

**Figure 3.Graphical presentation of observed and predicted strength**

Further, to examine and exhibit how close the pattern of experimental and predicted strength follows a graph is plotted between the theses two strengths for different curing periods (3 days, 7days, 14 days and 28 days) which is shown in Fig. 3. From the same, itcan be seen that there is fairly very good agreement between observed strength and predicted strength for all type of mixes for all curing days.Table 8indicates the summary of the values of the performance criteria for 3 days', 7days', 14 days' and 28 days' curing period by MLR method.

From Table 8it is observed that the performance MLR is very good with high  value and lesser and  values.

**Table 8.Performance Measures of MLR and ANN Models**

| Strength in Days | R | MSE | MAE |
|---|---|---|---|
| 3 days | 0.96 | 1.59 | 0.96 |
| 7 days | 0.94 | 4.00 | 1.72 |
| 14 days | 0.77 | 7.03 | 2.11 |
| 28 days | 0.89 | 2.59 | 1.30 |

## Conclusions

The compressive strength of concrete in ternary mixes was assessed with replacement of cement more than 40% with SCMs. The SCMs used in this project were industrial wastes. A recent product Ultra-fine SCM P100 was used. In a view to evaluate the effect of SCMs on the behavior of compressive strength of concrete, a systematically planned experimental investigation was conducted. From the results of our tests and analyses, the following conclusions can be drawn

- As a part of experimental study, the cement was replaced by ultra-fine Fly Ash and GGBS. The percentage of cement replaced with SCMs was 40%, 45%, and 50%. Each replacement was further divided into three parts with varying composition of Fly Ash and GGBS
- Four periods of curing (3days, 7days, 14 days and 28 days) for testing of compressive strength werecon-sidered
- There is substantial saving in quantity of cement; so less production of cement is required. Moreover, environmental degradation may reduce.Thereby, helping thesustainable development
- Further, the statistical model for predicting compressive strength is developed using multiple regression analysis. The model is capable of predicting the strength fairly using the values of the index properties and without any need to wait for the designated period of curing
- From the study, it may be concluded that the relationship between dependent and independent variables can be captured very well by MLR. These tools can also be effectively used to map for mapping the input and output data sets
- The study shows that MLR is highly capable and can act as an alternative computational tool for predicting compressive strength of HPC

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