Compressive strength enhancement of concrete using fly ash as a partial replacement of fine aggregate and model development

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Abstract: The aim of the study is to observe the strength increment of concrete by using fly ash as a partial replacement of fine aggregate. For that, three mix ratios – 1:1.25:2.5, 1:1.5:3 and 1:2:3 (weight-based) have been considered. For each ratio, fly ash was used as 0%, 10%, 20% and 30% of the fine aggregate. The curing period and the water-cement ratio (W/C) were 28 days and 0.5, respectively. It was revealed that the compressive strength of the concrete was increased with the addition of fly ash. And it was the maximum at 10% of fly ash content. A nonlinear relationship has been proposed where compressive strength has been used as the function of the weight of cement, fine aggregate, coarse aggregate and fly ash.

Keywords: concrete; fly ash; waste; compressive strength; elasticity; nonlinear regression.

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1 Introduction

Generally, fly ash is considered a waste from electrical power generation plant. By 2013, there were six potential coal fields in Bangladesh. But currently only one is operative – the Barapukuria coal field. Barapukuria coal field started its journey officially since 2004. It has a coal reserve capacity of 390 million tonnes. It also has the country's only coal fired thermal power plant. 65% of production is yielded out of this plant of a total of one million tonnes per year. The thermal plant has a capacity of 250 megawatts. 10% of the total mass of coal burnt is the total mass of produced ash. And 20% of which is bottom ash and the rest 80% is fly ash. Coal used in thermal power plant (per year) is 650,000 million tonnes. Total ash production after the combustion of coal (per year) is 65,000 million tonnes. Total fly ash produced from the coal combustion (per year) is 52,000 million tonnes (Tamim et al., 2013).

Outside the country fly ash is being produced tremendously. In India as the power generation is about to raise from 20,000 MW to 300,000 MW, the huge coal reserve of about 200 billion tonnes contributes to a fly ash generation rate of 131.09 million tonnes per year (Tiwari et al., 2016). About 25% to 45% of the coal utilised for power production is fly ash (Dikshit, 2011). It is a tremendous amount of fly ash production solely in India.

Of the huge production of fly ash a fraction is being utilised. About 25% of the total production of fly ash around the world is being utilised. However, a healthy utilisation has been perceived in Germany, Belgium and Netherlands to an extent of 95% of the total fly ash produced. But UK is far apart from this rate to the extent of 50% and finally USA and China to 32% and 40% respectively (Taneja, 1998). According to American Coal Ash Association (ACAA) in the year of 2012, fly ash production was about 52,100,000 tonnes where the reuse was 23,205,204 tonnes and specifically reused in cement production 2,281,211 tonnes (ACAA, 2013).

As more fly ash is being produced the more greenhouse gas is being emitted in the environment. This is the most disturbing fact which leads us to find some ways to compensate for this loss. Fly ash may be contribute to some other risks like health and water contaminations. The general public is not exposed to fly ash health risk as they do not encounter it in significant quantity but in extreme cases precautions are recommended. Even any pathological damage due to toxicity resulting from accidental ingestion of fly ash in various animals has not been found. The possible radiation generated from fly ash is well below EPA-2015's action standard. The chemical process that can cause radioactivity of fly ash that is actually resulted from radionuclides from the decay series of uranium, thorium and potassium is out of danger level (Sear et al., 2003). To prevent fly ash from leeching into any drinking water source special landfills can be constructed (EPRI, 1998). These landfills can be an effective way of utilising of fly ash in greater quantity. Fly ash cannot be associated with any CH_4 emission in the landfill environment as it is not biodegradable in anaerobic condition. In addition to fly ash's characteristics in anaerobic condition it is also not susceptible to aerobic decomposition and cannot be combusted (EPA, 2015).

So, it is a better way to use fly ash effectively within a construction material and has been being implemented in the construction field since a long time because of its value as a supplementary cementious material and fine particulate structure. This study focuses on fly ash's implementation as a filler material as it is very fine and can effectively fill the very miniature gaps left even after binding takes place. So, in this study it is been observed how fly ash contributes to concrete strength as a filler material with different weights of material combinations additionally offering some extra binding. As most of the previous similar studies did not focus on regression analysis, this study also intended to develop a regression model to mathematically describe the findings.

2 Literature review

M25 grade concrete mix (ratio 1:1:2) has been used in combination with water-cement ratio (W/C) of 0.35, 0.45 and 0.55 with fly ash replacing cement as 10%, 20% and 30% and with curing days variation of 7, 14 and 28 days. The result shows that concrete with 10% replacement of cement with fly ash shows optimum compressive strength for 28 days than normal concrete for 0.35 W/C ratio (Wankhede and Fulari, 2014). Another study has been conducted within grade M25 concrete for only W/C ratio of 0.35 with mineral admixture replacing cement by mass of 10%, 20% and 30% results in the optimum compressive strength at 10% replacement of cement by fly ash (Goud and Soni, 2016).

Similar research was conducted replacing fine aggregate with fly ash as 0%, 10%, 20%, 30%, 40% and 50% as weight with curing day variation of 7, 28 and 56. The compressive strength shows its optimum position at 20% replacement for curing days of 56 (Rkein, 2015).

An identical study is seen with concrete blocks utilising river sand replaced by fly ash. They have used concrete mixture ratios 1:2:4 and 1:4:8 with W/C ratio variation of 0.5 to 0.8 according to Indian standard. Compressive strength has been found increasing as the percentage of fly ash goes up to 20% replacement and decreasing thereafter (Thomas and Nair, 2015).

A study conducted replacing of fine aggregate by fly ash from 0% to 80% exposed to 200°C, 400°C, 600°C and 800°C temperatures. The compressive strength has been found to increase with increase in the percentage replacement of natural sand by fly ash up to 40% at elevated temperature of 200°C and thereafter decrease. Similarly when concrete is subjected to sustained elevated temperature of 400°C, 600°C and 800°C the compressive strength has been observed maximum corresponding to 40% replacement of natural sand by fly ash (Parvati and Prakash, 2013).

Fly ash can also reduce the acidic activity in concrete when subjected to exposure like acid rain. Kiran and Ratnam (2014) used fly ash as replacement of cement (0%, 5%, 10%, 15% and 20%). They varied the time of acidic exposure (28, 60 and 90 days) and also varied the acid concentration of 1%, 3% and 5%. The finding implicates that concrete with 10% replacement of cement with fly ash exhibits optimum strength.

Murthi and Sivakumar (2008) investigated on both HCl and Na_2SO_4 attack on concrete grade of M_{20}, M_{30}, M_{40} and the parameter investigated was the time in days taken to cause 10% mass loss and strength deterioration factor of fully immersed concrete specimen in a 5% H_2SO_4 and 5% HCl solutions with curing days variation as 28 days and 90 days. The result revealed that concrete with 20% fly ash and 8% silica fume acted best against acidic effect. Moreover, it took 32 weeks to the mass loss of 10% of the M_{20} and M_{30} grade concrete immersed in 5% H_2SO_4 and 5% HCl.

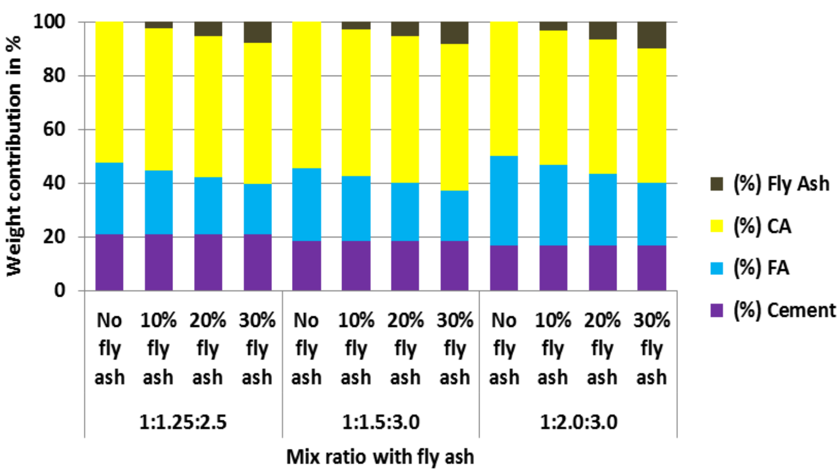
Fly ash has also been implemented along with other constituents like glass powder in concrete. Ali (2015) carried out a test where cement was partially replaced by fly ash and glass powder combined as 10%, 20%, 30% and 40%. The result concludes that it is possible to use fly ash and glass powder mix up to 40% as it exhibits lower capillary absorption. In another study, sugarcane ash was used along with fly ash and found the optimal strength at 10% replacement of cement. This study also observed that fly ash performs well when it comes to improve the concretes workability (Anand and Mishra, 2016).

3 Methodology

In present study, three weight-based ratios 1:1.25:2.5, 1:1.5:3 and 1:2:3 with varying quantity of fly ash have been considered. For each of the ratios fly ash varied by 0%, 10%, 20% and 30% making a total of 12 (3 × 4) actual variations. Two samples were prepared to get each result, therefore the total number of sample was 24 (12 × 2). A standard cylindrical shape (200 mm height and 100 mm diameter) has been chosen to be the mould shape. For the whole test ordinary Portland cement (OPC) has been used. The stones (19 mm downgraded) used were crushed and well graded in nature. The fineness modulus (FM) of sand was 2.17. The fly ash used in the whole study has been collected from Barapukuria Power Station, Bangladesh.

A bar diagram (Figure 1) visualise the material quantity used for the concrete mixture. The mixture plan has been made totally based on the ratios mentioned earlier.

Figure 1 Material percentage in mix (see online version for colours)

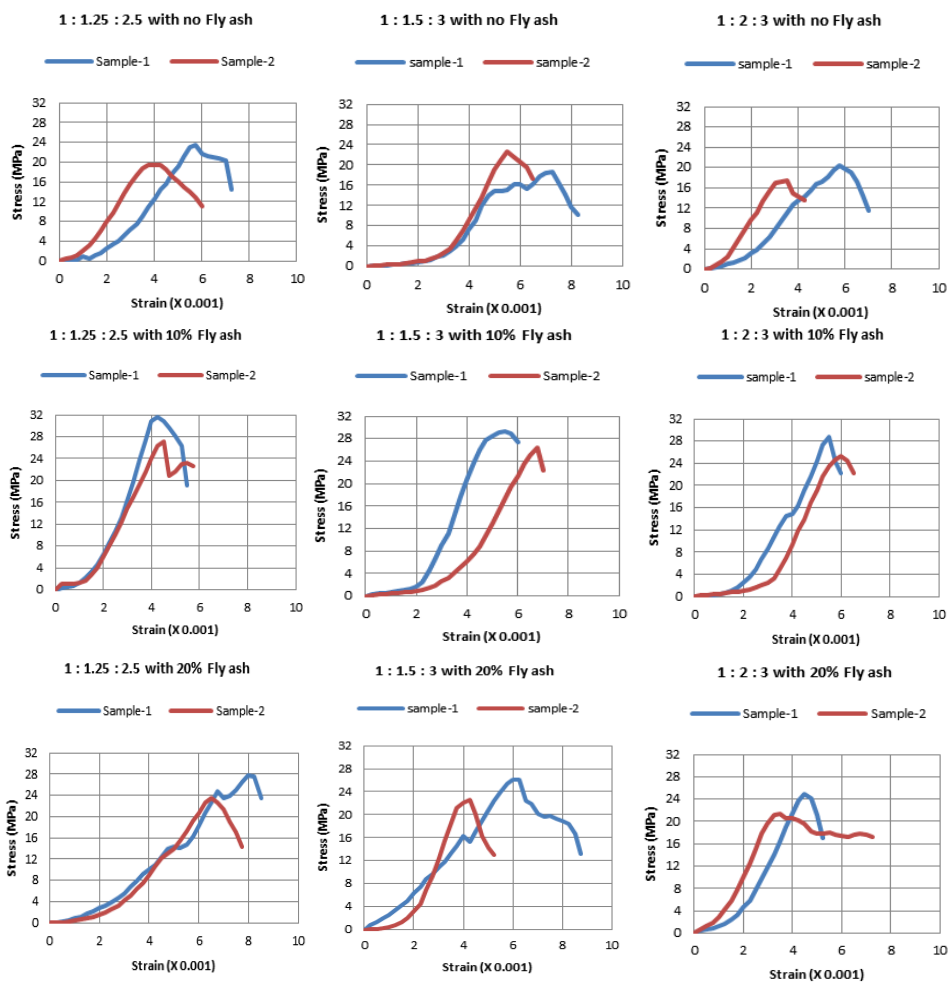


The water cement ratio was set constant at 0.5 as this study did not involve W/C ratio as a variable. The cylinders have been cured for 28 days in curing chamber. The compressive strengths have been determined for every individual concrete cylinder using UTM. The r data has been analysed with the help of a widely used popular computer program – IBM SPSS-23.

4 Result analysis

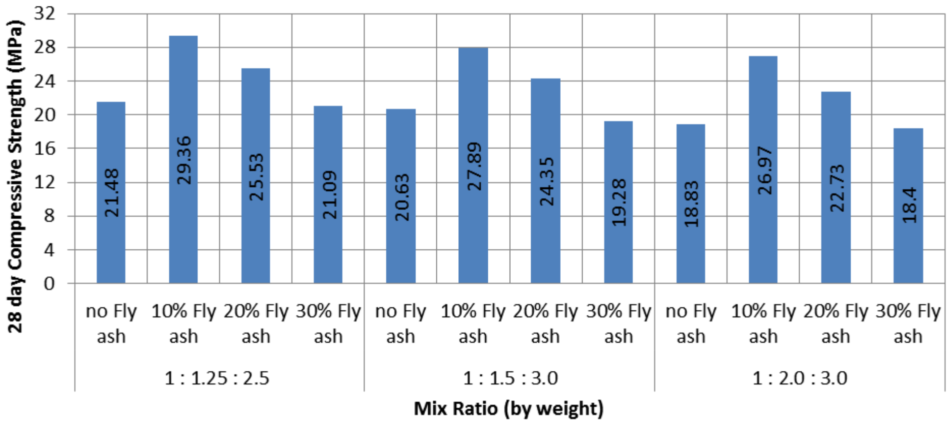
The stress-strain diagrams of the concrete cylinders are shown in Figure 2. From those figures, the average compressive strength is plotted in Figure 3.

Figure 2 Stress-strain diagrams of the concrete cylinders (see online version for colours)



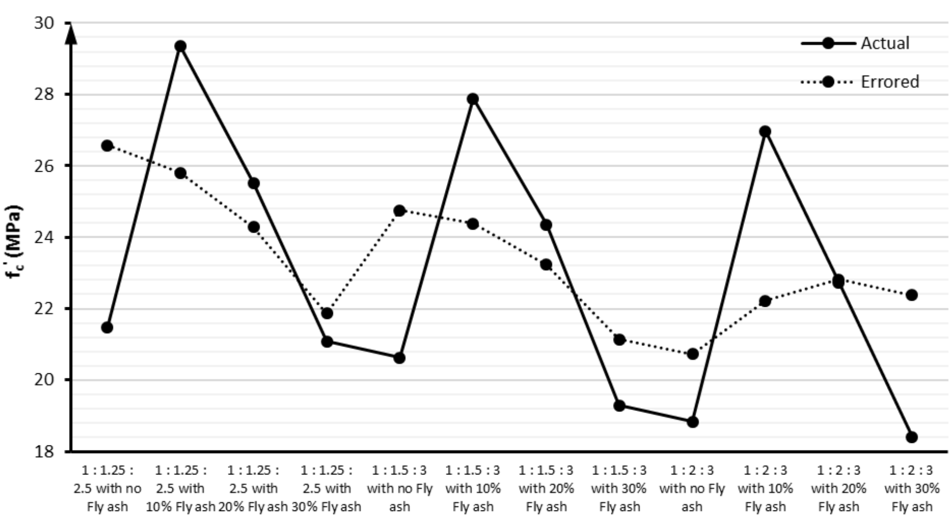
It is seen from Figure 3 that compressive strength of the concrete with 10% of fly ash achieved the maximum strength in all mix ratios. Concrete with 20% of fly ash possessed the second highest compressive strength. Concrete specimen with 0% and 30% fly ash has almost the same strength. From the pattern of the bar diagram, it can be said that, concrete having fly ash more than 30% may decrease in strength than the concrete having no fly ash.

Figure 3 A comparative diagram for the compressive strength at 28 days (see online version for colours)



As per the visual inspection of result it seems like the compressive strength varies nonlinearly along with fly ash content. At this stage the objective is to find a relationship between the inputs and the outputs. The inputs are the material weight of cement, sand, stone and fly ash, and the output is the maximum compressive strength (MPa). For this purpose, the computer program IBM SPSS Statistics v23 has been used.

Figure 4 Actual f_c' vs. errored f_c'



First, a linear relationship has been developed. As the resultant strength followed a nonlinear pattern the mathematical model appeared to be inadequate. For the ease of demonstration the calculated data is presented as 'errored' data. In Figure 4, the linear regression model [equation (1)] is presented and the comparison of the actual and calculated data is also visualised afterward.

$$f_c' = 0.453W_{cement} + 8.24\sqrt{W_{sand}} + 0.228W_{stone} + 0.127W_{flyash} - 1,038.16 \quad (1)$$

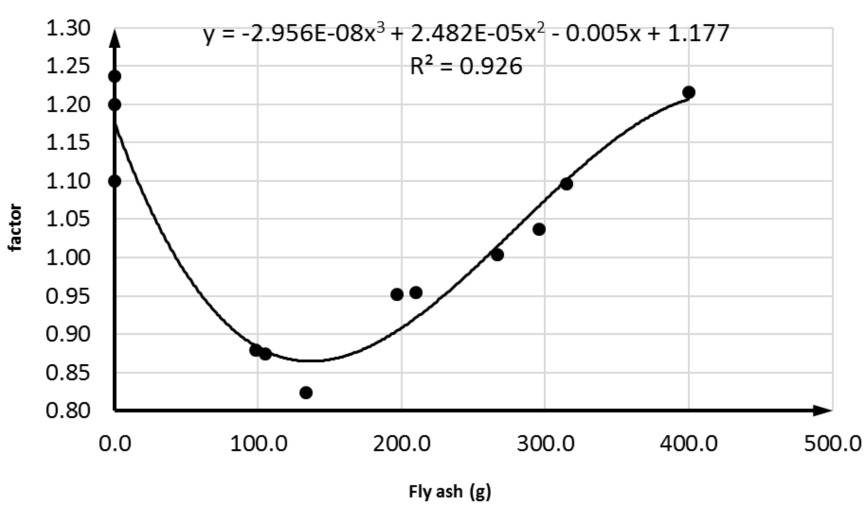
This linear model possesses R^2 value – 0.24, Pearson coefficient – 0.49 and coefficient of efficiency – 0.23. To come up with a good mathematical model a secondary nonlinear regression analysis has been executed to overcome the existing model's incapability.

Briefly, the secondary analysis can be called a filter for the existing model involving another nonlinear model. The idea led to prepare a new set of data which will act as an intermediate data that has direct relationship with the calculated or 'errored' strength and the actual strength. It has been done by dividing the errored data by the actual data. The new dataset can simply refer as 'factor' which is just a ratio. Having the new dataset prepared it had to be checked whether it has any significant linear or nonlinear relationship with other datasets – cement, sand, stone or fly ash. A total of ten types of regression analysis (Figure 2) have been executed and in Table 1 the model's quality is presented with its R^2 value in a matrix form to have a quick glimpse.

Table 1 R^2 matrix of multiple regressions

	Regression type	*Independent variables*			
		Cement	*Sand*	*Stone*	*Fly ash*
Dependent variable (factor)	Linear	0.01	0.01	0.00	0.00
	Logarithmic	0.01	0.01	0.00	0.00
	Inverse	0.01	0.01	0.00	0.00
	Quadratic	0.01	0.02	0.00	0.79
	Cubic	0.01	0.02	0.04	0.93
	Compound	0.01	0.00	0.01	0.00
	Power	0.01	0.00	0.01	0.00
	S curve	0.01	0.00	0.01	0.00
	Growth	0.01	0.00	0.01	0.00
	Exponential	0.01	0.00	0.01	0.00

Figure 5 Cubic regression model



The matrix is formed of a total of 36 regressions and the best result is $R^2 = 0.93$ as highlighted is found between the 'factor' and the fly ash as a cubic relationship (Figure 5). It can be contended that the new regression model [equation (2)] is firm enough as it is stated and visualised below:

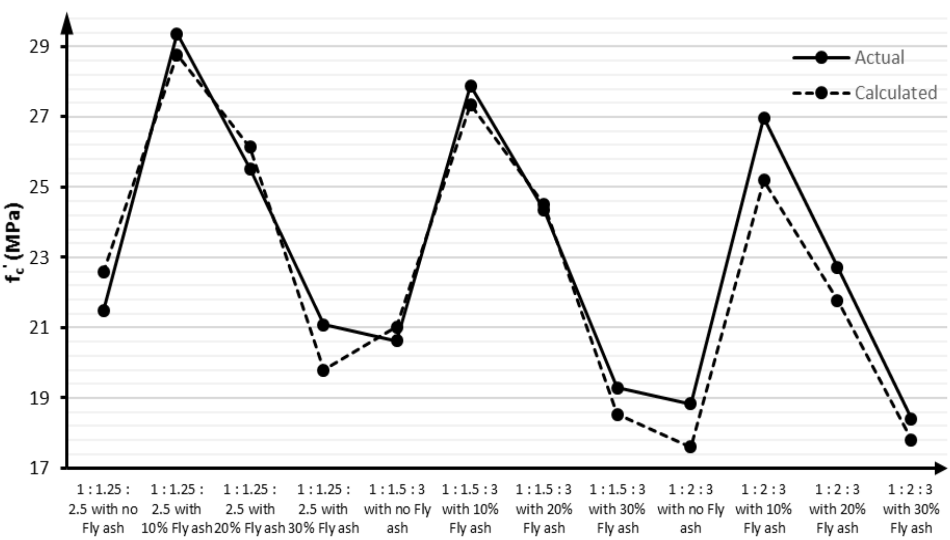
$$factor = 1.177 - 2.956 \times 10^{-8} W_{flyash}^3 + 2.482 \times 10^{-5} W_{flyash}^2 - 0.005 W_{flyash} \tag{2}$$

Based on the idea, the new cubic model can be prescribed as the predictor of the factor for the corresponding input of fly ash value with a success rate of 92.6%. Therefore, the combined new equation is proposed below [equation (3)].

$$f_c' = \frac{0.453 W_{cement} + 8.24\sqrt{W_{sand}} + 0.228 W_{stone} + 0.127 W_{flyash} - 1038.16}{1.177 - 2.956 \times 10^{-8} W_{flyash}^3 + 2.482 \times 10^{-5} W_{flyash}^2 - 0.005 W_{flyash}} \tag{3}$$

The final equation possesses a R^2 value – 0.95, Pearson coefficient – 0.97 and coefficient of efficiency – 0.93, which makes it a solid predictor of compressive strength within the experimental data range. Figure 6 shows a visualisation of the comparison of predicted values with the actual values.

Figure 6 Actual f_c' vs. calculated f_c'



5 Conclusions

The optimal compressive strength lies at 10% of the fly ash content of the fine aggregate. Concrete with 20% of fly ash entails the second highest compressive strength. Also, concrete specimen with 0% and 30% fly ash has almost the same strength. Equation (3) is applicable within certain ranges shown in Table 2.

Table 2 Applicable parameter range for regression model

Parameter	*Range of weight in one sample (gm)*
Cement	$666.7 \leq W_{cement} \leq 788$
Sand	$689.5 \leq W_{sand} \leq 1,333.3$
Stone	$1,970 \leq W_{stone} \leq 2,100$
Fly ash	$0 \leq W_{flyash} \leq 400$

Note: For one specimen of concrete cylinder having the diameter 100 mm and the height 200 mm.

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