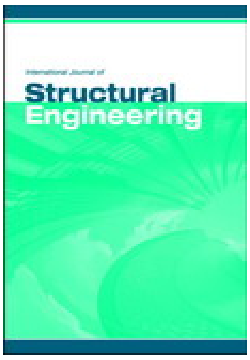

International Journal of Structural Engineering

ISSN online: 1758-7336 - ISSN print: 1758-7328
https://www.inderscience.com/ijstructe

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DOI: 10.1504/IJSTRUCTE.2022.10050097

Article History:

Received:	12 July 2020
Accepted:	12 December 2021
Published online:	07 November 2022

A generous review of fly ash engineering characteristics on concrete in trait of compressive strength

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Abstract: Fly ash is a fine grey powder consisting mostly of spherical, glassy particles produced as a by-product in coal-fired power stations having pozzolanic properties that exhibits supplementary cementitious material. This paper essentially investigated about the effects of fly ash on concrete 'with and without admixture, and as well as mixed form' in aspect of water-binder ratio, fly ash replacement percentages and curing ages (days). For modelling and analysis of these properties statistical best fit functions were used. This comprehensive study shows that in all types of concrete, compressive strength decreasing with increasing water-binder ratio. However, in maximum cases, highest compressive strength observed in case of 'with admixture fly ash concrete' is at 20% fly ash (FA) replacement level and shows maximum strength gaining initiates between 7–90 days in case of 'with admixture FA concrete' whereas significant strength gaining observed after 90 days onwards and ultimate strength gaining at 365 days.

Keywords: fly ash; compressive strength; w/b ratio; FA; ages; composition; statistical distribution.

Reference to this paper should be made as follows: Shaw, S.K. and Sil, A. (2023) 'A generous review of fly ash engineering characteristics on concrete in trait of compressive strength', *Int. J. Structural Engineering*, Vol. 13, No. 1, pp.109–149.

Biographical notes: Sayan Kumar Shaw is working as a PhD research scholar in the Department of Civil Engineering, NIT Silchar, India. His area of interest is structural engineering, He is working on Beam Column Joint (BCJ) with the effect of flyash behaviour in normal concrete experimentally in lab. He found that 20 % replacement provides best results similar to ordinary cement concrete compressive strength at min of 90 days and higher duration. However, ductlity found better in higher work done or higher energy dissipation reported in his studies.

Arjun Sil is currently an Associate Professor and the Head of the Department of Civil Engineering, National Institute of Technology Silchar, India. He obtained his BTech from North Eastern Regional Institute of Science and Technology (NERIST), India, MTech from National Institute of Technology (NIT) Silchar, and PhD from Indian Institute of Science (IISc), Bangalore, India. His specific areas of research are interdisciplinary such as earthquake engineering including structural engineering, geotechnical earthquake engineering, seismology, seismic hazard, site response, microzonation, risk evaluation, solid mechanics, condition assessment and health monitoring of structures, reliability and probability, Monte Carlo simulation, GIS and remote sensing, corrosion modelling, and landslide hazard assessment.

1 Introduction

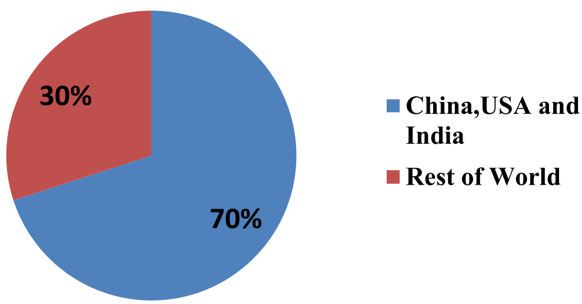
Fly ash (FA) is a fine grain particle recovered from the burning coal during the production of electricity as a derivative and treated usually as a waste product. These micron-sized earth elements consist primarily of silica, alumina and iron as chemical elements. However, because of micron-size particles, ecological cycles would be effected badly if FA is not disposed of properly (Nadesan and Dinakar, 2017). Therefore, in an economical advantageous way it should be a key concern to transform it as a recycle materials (Nadesan and Dinakar, 2017). However, FA has reasonable binding/adhesive properties similar to cement because of its chemical composition present in the by-product of FA. Hence, FA may be called as a supplementary cementitious material accounted for cement replacement material. Alternatively, FA increases workability, decreases heat of hydration and thermal cracking in concrete at early ages. FA also increases mechanical as well as durability characteristics of concrete essentially at later ages (Hemlatha and Ramaswamy, 2017). Although, there are advantages of FA, however so far, using 100% FA replacement has not been gained due to some limitations. Further, the China, USA and India acquire almost 70% of the total coal consumption of the world (Figure 1). According to CEA report, about 166 million tons of FA produced from 132 thermal plants annually in India (Figure 2). There is essentially about 56% FA use, fruitfully made through many ways shown in Figure 2 and the rest part of FA becomes under consideration yet. There is much interest/demand that FA could be applied in the commercial purpose as a cement replacement material. At the same time, industrial wastes were absorbed and the necessity of cement clinker diminished by this method. For producing cement and concrete, a high quality FA with low dosage carbon content normally used as addition of minerals. However, for land filling/ground improvement techniques, FA essentially used containing high and varying level of carbon (Nadesan and Dinakar, 2017). By investigating the chemical composition of FA indicating its potential to use as raw material in cement industry. Indeed, increasing trends in production of FA around the world from various sectors attract one and all to use FA in the construction industry. However, in order to develop a clear understanding for it is spacious application, the aim of this study is to identify, quantify the key ingredients/ factors in FA, responsible for enhancing engineering properties thereby attaining/ contributing strength, workability and its variability with ages in FA concrete. However, as per literature, much study is not being carried out so far to extract the various engineering properties of FA till date, it is still confined within the experimental/insitu judgement policy in various sectors as well as construction industry and the code of practice about FA is not mature enough to address these issues with clarity and bringing the limitations about it is applicability in the field/industry. Therefore, for gaining the idea, various research papers/reports are being followed globally with various aspects such as degree of hydration of high volume FA (HVFA) cement systems, durability characteristics of HVFA engineered cement composites mechanical and fracture properties of FA concrete, influences the type of FA on freeze thaw resistance reported to account in large area (Hemlatha and Ramaswamy, 2017).

However, as per Indian standard (IS-1489, 2000), the higher limit of FA uses is restricted to 35% in the processing of Portland pozzolona cement. Indeed, from the research papers, it is observe that FA becomes incapable in enhancing the strength characteristics in its original form when used beyond 35% replacement. In such circumstances, FA requires improvement in the mix in order to form more hydration products to increase the strength. It is also reported that gaining strength depends on above 50% replacement of FA (Hemlatha and Ramaswamy, 2017). There are main two reasons to use the FA, i.e.:

a fine aggregate replaced by it

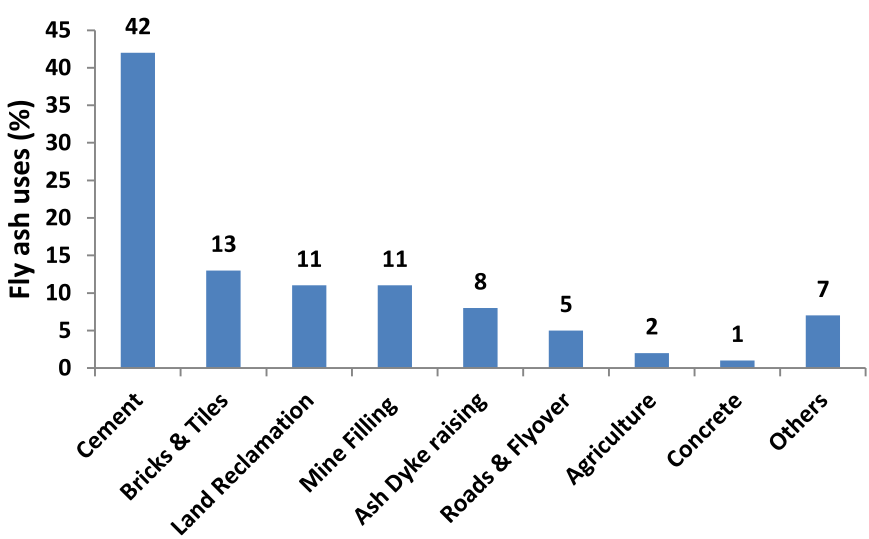
b effective pozzolanic action provided by it (Christy and Tensing, 2010).

Figure 1 Consumption of FA (%) in respective of country (see online version for colours)



Source: Nadesan and Dinakar (2017)

Figure 2 As per Indian scenario FA uses in percentages at various fields (see online version for colours)



Source: Nadesan and Dinakar (2017)

There is a likelihood of creation of huge quantity of CO_2, SO_2 and NO_x by the production of cement. From the beginning of 1960s, there was incorporation of FA as a pozzolanic material into the concrete. There is a utility of FA into concrete as a pozzolanic material that could be utilised either as a component of blended Portland cement or as a mineral admixture. There are some benefits of replacement of cement by FA or as a mineral admixture in concrete. Firstly, there is an increase of environmental greenness and decrease the heat of hydration. Secondly, durability enhanced by addition of FA. Thirdly, presence of FA provides higher workability, better compactness in the interfacial transition zone and a finer pore structure in the system. FA (15–30%) used as replacement of binder extensively but 30–60% FA developed as HVFA by engineer or researcher. There is increment of using coal above 3.4% in the next two decades in spite of retirement of many coal plants. In aspect of chemical composition, calcium-silicate-hydrate (C-S-H) and or calcium aluminate silicate hydrate produce by pozzolanic reaction. There is a contribution of FA in concrete at later ages due to relatively slow process of pozzolanic reaction. Various papers reviewed to understand/examine the effects on concrete by FA. It has been shown that, all strengths (compressive strength, flexural strength, splitting tensile strength and bond strength) increases in later ages due to earlier mentioned slow pozzolanic reaction essentially for the without admixture cases. It has been noticed that there is a gaining of early strength in some cases for 'mixed' and 'with admixture' cases (Yu et al., 2017).

In this paper, authors discussed about the effects of FA in aspects of three categories stated above such as

a mixed type of FA concrete

b with admixture type of concrete

c without admixture type of concrete.

Further, authors have made an attempt to investigate and discuss mainly to extract generalised behaviour that effects on FA concrete considering with, without and mixed type of admixture FA concrete to bring into a standard form similar to cement concrete for its wider applicability in future by properly quantifying these engineering properties presented such as compressive strength, flexural strength, splitting tensile strength and bond strength of FA concrete and found a fruitful correlation among them. Alternatively, the main aim of this work becomes to gather the findings from the reported researches to obtain more data/information about various mechanical properties of FA in aspect of 'with admixture, without admixture as well as mixed conditions'.

2 Reviews on FA concrete

Authors have reviewed essentially considering papers where intense discussions done on the effect of FA as a cement replacement material in aspects of various engineering properties. The recent papers on FA comprehensively reviewed to extract, how FA effects on compressive strength, flexural strength, splitting tensile strength, slump and bond strength respectively. Christy and Tensing (2010) discussed the effects of class F FA at various replacement levels on concrete in aspects of compressive strength at various cement mortar proportions. Rashad (2015) represented a total summary on the use of high volume class F FA as a partial replacement of cement on OPC. Mahalingam et al. (2016) assessed the hardened characteristics of raw FA blended self-compacted concrete. Chousidis et al. (2016) discussed the influence of chemical composition of FA on mechanical properties of concrete and the resistance of RCC against chlorination. Rafieizonooz et al. (2016) investigated to study the effects of coal bottom ash and FA as replacement for sand and cement in aspects of various properties of concrete. Nawaz et al. (2016) made a review in the progress of discussion on effects of free lime on compressive strength of FA concrete along with their limitations. Shehab et al. (2016) reviewed the effects of geo-polymer on FA concrete in aspects of various factors and different levels of FA percentages. Further, Saha (2017) reviewed on effects of class F FA on compressive strength of concrete at various replacement levels of FA percentages. Karthik et al. (2017) reviewed on effects of bio-additives of the various properties on bio-geopolymar concrete. Yu et al. (2017) studied that increasing the compressive strength of UHVFA concrete in a simple and practical method, by reducing water-binder ratio while adding super plasticisers to maintain the workability at various replacement levels. Liao et al. (2017) discussed on effects of compressive strength by using low grade FA at various percentages in magnesia phosphate cement-based concrete. Mehta and Siddique (2017) showed the effects of low calcium FA at various replacement percentage on OPC in aspect of compressive strength. Khodair and Bommareddy (2017) discussed on the effects of various percentages recycled aggregate and FA on concrete in aspect of various factors. Silva and Andrade (2017) investigated the effects of different replacement levels of RCA and FA on concrete in aspects of various ways at different water-binder ratio. Moffatt et al. (2017) represented the effects of HVFA on concrete in aspect of durability at various replacement levels of FA and different water-cement ratio. George and Sofi (2017) reviewed that the effects of FA and lime on OPC in aspect of various factors. Golewski (2018a, 2018b) showed the effects of class F FA on OPC in aspect of compressive strength, respectively.

However, from these papers, after the data (compressive strength, w/b ratio, FA replacement % and strengths on various curing ages) extracted with care, thereafter an attempt has been made to obtain the population statistics (population mean strength and its variability) on characterisation of FA as a cement replacement material. The main objective of this review paper is to investigate the effects of FA on compressive strength as a cement replacement material after obtaining and compilation of required available data collected from the various experimental reports/results presented that could provide as a reference and helps in use as guideline for the researcher and engineer who would be working with FA concrete in these aspects as well as could be used in various civil engineering construction activities keeping the basic design aspects as sustainable materials by replacing cement. The literature gathered for this review are summarised as on

1 Effects of FA including with and without admixture on compressive strength of concrete in aspects of various properties [to examine how admixture contributes gaining various engineering properties in FA concrete].

2 Effects of external influence such as water-cement ratio, and the level of replacement respectively.

3 Types of FA

There are two kinds of FA such as ‘class C’ and ‘class F’ according to American Society for testing and materials (ASTM-C618-8a, 2009). There is formation of ‘class F’ FA essentially due to flaming anthracite or bituminous coal where composition of SiO_2, Al_2O_3 and Fe_2O_3 materials contains/passed 70%, whereas flaming lignite or sub-bituminous coal forms ‘class C’ FA where composition of earlier mentioned chemicals ranges between 50%–70%. However, class F FA behaves as a normal pozzolona and this FA formed by silicate glass reformed by aluminium and iron (RILEM TC 73-SBC, 1988). In class F FA, CaO content becomes less than 10%. Indeed portlandite (CH) produced by cement hydration. This portlandite (CH) is needed to produce calcium silicate hydrate (C-S-H) in pozzolanic reaction. There is slow reaction rate of low calcium FA specifically during the initial periods of hydration because of the phases of existing additional crystalline, which behaves chemically inert in concrete (Hemmings and Berry, 1988). There is not only differentiation between class C and class F FA in aspect of percentage of lime, also in aspect of depolymerised glass phase (Ghosh et al., 1993). There are inactiveness of containing high calcium FA for curing (Poon et al., 1997). There are less efficiency of high calcium fly ashes to control the growth because of alkali silica reaction (Smith, 1988) and sulphate attack (Dunstan, 1980) differentiate with low calcium fly ashes. It is assumed that there is increment of the reactivity of the high calcium fly ashes due to replacement of calcium in the glass phase (Mehta, 1985, 1998). There is higher reactivity due to higher percentage of calcium following to the less quantity SiO_4 polymerisation (Odler, 2009; Mehta, 1985). There are some studies where less enlargement of concrete occurred due to few amount of alkali ions existing in the vent solution that react with aggregates likely (Bleszynski and Thomas, 1998; Medhat and Michail, 2000). There are also bad effects for reinforcement corrosion in concrete due to less pH reacts with it. Further, calcium hydroxide is not only responsible for the alkalinity of pore solution but the sodium and potassium ions in cement and FA (Diamond, 1981) too. For high FA content, there is less pH because of low amount of CH then pH value balanced by Na+ and K+ (Wesche, 1991). There is less erosion comparatively in spite of less pH of concrete by reason of pozzolanic reaction due to commonness of same alkaline environment in both FA as well as normal concrete (ACI, 1979). It has been shown that rather presence of FA increases the erosion resistance with concrete having more dense being well proportionate as well as proper curing (Joshi and Lohita, 1997). Indeed, Hemlatha and Ramaswamy (2017) have shown (Figures 3 and 4) the percentages of class C and class F FA as given in Figures 3 and 4.

Figure 3 Ranges (%) of various chemical components considering class C FA (see online version for colours)

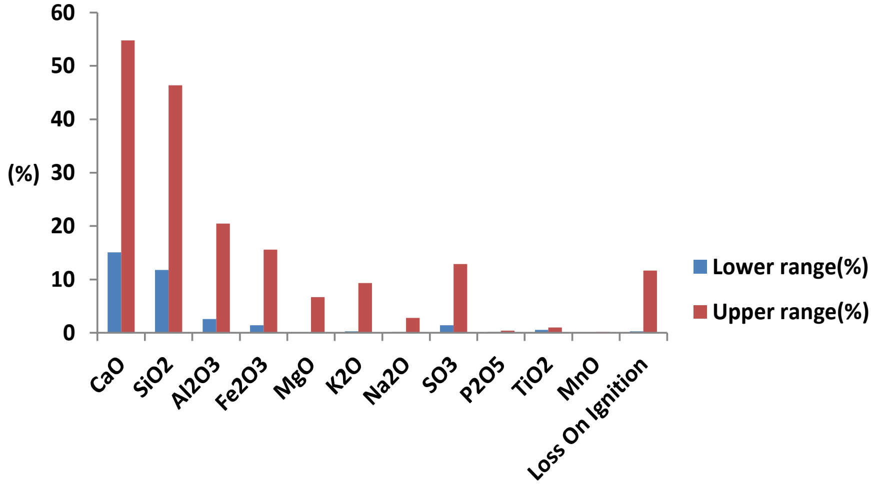
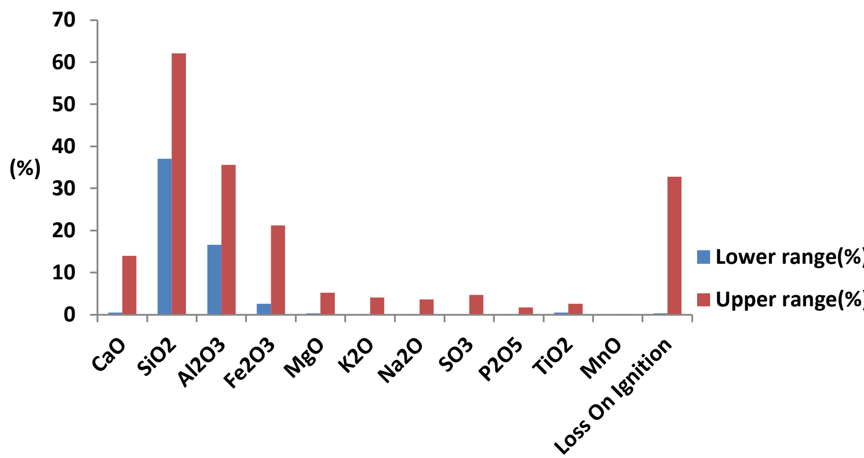


Figure 4 Ranges (%) of various chemical components considering class F FA (see online version for colours)



4 Foggy nature of FA

According to above discussion, FA is produced largely by coal burning in which material owing intrinsic varying features. Ward and French (2005) presented that FA has three ingredients, these are crystalline minerals, unburnt carbon materials and non-crystalline alumina silicate glass. Every single particle has distinctive reaction ability when it replaces cement (Hemlatha and Ramaswamy, 2017), however, few unwanted existence of combusting carbon observed in FA. It has been reported that calcination process abolishes this combusting carbon (Temuujin and Van Riessen, 2009) with a limited extend crystalline phases converted from indeterminate phases (Hemlatha and

Ramaswamy, 2017). Approximately, in all case glassy materials owing of very less sequence of atomic structure makes FA and these components mainly chemically react (Durdzinski et al., 2015). Further, it has been shown that high pozzolanic reaction occurred due to more unshaped FA (Hemlatha and Ramaswamy, 2017). It has been noticed that at a later periods pozzolanic reaction effected due to unshaped nature of FA (Sakai et al., 2005). More amount of unshaped components of the FA offer higher pozzolanic reaction. Further described that, for most crystalline phases, low calcium FA remains inert due to alkaline environment, additionally it has been seen that because of few reactive crystalline phases, high calcium FA reacts. Chancey (2008) and Tkaczewska (2014) reported that pozzolanic reaction increased due to higher degree of depolymerisation by using of finer FA.

5 Shape of FA particles

There is one of the main characteristic of FA such as fineness (Slanicka, 1991). The production of concrete done by FA due to advantageous of fineness of FA and found remarkable effects on FA cement or concrete (Erdogdu and Turker, 1988). There is an effects of size of FA which provides filling and nucleation in cement hydration (Chindaprasirt et al., 2007), however reported that there are some benefits for finer FA which increases compressive strength, decreases shrinkage, expansion, etc. further, it has been noticed that there is less reaction due to coarser FA and to suspect the sulphur attack, require more water in the porous mortar. Also, it decreased strength, expansion of drying shrinkage and for sulphate attack, coarser FA is mainly responsible and it has better performance against sulphuric acid (Chindaprasirt et al., 2004). Indeed, there is better bonding for the less specific gravity of coarser FA and less volume of OPC due to higher resistance of sulphuric acid (Hemlatha and Ramaswamy, 2017). Itskos et al. (2010) described that there becomes a better pozzolanic reaction features by the 7–150 μm with the existence of more deep glass and feeble crystalline periods.

6 Reported percentage of FA in concrete

In recent years, it has been seen that FA becomes used as a cement replacement material in concrete considering the typical cases of application. Bendapudi (2011) suggested that there is a limitation of 15–20% replacement of FA among total binder content. Indeed, there becomes a highest 35% replacement of FA as binder content according to British Standard (BSI, 1997a, 1997b) as well as also for Indian standards (IS-1489, 2000). It has been observed that there is intense study on replacement of HVFA in concrete (Alasali and Malhotra, 1991; Malhotra, 1986, 1990). However, durability, permeability, and strength are possible to improve above 50% replacement of FA in concrete (Malhotra, 1986, 1990). The HVFA above 56% replaced FA concrete also becomes effective in freezing and thawing test (Langley et al., 1989).

7 Efficiency of cement and reaction of Pozzolona

Smith (1967) described the idea of cementing factor (*k*), by which replacement of FA procedure becomes flourished. Cementing efficiency defines the durability and performance of concrete and similar type of other quality. It has been shown that at initial periods, less cementing efficiency showed by FA and behaves as filler material. Again, there is a fruitful effect of this pozzolanic reaction for increasing the strength (Hemlatha and Ramaswamy, 2017). However, Smith described that "the mass of FA could be equivalent to the mass of cement in relation to the development of compressive strength." Also, the '*k*' factor defines the distinction between the effect of Portland cement and mineral admixtures for evolution of a particular feature. For simplicity and reliability, compressive strength test defines the cementing efficiency (Hemlatha and Ramaswamy, 2017). There are advantageous effects such as lubrication, pozzolanic and filler effect as well as cementing efficiency (Siddique, 2004; Sua-iam and Mukul, 2015) of FA, nevertheless it becomes observed that pozzolanic reaction perform the major part in the whole reaction process. The component of Al_2O_3 and SiO_2 play a major role for pozzolanic reaction and form much hydrated gel in the period of hydration of cement. However, an increased strength observed due to filling of capillary pores by the gel (Cao et al., 2000). So, these chemical compositions become the main reason of reaction of FA. However, aluminosilicate gel forms all pozzolanic material and reacted with calcium hydroxide that formed in the period of cement hydration as shown by (Papadakis, 1999; Zeng et al., 2012).

$$3CH + 2S \rightarrow C_3S_2H_3$$

$$A + F + 8CH + 18H \rightarrow C_8AFH_{26}$$

$$A + CSO_3H_2 + 3CH + 7H \rightarrow C_3ACSO_3H_{12}$$

$$A + 4CH + 9H \rightarrow C_4AH_{13}$$

where CH = portlandite, S = SiO_2, H = H_2O, A = AL_2O_3 and F = Fe_2O_3.

Indeed, there are various hydrated products/compounds formed during the various phases of curing. It has been seen that age and limit of FA replacement is the main key factors causing strength variations. Further, calcium hydroxide becomes the essential component for pozzolanic reaction. Succeeding the hydraulic reaction, pozzolanic reaction usually takes place (Hemlatha and Ramaswamy, 2017).

8 Data collection

As discussed, the catalogue/data of FA compressive strength collected through extensive study from literature reported so far. The objective becomes to extract, compile and present generalised relationships/characteristics for its wide applicability in various engineering applications in general and could be considered as standard guidelines in design so that it could be used as cement replacement materials effectively and could be used this as useful-materials from wasteful-materials which application becomes still limited. This becomes essentially because of lack of our limited understanding about this material which becomes a by-product producing from power plant and considered as waste product as reported above. However, in this study after the data collection from various research papers, these data has been thoroughly processed, analysed and divided into three categories stated above. There are total 713 (Figure 5) compressive strength data collected for water-binder ratio, in which 146 data (w/b – 0.2, 0.25 and 0.6) are not considered from the database due to misfit and limited extraction from the overall data collected for this study. Alternatively, there are 567 compressive strength data taken in mixed form, of which 394 data with admixture FA concrete and 173 data without admixture collected in aspect of water-binder ratio [Figure 6(a)]. However, there are all total 758 compressive strength data collected considering FA replacement percentage (Figure 5), of which there are 186, 15, 33, 21, 211, 56, 74, 76, 37, 29, 8, 4 and 8 data respectively [Figure 6(c)] collected consecutively for 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 75, 80 and 100% replacement of FA concrete. Again there are total nos. of 186, 211 and 74 data collected for 0%, 20% and 30% FA concrete successively for mixed fly ash (MFA) concrete. There are 113, 90 and 39 compressive strength data successively collected for 0%, 20% and 30% FA replacement for with admixture fly ash (WAFA) concrete as well as 73, 121 and 35 [Figure 7(c)] data successively collected for 0%, 20% and 30% replacement for without admixture fly ash (WOFA) concrete in aspect of 7, 28, 56, 90 and 365 curing days of concrete. From the processed data, the average value estimated for each FA percentage. There are total 15 data taken in average for each type of concrete. Other data in aspect of other FA replacement percentage as well as days removed due to tally the data with each other. In mixed form, a total of 'with and without admixture' form data finally collected for those specified percentage at various specified days. A total 733 data collected for MFA, 314 and 419 compressive strength data [Figure 6(c)] collected for successively WOFA and WAFA concrete in aspect of all days. The average 13, 11 and 9 data are found successively for MFA, WAFA and WOFA concrete and these used for further studies.

Figure 5 Total data collected in aspect of various way (see online version for colours)

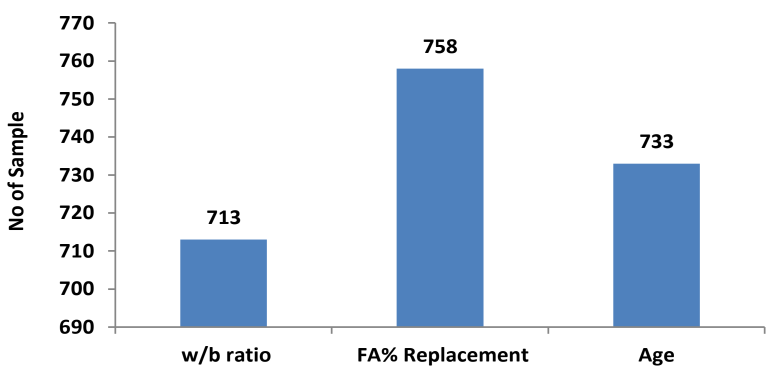
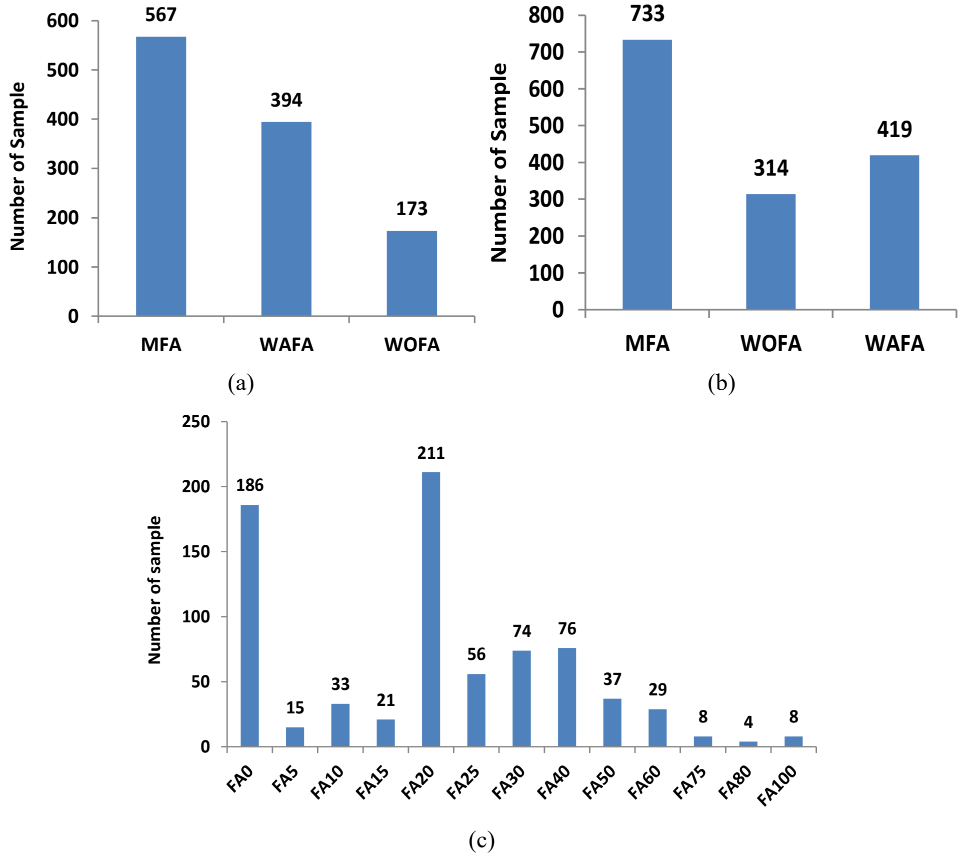
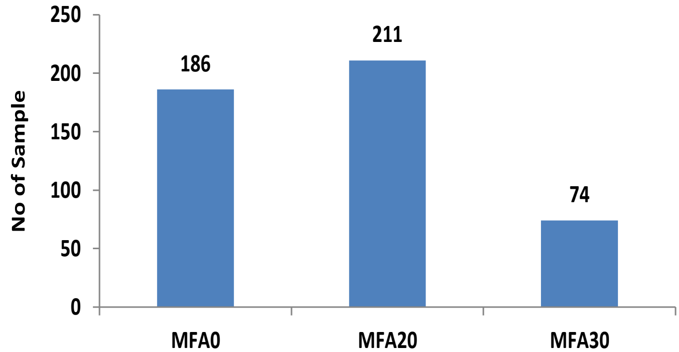


Figure 6 Data extracted and presented considering, (a) w/b ratio (b) ages (days) (c) FA% replacements

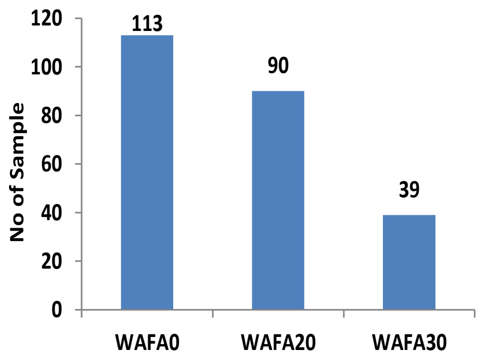


There are in total 128, 233, 17, 75, 16 and 11 no. of data [Figure 8(c)] collected consecutively for 7, 28, 56, 90, 180 and 365 curing days for MFA concrete in aspect of all kind of w/b ratio and all FA%. However among this data, there are 26, 27, 10, 16, 10 and 8 data reserved considering the averaging technique. For WAFA concrete, there are 59, 120, 8, 8 and 3 no. of data [Figure 8(b)] collected successively for 7, 28, 90, 180 and 365 days. There is no data found about 56 days respectively for this type of concrete. Considering this data, there are 12, 14, 5 and 5 samples averagely taken for 7, 28, 90 and 180 days successively. There is no data found about 56 days as earlier mentioned and also for 365 days, because of only three single data exist respectively of different FA replacement categories. On the other hand, there are 69, 113, 17, 67, 8 and 8 data [Figure 8(a)] taken consecutively for 7, 28, 56, 90, 180 and 365 days, of which there are 16, 17, 9, 15, 8 and 8 data averagely collected for those days for WAFA concrete. As a result, all total there are 480, 198 and 282 data [Figure 8(d)] successively collected for MFA, WOFA and WAFA concrete, also there are 97, 36 and 73 average data collected consecutively for earlier mentioned concrete. These collected data have been processed carefully and extended for further studies.

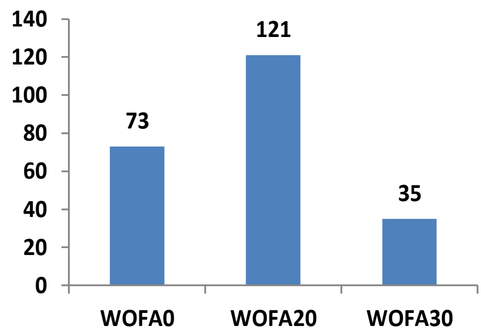
Figure 7 Selected maximum % of FA such as 0, 20 and 30 are considered for further study taking, (a) mixed form FA concrete (b) with admixture FA concrete (c) without admixture FA concrete (see online version for colours)



(a)

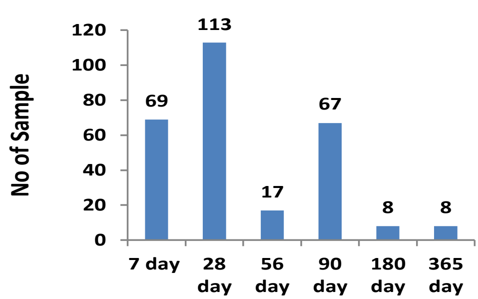


(b)

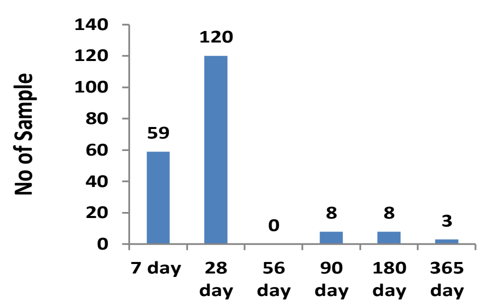


(c)

Figure 8 Data extracted and presented showing 2D graph in aspect of all w/b ratio (0.2–0.6), FA% (0–100) and ages (7–365 days) considering, (a) WAFA (b) WOFA (c) MFA concrete for further studies (d) represents the total data collection of respective concrete (see online version for colours)

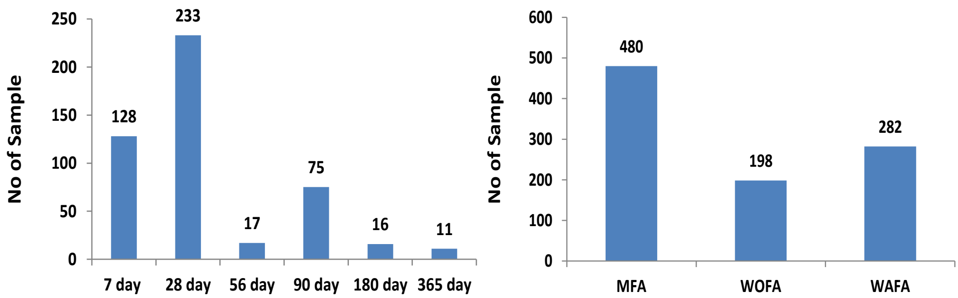


(a)



(b)

Figure 8 Data extracted and presented showing 2D graph in aspect of all w/b ratio (0.2–0.6), FA% (0–100) and ages (7–365 days) considering, (a) WAFA (b) WOFA (c) MFA concrete for further studies (d) represents the total data collection of respective concrete (continued) (see online version for colours)



(c) (d)

9 Data analysis

For evaluating general characteristics of FA concrete from the large datasets collected from the reported results by various researchers, however, it becomes important to extract the information from a large population of datasets to represent the average behaviour statistically that would represent/help in obtaining the mean population statics along with the variability of concerned engineering parameter for the design process as well as various application in the field/industry. Authors have selected suitable statistical functions such as normal, lognormal, and Weibull for identifying the best fitting model to capture the realistic behaviours according to the available data sample. The characteristics of these functions are discussed as follows such as:

1 *Normal distribution function:* A function that represents the distribution of many random variables as a symmetrical bell-shaped graph. The normal distribution is useful because of the central limit theorem. In its most general form, under some conditions (which include finite variance), it states that averaging of observed samples represents random variables independently drawn from independent distributions to the normal, become normally distributed when the number of observations is sufficiently large or infinite mathematically. Physical quantities expected to be the sum of many independent processes (such as measurement errors) often have distributions that are nearly normal. Moreover, many results and methods (such as propagation of uncertainty and least squares parameter fitting) could be derived analytically in explicit form when the relevant variables are normally distributed. The probability density function of the normal distribution is as:

$$f\left(x \middle| \mu, \sigma^2\right) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

where

- μ is the mean or expectation of the distribution (and also its median and mode)
- σ is the standard deviation
- σ^2 is the variance.

2 *Lognormal distribution function:* In probability theory, a lognormal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. Thus, if the random variable X is log-normally distributed, then $Y = \ln(X)$ has a normal distribution. Likewise, if Y has a normal distribution, then the exponential function of Y, $X = \exp(Y)$, has a lognormal distribution. A random variable which is log-normally distributed takes only positive real values. The probability density function of the lognormal distribution could be expressed in the following form:

$$f_X(x) = \frac{1}{x}\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right) \quad (2)$$

where

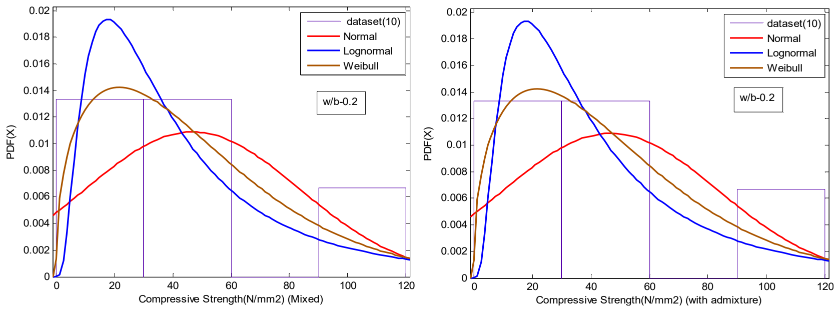
- μ is the mean or expectation of the distribution (and also its median and mode)
- σ is the standard deviation
- σ^2 is the variance.

3 *Weibull distribution function:* The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. It is a resourceful distribution that could take on the characteristics of other types of distributions, based on the value of the shape parameters. This function becomes feasible to analyse the life time failure such as hazard rate; life cycle cost studies and time dependant failure of a system according the ages. The probability density function of the Weibull function is

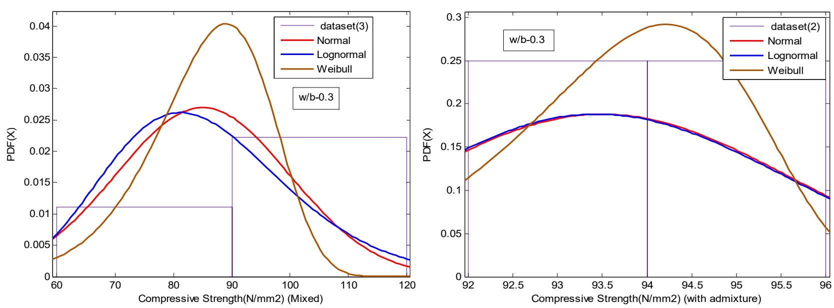
$$f(x, \lambda, k) = (k/\lambda)(x/\lambda)^{k-1} e^{-(x/\lambda)^k} \text{ for } x \geq 0 \text{ and } 0 \text{ for } x < 0 \quad (3)$$

where $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution. Its complementary cumulative distribution function is a stretched exponential function. This distribution is related to a number of other probability distributions; in particular, it interpolates between the exponential distribution ($k = 1$) and the Rayleigh distribution ($k = 2$) and $\lambda = \sqrt{2}\sigma$. The models were shown (Figure 9) in the following form considering the compressive strength data varying w/b ratios such as 0.2, 0.3, 0.4, 0.5, 0.55 and 0.6 (with admixture, without admixture, and mixed form) as well as the analysis of results such as mean and variance presented in tabular form in Table 1.

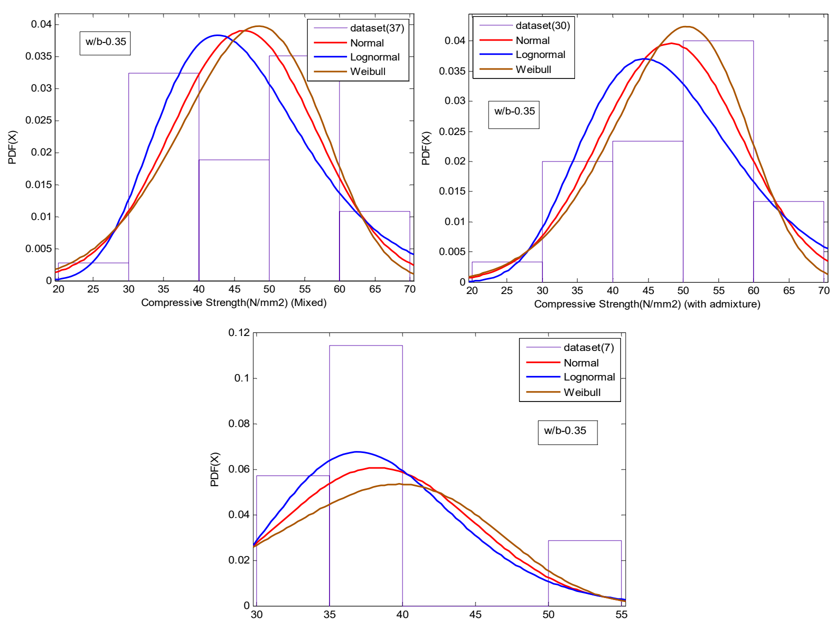
Figure 9 All various compressive strength statistical models at various water-binder ratios presented considering such as normal, lognormal and Weibull distribution functions, (a) at w/b ratio 0.2 (b) at w/b ratio 0.3 (c) at w/b ratio 0.35 (d) at w/b ratio 0.4 (e) at w/b ratio 0.5 (f) at w/b ratio 0.55 (g) at w/b ratio 0.6 (see online version for colours)



(a)

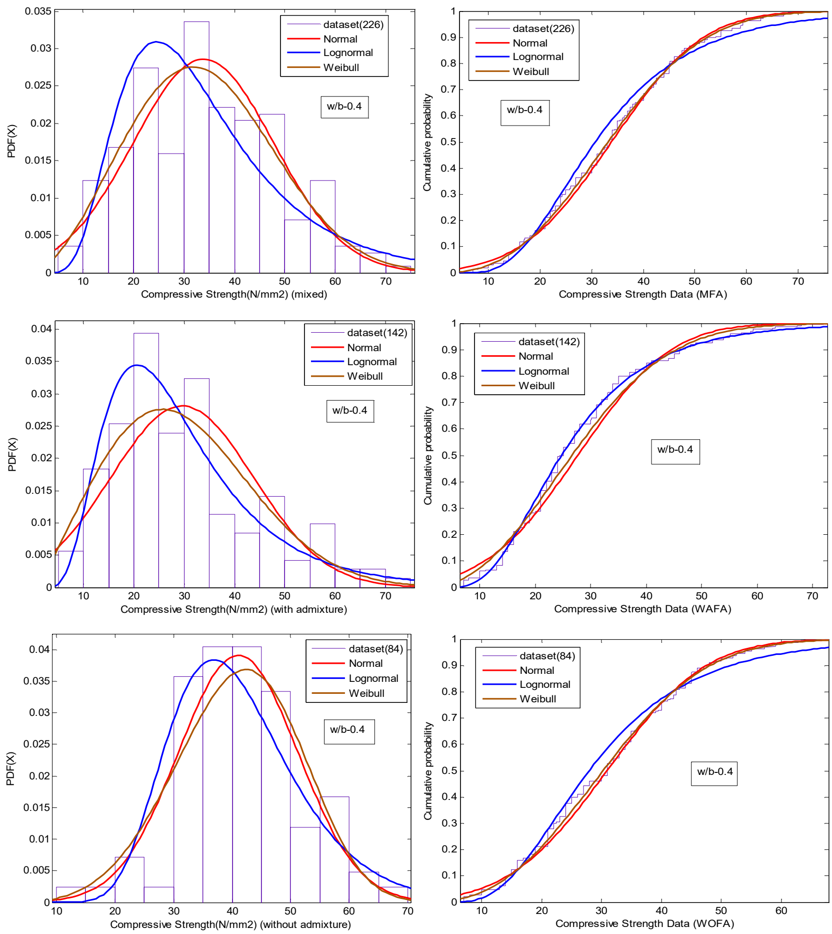


(b)

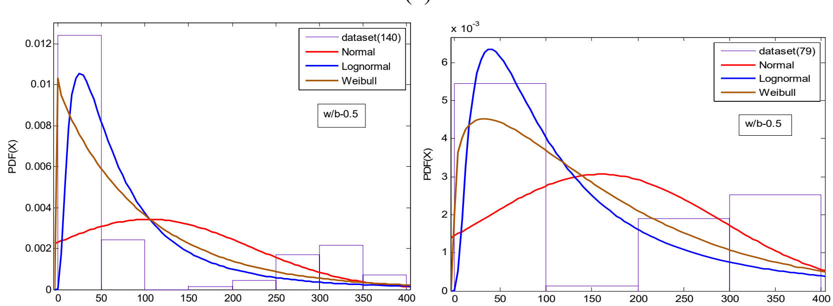


(c)

Figure 9 All various compressive strength statistical models at various water-binder ratios presented considering such as normal, lognormal and Weibull distribution functions, (a) at w/b ratio 0.2 (b) at w/b ratio 0.3 (c) at w/b ratio 0.35 (d) at w/b ratio 0.4 (e) at w/b ratio 0.5 (f) at w/b ratio 0.55 (g) at w/b ratio 0.6 (continued) (see online version for colours)

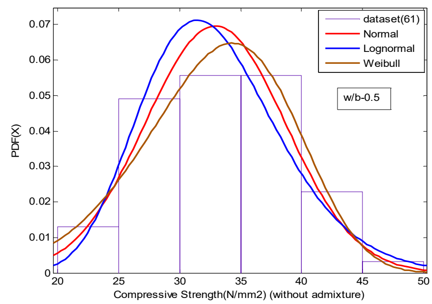


(d)

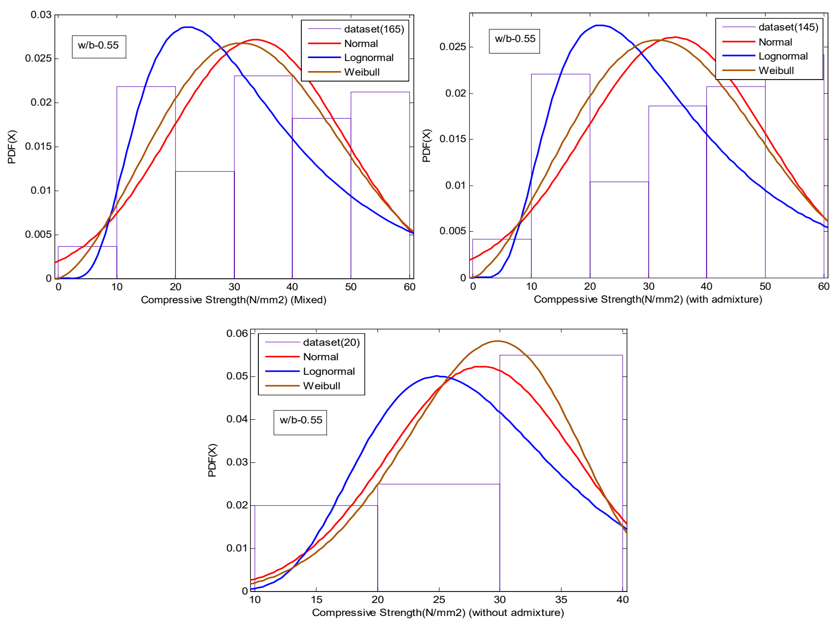


(e)

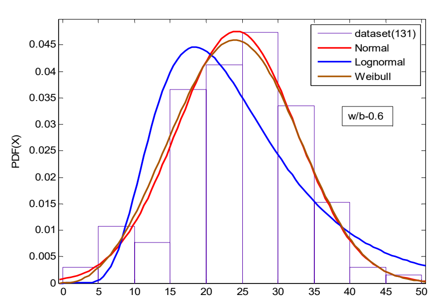
Figure 9 All various compressive strength statistical models at various water-binder ratios presented considering such as normal, lognormal and Weibull distribution functions, (a) at w/b ratio 0.2 (b) at w/b ratio 0.3 (c) at w/b ratio 0.35 (d) at w/b ratio 0.4 (e) at w/b ratio 0.5 (f) at w/b ratio 0.55 (g) at w/b ratio 0.6 (continued) (see online version for colours)



(e)



(f)



(g)

9.1 Data statistics for selecting best fit model

Earlier the models at various water-binder ratios have been shown as well as extracted and used many data about these models for selecting best fit models shown in Table 1. It has been found that mixed compressive strength data sample having 757 no's found for water-binder ratio ranging from 0.2–0.6 exhibiting that the best fit model follows Weibull distribution in maximum case. From Table 1, considering these aspects, authors could conclude that the best fitting function for mixed sample may be due to mixing of the various characteristics of the materials. Alternatively, it could be concluded that for the mixed grade of FA concrete, Weibull distribution would be the appropriate distribution to represent the real characteristics of the concrete mix grade. Further, it has been found from Table 2 that in case of sample (with admixture) exhibits the best fitting function following lognormal in maximum case. Similarly from Table 3, the sample (without admixture or normal FA concrete) shows the best fitting functions are the normal and lognormal in maximum cases.

Table 1 Compressive strength (mixed)

Water-binder ratio (w/b)	*Weibull parameters (scale and shape)*	*Mean value (N/mm^2)*	*Standard deviation (N/mm^2)*	*Log likelihood value*	*Type of model*	*Best fit model*
0.2	Scale-51.71	46.8	36.64	–49.7	Normal	Lognormal
	Shape-1.41	3.55	0.82	–47.38	Lognormal	
		47.07	33.77	–47.6	Weibull	
0.3	Scale-90.01	85	14.8	–11.84	Normal	Weibull
	Shape-9.82	4.43	0.18	–11.98	Lognormal	
		85.57	10.47	–11.45	Weibull	
0.35	Scale-50.36	46.35	10.22	–138.01	Normal	Weibull
	Shape-5.34	3.81	0.23	–139.71	Lognormal	
		46.41	10	–137.51	Weibull	
0.4	Scale-38.17	33.86	13.96	–916.02	Normal	Weibull
	Shape-2.62	3.42	0.46	–923.15	Lognormal	
		33.91	13.87	–910.75	Weibull	
0.5	Scale-103.83	104.49	116.26	–863.97	Normal	Lognormal
	Shape-0.98	4.13	0.94	–769.10	Lognormal	
		104.39	105.7	–790.85	Weibull	
0.55	Scale-38.07	33.73	14.7	–677.15	Normal	Weibull
	Shape-2.52	3.39	0.54	–692.9	Lognormal	
		33.8	14.31	–674.37	Weibull	
0.6	Scale-27	24.22	8.38	–463.96	Normal	Normal
	Shape-3.19	3.10	0.43	485.06	Lognormal	
		24.18	8.3	–464.42	Weibull	

Table 2 Compressive strength (with admixture)

Water-binder ratio (w/b)	*Weibull parameters (scale and shape)*	*Mean value (N/mm^2)*	*Standard deviation (N/mm^2)*	*Log likelihood value*	*Type of model*	*Best fit model*
0.2	Scale-51.71	46.8	36.64	–49.7	Normal	Lognormal
	Shape-1.41	3.55	0.82	–47.38	Lognormal	
		47.07	33.77	–47.6	Weibull	
0.35	Scale-52.12	48.23	10.07	–111.35	Normal	Weibull
	Shape-5.92	3.85	0.23	114.18	Lognormal	
		48.31	9.47	–110.31	Weibull	
0.4	Scale-55.36	29.62	14.18	–577.58	Normal	Lognormal
	Shape-2.23	3.27	0.49	–566.13	Lognormal	
		29.72	14.06	–568.82	Weibull	
0.5	Scale-168.98	159.74	130.25	–496.28	Normal	Lognormal
	Shape-1.17	4.63	0.98	–477.16	Lognormal	
		160	137.02	–478.39	Weibull	
0.55	Scale-38.89	34.46	15.3	–600.8	Normal	Weibull
	Shape-2.47	3.4	0.56	–617.02	Lognormal	
		34.5	14.88	–598.87	Weibull	

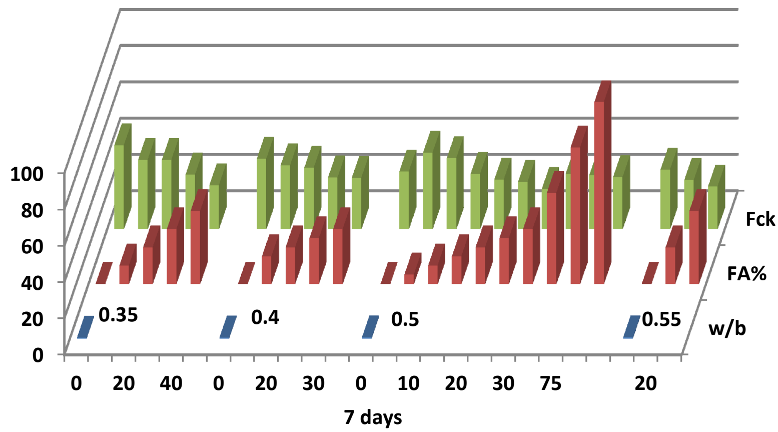
Table 3 Compressive strength (without admixture)

Water-binder ratio (w/b)	*Weibull parameters (scale and shape)*	*Mean value (N/mm^2)*	*Standard deviation (N/mm^2)*	*Log likelihood value*	*Type of model*	*Best fit model*
0.35	Scale-41.02	32.8	6.57	–22.61	Normal	Lognormal
	Shape-5.85	3.63	0.15	–21.95	Lognormal	
		38	7.52	–23.35	Weibull	
0.4	Scale-44.93	41.03	10.2	–313.80	Normal	Normal
	Shape-4.37	3.68	0.27	–318.47	Lognormal	
		40.94	10.59	–315.01	Weibull	
0.5	Scale-35.34	32.93	5.73	–192.57	Normal	Lognormal
	Shape-6.13	3.47	0.17	–192.10	Lognormal	
		32.83	6.23	–194.69	Weibull	
0.55	Scale-28.47	28.47	7.62	–68.5	Normal	Normal and Weibull
	Shape-7.62	3.3	0.3	–70.32	Lognormal	
		28.64	7.62	–68.5	Weibull	
0.6	Scale-26.47	23.96	8.35	–449.33	Normal	Normal
	Shape-3.15	3.09	0.44	–469.19	Lognormal	
		23.92	8.30	–449.80	Weibull	

9.2 3D model graphical explanations

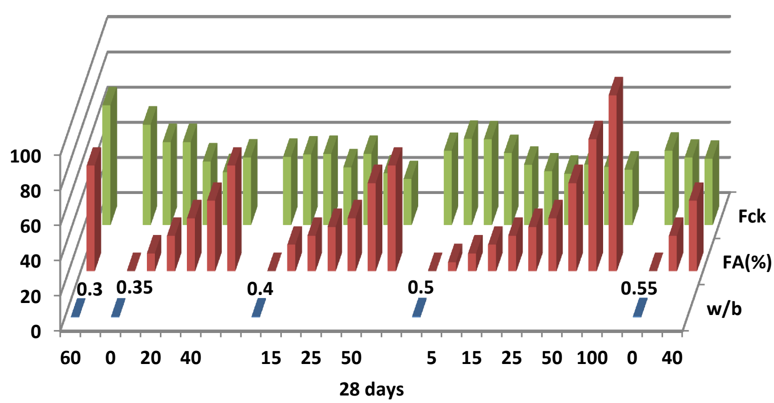
Further, considering the datasets obtained, an attempt has been made to represent all collected sets of catalogue in the form of 3D graphs depicted on the basis of w/b ratio (0.2–0.6), FA% replacement (0–100%) and curing ages (from 7–365 days) regarding compressive strength. All graphs and their respective rationalisation are given in Figures 10–29.

Figure 10 Compressive strength in aspect of all w/b ratio and FA% for MFA concrete at seven days (see online version for colours)



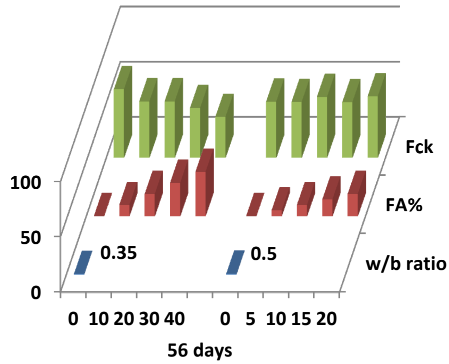
From this graphical model (Figure 10), it has been seen that at all w/b ratios, with increasing the FA%, there is a general trend of decreasing of compressive strength at seven days.

Figure 11 Compressive strength in aspect of all w/b ratio and FA% for MFA concrete at 28 days (see online version for colours)



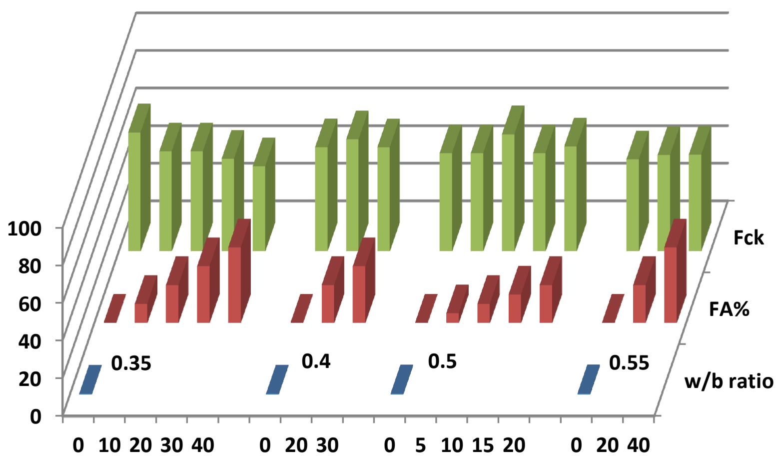
From this graphical model (Figure 11), it has been seen that at all w/b ratio, with increasing the FA%, there is general trend of decreasing of compressive strength.

Figure 12 Compressive strength in aspect of all w/b ratio and FA% for MFA concrete at 56 days (see online version for colours)



From this graphical model (Figure 12), it has been seen that at w/b ratio 0.35 with increasing of FA%, represents decreasing of compressive strength, but at w/b ratio 0.5 with increasing of FA%, no significant change observed, rather at 10% FA replacement it has been seen that compressive strength becomes slightly higher.

Figure 13 Compressive strength in aspect of all w/b ratio and FA% for MFA concrete at 90 days (see online version for colours)



From this graphical model (Figure 13), it has been seen that except w/b 0.35, in all cases compressive strength becomes approximately equal/same at 90 days for all FA% and w/b ratios. Indeed, at w/b ratio 0.4 and 0.5, a high compressive strength observed for 20% and 10% of FA replacement successively. Also, at w/b ratio 0.55, a slight increase of compressive strength found at 20% FA and thereafter remains same up to 40%.

From this graphical model (Figure 14), it has been observed that at 0.35 w/b ratio, the compressive strength becomes higher for controlled concrete (FA, 0%) and there after strength gradually decreasing. At w/b ratio 0.4, it has been observed that at 20% FA replacement, strength exhibits higher, whereas at 30% replacement, strength becomes almost same with controlled concrete. Further at w/b ratio 0.55, there are no significant changes of strength.

Figure 14 Compressive strength in aspect of all w/b ratio and FA% for MFA concrete at 180 days (see online version for colours)

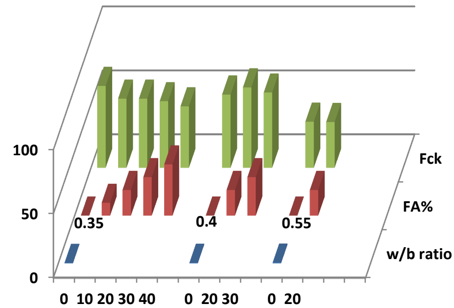


Figure 15 Compressive strength in aspect of all w/b ratio and FA% for MFA concrete at 365 days (see online version for colours)

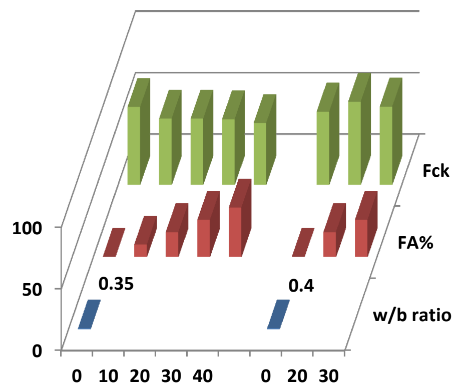
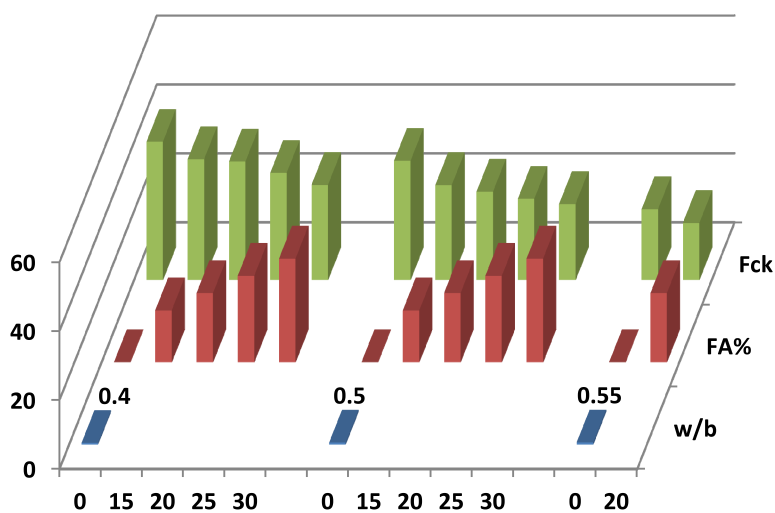


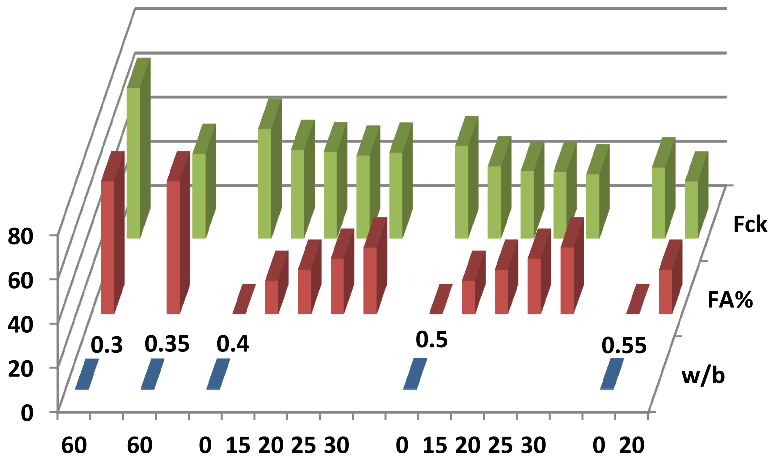
Figure 16 Compressive strength in aspect of all w/b ratio and FA% for WOFA concrete at seven days (see online version for colours)



Similarly, from this graphical model (Figure 15), it has been observed that, at w/b ratio 0.35, strength is higher for controlled concrete and there after strength becomes gradually decreasing up to 40%. However, at w/b ratio 0.4 with 20% FA replacement, strength exhibits higher and at 30% replacement, strength almost similar with controlled concrete.

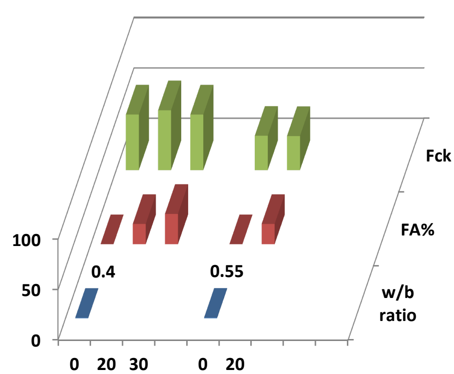
Similarly, from this graphical model (Figure 16), it has been seen that, strength decreasing gradually for all w/b ratio with increasing FA replacement percentages.

Figure 17 Compressive strength in aspect of all w/b ratio and FA% for WOFA concrete at 28 days (see online version for colours)



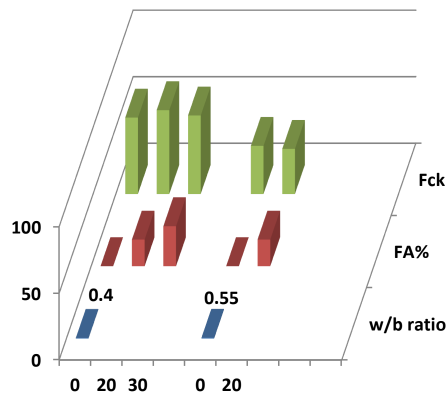
From this graphical model (Figure 17) considering 28 days, it is seen that at w/b ratio 0.3, strength becomes higher than other strength. For all other w/b ratio, it is observed that with increasing FA percentages, strength gradually decreasing.

Figure 18 Compressive strength in aspect of all w/b ratio and FA% for WOFA concrete at 90 days (see online version for colours)



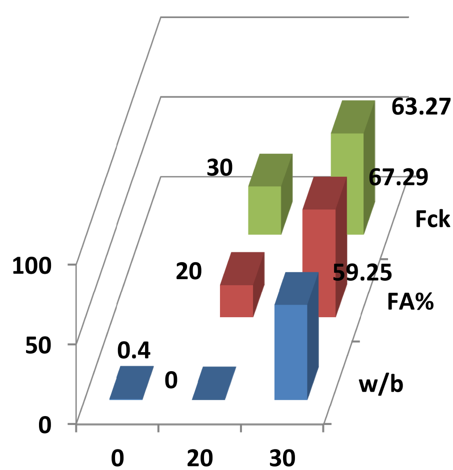
From this graphical model (Figure 18) considering 90 days, it is seen that at w/b ratio 0.4 with 20% FA replacement, strength becomes higher and thereafter at 30% FA replacement, strength almost similar with controlled concrete. At w/b ratio 0.55, there is approximately same strength observed.

Figure 19 Compressive strength in aspect of all w/b ratio and FA% for WOFA concrete at 180 days (see online version for colours)



From this graphical model (Figure 19) considering 180 days, it is seen that at w/b ratio 0.4 with 20% FA replacement, strength is higher and thereafter at 30% FA replacement, strength is almost similar with controlled concrete. At w/b ratio 0.55, approximately same strength is being observed.

Figure 20 Compressive strength in aspect of all w/b ratio and FA% for WOFA concrete at 180 days (see online version for colours)



From this graphical model (Figure 20) considering 180 days, it is seen that at w/b ratio 0.4 with 20% FA replacement strength becomes higher than others.

Alternatively, considering WAFA concrete data, with the graphical model shown in (Figure 21), it is observed that in all cases with increasing of FA%, strength becomes gradually decreasing. But there is an exception that at w/b ratio 0.5 with 5% FA replacement, strength becomes higher than controlled concrete.

Indeed, from this graphical model (Figure 22), it is observed that there is general trend of decreasing compressive strength with increasing FA%. But there are some exceptions that at 0.4 and 0.5 successively with 20% and 5% FA, higher strength noticed for 28 days curing.

Figure 21 Compressive strength in aspect of all w/b ratio and FA% for WAFA concrete at seven days (see online version for colours)

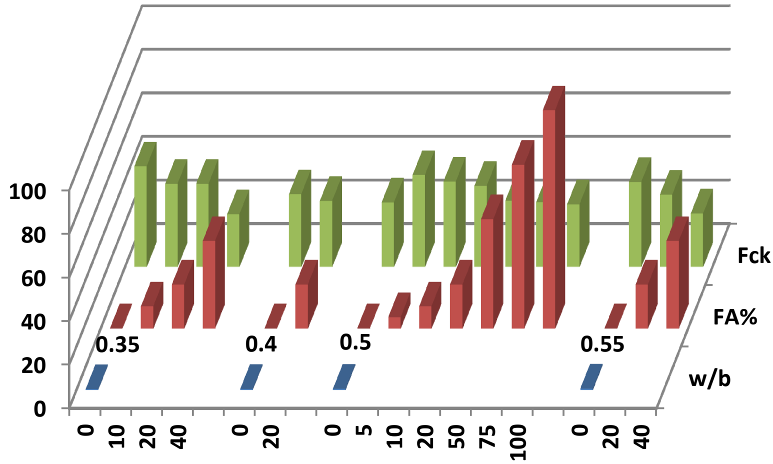
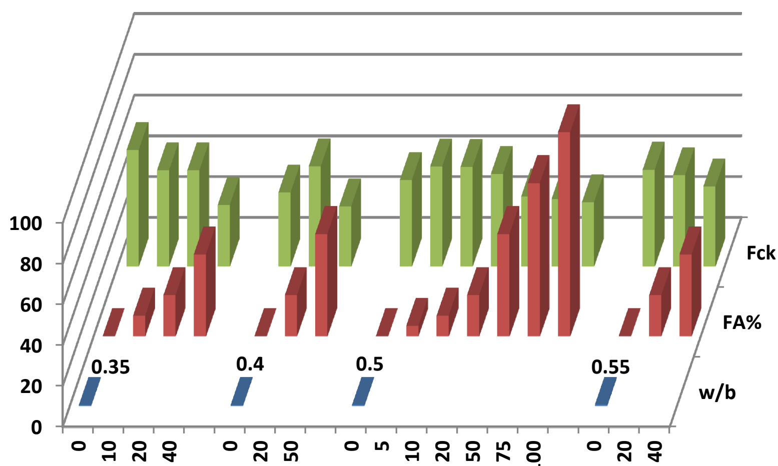


Figure 22 Compressive strength in aspect of all w/b ratio and FA% for WAFA concrete at 28 days (see online version for colours)



From this graphical model (Figure 23), it is observed that there is general trend of decreasing compressive strength with increasing FA%. But, there is some exception that at w/b ratio 0.5 with 10% FA replacement higher strength observed for 56 days curing.

From this graphical model (Figure 24) considering 90 days, it is seen that in all maximum case, compressive strength decreasing with increasing of FA%. But, there are some exceptional case that at w/b ratio 0.4, 0.5 and 0.55, successively with 20%, 10% and 20% FA replacement, there are comparatively higher strength observed at 90 days curing compared to 28 and 56 days.

Figure 23 Compressive strength in aspect of all w/b ratio and FA% for WAFA concrete at 56 days (see online version for colours)

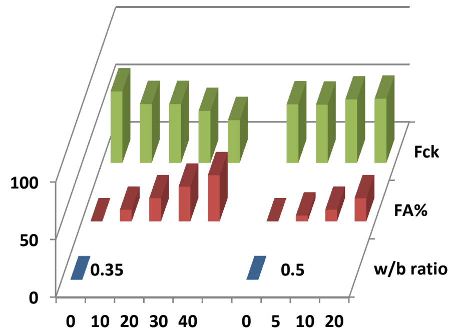


Figure 24 Compressive strength in aspect of all w/b ratio and FA% for WAFA concrete at 90 days (see online version for colours)

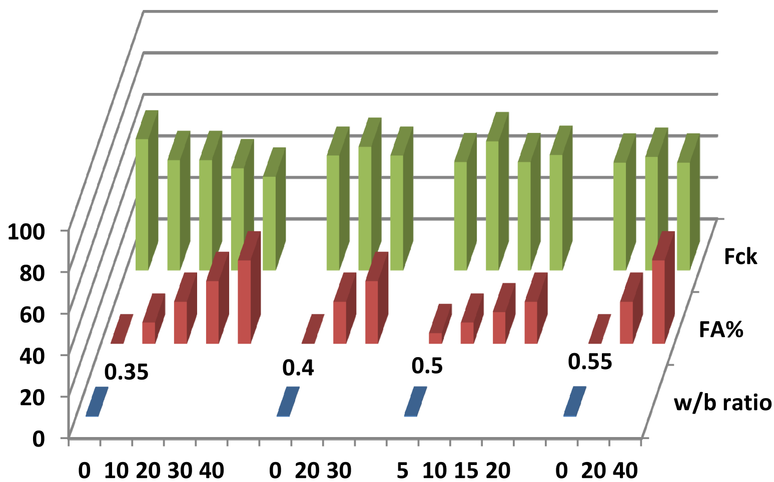
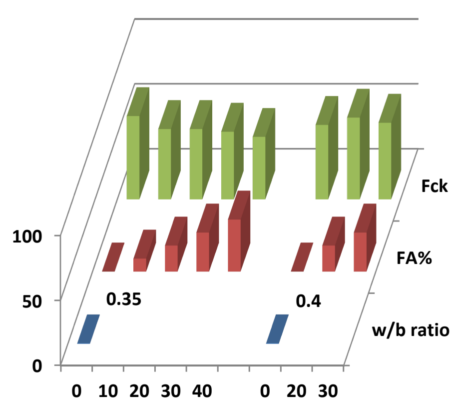
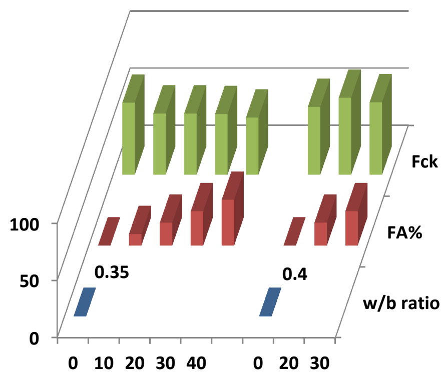


Figure 25 Compressive strength in aspect of all w/b ratio and FA% for WAFA concrete at 180 days (see online version for colours)



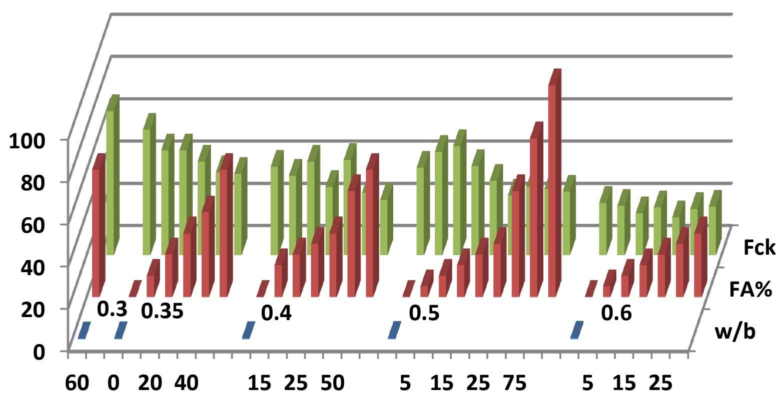
From this graphical model (Figure 25) considering 180 days, it has been observed that there is general tendency of decreasing strength in all cases. But, there is exception that at w/b 0.4 with 20% FA, showing higher strength.

Figure 26 Compressive strength in aspect of all w/b ratio and FA% for WAFA concrete at 365 days (see online version for colours)



From this graphical model, generally it is noticed that there becomes a trend of decreasing strength. But, there is higher strength observed at w/b ratio 0.4 with 20% FA, than earlier strength found for 28, 56 and 90 days.

Figure 27 Compressive strength in aspect of FA% and w/b ratio respectively for all days for MFA concrete (see online version for colours)



Considering all the datasets irrespective of ages has been drawn in graphical model shown in Figure 27, however, generally noticed that there is a trend of decreasing strength in maximum cases. The highest strength observed for at w/b ratio 0.3 with 60% FA, among all cases. However, higher strength observed at w/b ratio 0.4 with 20% FA, w/b ratio 0.5 with 10% FA with w/b ratio 0.6 with 15% FA.

From this graphical model (Figure 28), generally it is noticed that there is a trend of decreasing strength in maximum case. The highest strength is observed at w/b ratio 0.3 with 60% FA, among all cases. There is some exception that the higher strength observed at w/b with 20% FA and 30% FA and at w/b 0.6 with 15% FA.

Figure 28 Compressive strength in aspect of FA% and w/b ratio respective all days for WOFA concrete (see online version for colours)

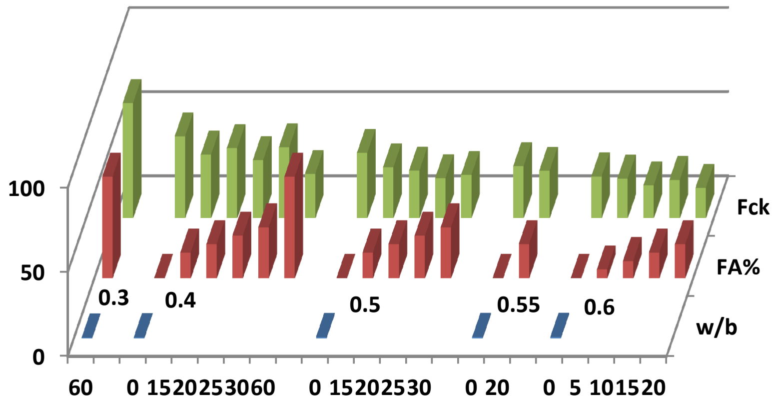
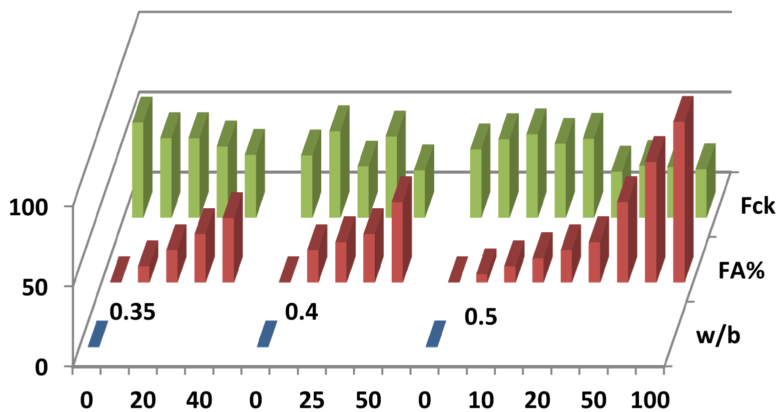


Figure 29 Compressive strength in aspect of FA% and w/b ratio respective all days for WAFA concrete (see online version for colours)



From this graphical model (Figure 29), generally noticed that there is a trend of decreasing strength in all cases. The highest strength observed for at w/b ratio 0.35 with controlled concrete. It is observed in some exception that at w/b ratio 0.4 with 20% and 50% replacements and likewise at w/b ratio 0.5 with 10% and 20% replacements, a higher compressive strength observed. However, from this study, it could be understood that, in general, FA, w/b ratio and admixture has a great influence on compressive strength on FA concrete, indeed of these parameters, the most influential parameter becomes the w/b ratio indicating at lower w/b ratio (i.e., 0.3) even with 60% FA replacement provides higher comprehensive strength (in case of MFA and WOFA) in FA concrete. However, in case of WAFA concrete, with 0.35 w/b ratio provides higher strength at 0% FA indicating limitation of using admixture in FA concrete production, reduces the application of FA.

10 Water-binder ratio

Water-binder ratio is the most important parameter in the concrete mix design, as well as crucial for fresh and hardened concrete provides the mobility, consistency and forming homogeneous composition of products after chemical reaction or hydration among the ingredients present in the materials that develops strength in concrete. Generally, it has been noticed that with increasing of water-binder ratio, compressive strength exponentially decreased. There are many studies conducted experimentally regarding water-binder ratio that varies between 0.21–0.94 respectively (Vakhshouri and Nejadi, 2016). Dinakar et al. (2013) showed that for the normal weight concrete with increasing w/b ratio, compressive strength decreases. However, based on the present study with the collected data from various studies reported by researchers, an attempt has been made to show some relationships about compressive strength vs. w/b relationship for normal weight FA concrete considering, with, without and mixed data (Figures 30, 31 and 32). It has been observed that the highest R^2 value found for without admixture FA concrete and the lowest found with admixture FA concrete that representing the abrupt decrease of strength gaining in the mix obtained from population of data samples and intermediate values shows in mixed data of FA concrete. The best fitting is being found with the exponential distribution function representing the similar trends of decreasing, as w/b ratio goes on increasing that normally varies 0.3–0.6 or indicating higher w/b ratio reduces gaining lower strength. Alternatively, the reason for obtaining higher R^2 in case of without admixture may be due to gradual increase of compressive strength with the w/b ratio whereas in presence of admixture reaction takes accelerated mode, however, abruptly decrease in presence of more water present in the mix/gel may isolate to participating in the chemical process and the resulting outcome reduces strength of concrete.

Figure 30 Relationship between compressive strength vs. w/b ratio for mixed FA concrete (see online version for colours)

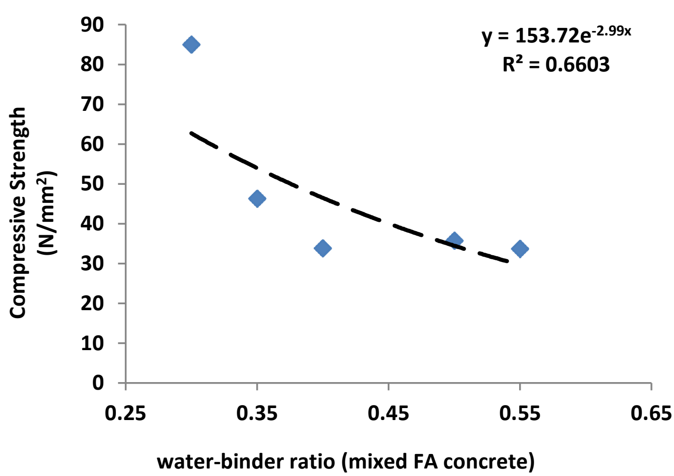


Figure 31 Relationship between compressive strength vs. w/b ratio for with admixture FA concrete (see online version for colours)

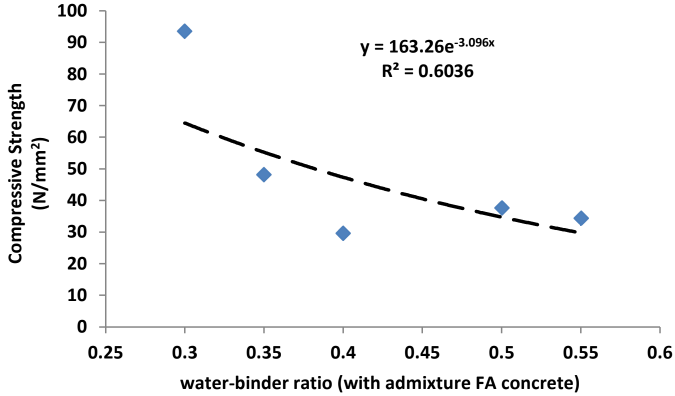
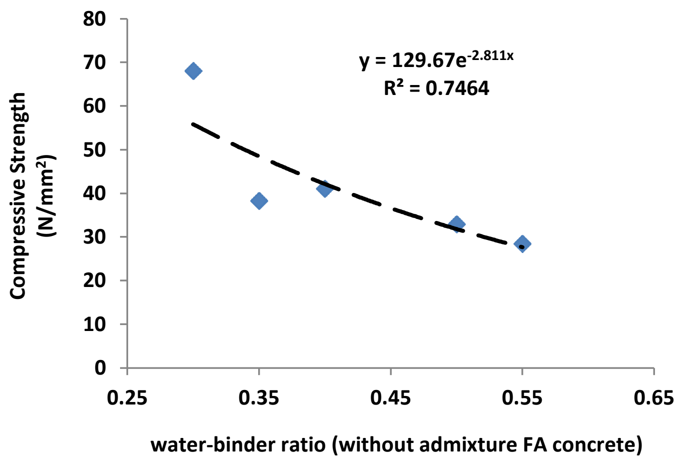


Figure 32 Relationship between compressive strength vs. w/b ratio for without admixture FA concrete (see online version for colours)



Moreover, Figures 30, 31 and 32, it has been shown that in every case with increasing w/b ratio, compressive strength decreasing in all cases. We have reviewed on FA concrete in three categories stated above and like to articulate that Figures 30, 31 and 32, the results validated by the figure of w/b ratio reported by Dinakar et al. (2013). From the Figures 30, 31 and 32 shown that, the regression becomes very high for without admixture FA concrete, slightly less for mixed FA concrete and lowest for with admixture FA concrete. However, with admixture FA concrete, decreasing compressive strength with w/b ratio exhibits successively lower than other two. Hence, we may say that there are beneficial effects of admixture on FA concrete for quick gaining strength at min w/b ratio where strength gaining becomes necessary in much faster way that may reduce even the stripping time. It was reported by Dinakar et al. (2013), to represent the general concept of relationship for compressive strength vs. w/b ratio of FA concrete in their work. However, in the present work, an attempt has been made to gain more insights/specific general characteristics classifying/categorising among the mixed FA concrete, with admixture FA concrete and without admixture FA concrete. There is 10–15% increment of strength due to metakaolin (MK) in early period as well as for long period too. This result found from both physical and chemical effects even after increasing of w/b ratio (Wild et al., 1996). There are high early strength of MK-rich ternary mixtures than FA-rich mixtures because, having the greater inertness of FA than MK which produces calcium silicate hydrate very fast during the hydration process (Siddique and Klaus, 2009). Depending on curing, metakaolin binary mixture develops greater compressive strength than normal concrete. However, the compressive strength also varies with the replacement % of binder and greatly showing the applicability of FA in concrete.

11 Effects considering FA replacement percentage in compressive strength of concrete

Siddique et al. (2012) has shown that with increasing of FA content, compressive strength decreasing gradually. It is observed that with increasing of ages compressive strength increasing. He has also shown that higher compressive strength observed in every FA% in aspect of days. In the present study investigated with the data in three different ways, considering all three classes. These all are shown in Figures 33, 34 and 35, respectively. However, from Figures 33–35, initial compressive strength goes on decreasing with the increase of FA till 20% in case of mixed and without admixture FA concrete, however thereafter increases continuously. It has also been observed that strength gaining becomes almost two times at later ages for an every FA%. Therefore, initial strength could only be achieved through addition of admixture with FA concrete. However, it is has been found from this study that later age strength becomes much higher than even normal concrete, hence recommended for massive construction works such as foundation structures. This study provides a clear understanding about the utility of FA in concrete production process in a wide spread manner as one of the construction materials in industry along with it applicable ranges that would help while in mix design using FA as one of the ingredients in mix.

Figure 33 Compressive strength vs. FA (%) in aspect of days in the form of mixed FA concrete (see online version for colours)

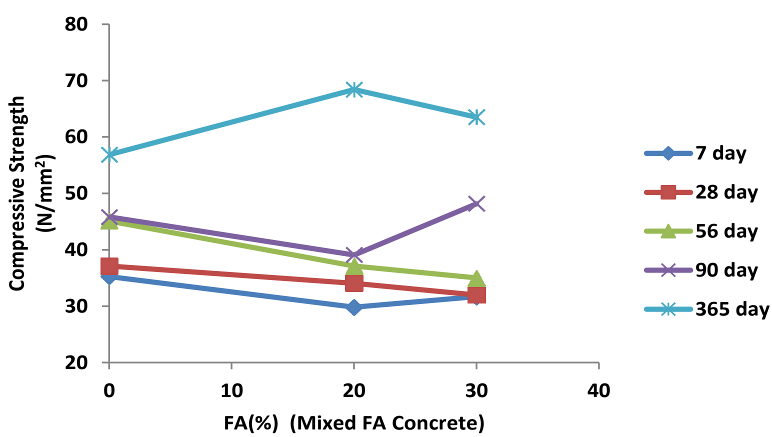


Figure 34 Compressive strength vs. FA (%) in aspect of days in the form of with admixture FA concrete (see online version for colours)

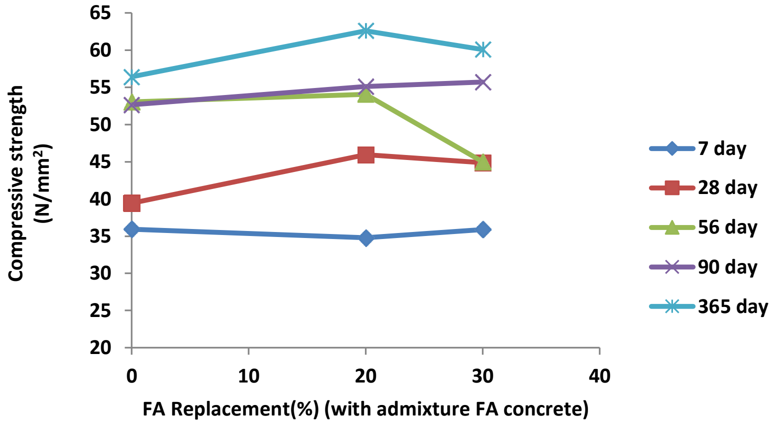
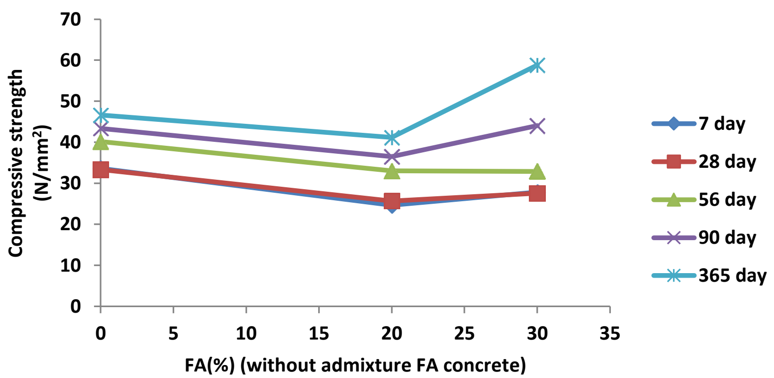


Figure 35 Compressive strength vs. FA (%) in aspect of days in the form of without admixture FA concrete (see online version for colours)



On the other hand, alternatively, from Figure 33, it is shown that initial strength becomes higher for 365 days curing than other days and near about 57–60 N/mm^2. It is also seen that in every case higher curing days provides relatively higher strength than lower curing days. We have got values in aspect of various curing in days at 0%, 20% and 30% of FA replacement of concrete. Further, it is observed that in all cases except for 365 days, strength getting decreased specifically at 20% FA replacement and thereafter the strength decreased at 30% FA replacement for all days except 7 and 90 days of curing.

Again from Figure 34, it is shown that initial strength is higher for 365 days curing than other days and it becomes near about 57–60 N/mm^2. It conveys that in every case, higher days provides relatively higher strength than lower curing days. We have got values in aspect of various curing days at 0%, 20% and 30% of FA replacements of concrete. It is observed that in all cases, strength increased at 20% FA replacement except seven days strength and thereafter strength decreased suddenly at 30% FA replacement for all days except 7 and 90 days. However, from Figure 35, it is shown that initial strength becomes higher for 365 days curing than other days and about 48–50 N/mm^2. It represents that in every case, higher days would give relatively higher strength than the low curing days. We have got values in aspect of various curing days at 0%, 20% and 30% of FA replacement of concrete. It is observed that in all cases at 20% FA replacement, strength decreased and again at 30% replacement strength increased for all days except 56 days.

In general, there is reducing of compressive strength due to addition of FA at an early age. Indeed, at FA 20%, highest strength found, this may be due to increasing of products of pozzolanic reaction after curing along long time (Golewski, 2018a, 2018b). Further, it has been found that the compressive strength becomes increased till by 20% replacement of FA and decreased gradually thereafter. At 365 days by 20% FA replacement optimum strength is found. The reason of increment of strength is that the more reaction between alkalis and OPC. There are also CASH and C-SH found as an additional product during hydration which remain in additional period with NASH. The polymerisation produces more heat because of hydration reaction. Hardening acceleration and dissolution due to more sites of nucleation occurred by additional calcium. There is no remarkable increment of strength after seven days. The trend of increasing compressive strength occurred about at by 20–30% FA replacement (Mehta and Siddique, 2017). It is noticed that for high range of compressive strength gained at by replacement of 20% FA due to higher percentage of SiO_2 content (61.4%) which increases pozzolanic reaction in long-term. The compressive strength found higher at 20% FA replacement with 10% free lime admixture at early age. At later age mixture with 20% FA replacement gives higher strength than 20% FA replacement mixture with added of free lime including percentages of 5%, 7% and 10%. The main reason of increasing the compressive strength due to inclusion of free lime content, (FA and calcium hydroxide reacted with each other) at an early ages. Calcium increases the smoothness of the FA (Somna and Bumrongjaroen, 2011). The CSH gel form by calcium oxide and free lime (Yip et al., 2005; Alonso and Palomo, 2001; Kumar et al., 2010). The early strength gained by free lime component (Nawaz et al., 2016). Free lime particles are easily accessible and go through quick hydration. For initial function of FA, there are requirements of appropriate amount of free lime which gives much more strength (Tsimas and Moutsatsou-Tsima, 2005). Saha (2017) reported that quick strength gained by 20% FA replacement in presence of admixture. The Christy and Tensing (2010) presented that a higher strength found of FA concrete containing 20% FA replacement instead of fine aggregate than controlled concrete.

12 Effects of age on FA concrete with various FA fraction

From Figures 36, 37 and 38, it has been seen that the regression value becomes highest for ‘without admixture’ concrete and the lowest for ‘with admixture’ concrete. Also observed that the initial strength shown highest for ‘with admixture concrete’ and lowest for ‘without admixture concrete’. For both cases, mixed concrete becomes in medium state. Golewski (2018a, 2018b) has reported that increasing of strength is occurred between 7 to 28 days with admixture FA concrete and it continued approximately up to 90 days. It happened for the sharp increment of pozzolanic reaction materials after long periods. Nawaz et al. (2016) described that strength of FA found higher than controlled concrete for 91 days. They have also reported that comparatively higher strength observed for ‘with admixture’ FA concrete. Saha (2017) presented that at earlier ages comparatively higher strength observed from 7 to 28 days, thereafter up to one year, there is no significant changes. Again, there is lower compressive strength due to addition of FA at earlier ages for less content of lime. It is also observed that gaining of strength becomes quick from 7–90 days curing due to 20% FA replacement and thereafter up to 30–40% of FA, gaining of more strength due to for 7–180 days. Moreover, there are gaining about 80–90% strength similar to normal concrete. Khodair and Bommareddy (2017) has reported that FA concrete gives lower strength at earlier ages than slag cement concrete. Liao et al. (2017) has presented that the increment of strength of with admixture FA concrete becomes very limited after 90 days. It is occurred due to completion of reaction of FA and MKPC between 90 days. Christy and Tensing (2010) has reported that at early age FA concrete develops higher strength than normal concrete when various type of cement mortar ratio used.

Figure 36 Relation between compressive strength vs. age (days) for mixed concrete (see online version for colours)

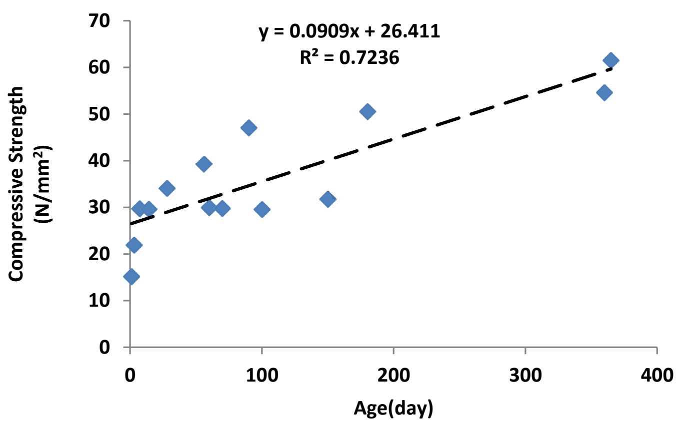
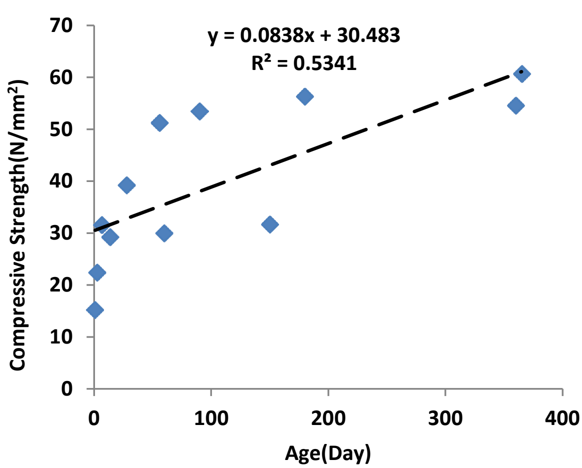
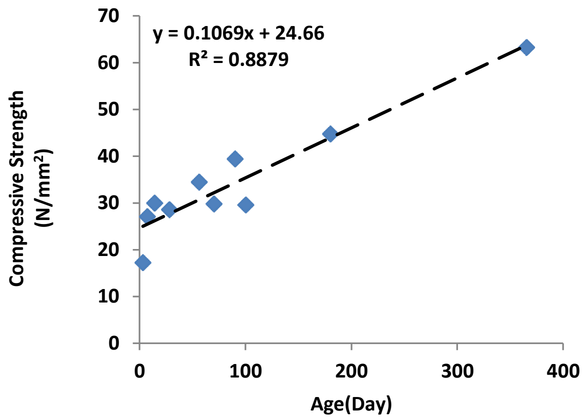


Figure 37 Relation between compressive strength vs. age (days) for with admixture concrete (see online version for colours)



Tkaczewska (2014) has presented that pozzolanic reaction underway due to the suspension of glassy layer on the outside part of FA. There is also increment of strength at initial periods due to inclusion of such type of FA which increases the rate of C3A production. Suryavanshi et al. (1996) have presented that strength development occurred due to high producing rate of C3A produced by inclusion of high content of silicon oxide. Zhao et al. (2015) described that C-S-H gel formed for the more hydration materials due to high temperatures which increases compressive strength from 7 to 28 days.

Figure 38 Relation between compressive strength vs. age (day) for without admixture concrete (see online version for colours)



13 Results and discussion

In this study, an attempt has been made to examine the relationship between compressive strength vs. water-binder ratio in the mixed, with admixture and without admixture form after extracting data/information from various papers published. The objective is to obtain comprehensive characteristics for its wide engineering application. However, to analyse more specific conception about the FA concrete, the authors have segregated the data such as mixed FA concrete, with admixture FA concrete and without admixture FA concrete. There is 10–15% increment observed, of strength due to in presence of metakaolin in early period as well as also for long period. This result was also found from both physical and chemical effects even after increasing of w/b ratio. There is high early strength of MK-rich ternary mixtures than FA-rich mixtures having the greater inertness of FA than MK which produces calcium silicate hydrate fast during the hydration process. Indeed, depending on curing, metakaolin binary mixture provides greater compressive strength than normal concrete, therefore, it is seen that proposed regression equation extracted from the data shows lower value for 'with admixture FA concrete' while comparing with the mixed and without admixture FA concrete. Among all admixture, and metakaolin has great impact on compressive strength in respect of water-binder ratio, observed from the limited study.

Further, in relation of compressive strength vs. FA replacement level in aspect of days for mixed FA concrete, it is noticed that initial strength becomes higher for 365 days curing than other days and near about 57–60 N/mm². It is also seen that in every case higher curing days give relatively higher strength than lower curing days. We have obtained values in aspect of various curing days at 0%, 20% and 30% of FA replacement of concrete and observed that in all case except for 365 days, strength decreased at 20% FA replacement and thereafter strength decreased at 30% FA replacement for all days except 7 and 90 days of curing. For the same relation observed with admixture FA concrete, and found that initial strength getting higher for 365 days curing than other days and it is near about 57–60 N/mm^2. It express that in every case higher days would give relatively higher strength than lower curing days.

Again, for the same relation observed without admixture FA concrete, it is shown that initial strength becomes higher for 365 days curing than 28, 90, 180 days and near about 48–50 N/mm^2. It represents that in every case higher days give relatively higher strength than the low curing days. Authors extracted data in aspect of various curing days at 0%, 20% and 30% of FA replacement of concrete. It is observed that in all cases at 20% FA replacement, strength decreased and at 30% replacement, strength increased again for all days except 56 days.

Further, there is reducing of compressive strength due to addition of FA at an early age. At FA 20%, there is highest strength at FA-20 for increasing of products of pozzolanic reaction after curing for long time. It has been found that the compressive strength increased till by 20% replacement of FA and it is decreased gradually afterwards. At 365 days by 20% FA replacement, optimum strength is found, the reason of increment of strength is that the more reaction between alkalis and OPC. There are also CASH and C-SH found as an additional product during hydration which remain in additional period with NASH. The polymerisation produces more heat because of hydration reaction. Hardening acceleration and dissolution due to more sites of nucleation was occurred by additional calcium. There is no remarkable increment of strength after seven days. The trend of increasing compressive strength is of about at by 20–30% FA replacement. It is observed that for high compressive strength is gained at by replacement of 20% FA due to higher percentage of SiO_2 content (61.4%) which increases pozzolanic reaction in long-term. The compressive strength is higher at 20% FA replacement with 10% free lime admixture than 20% FA replacement mixture at early age. At later age mixture with 20% FA replacement gives higher strength than 20% FA replacement mixture with added of free lime including percentages of 5%, 7% and 10% respectively. The main reason of increasing the compressive strength due to inclusion of free lime content essentially due to FA and calcium hydroxide reacted with each other at an early age. Calcium increases the smoothness of the FA. However, CSH gel was formed by calcium oxide and free lime. Free lime particles are easily accessible and go through quick hydration. For initial function of FA, there are requirements of appropriate amount of free lime which gives more strength. It has been found that quick strength gained by 20% FA replacement in presence of admixture. It is observed that a higher strength of FA concrete achieved containing 20% FA replacement instead of fine aggregate than controlled concrete.

Consequently, it is noticed that among all admixture, free lime has high influence on FA concrete at 20% FA replacement to gain higher strength observed from the limited study. From the study, approximately it is seen that with 30% FA replacement, concrete gives highest strength for ‘without as well as with admixture’ FA concrete from the limited study.

For relation between compressive strength with age, it has been noticed that regression becomes highest for without admixture FA concrete and lowest for with admixture FA concrete. The initial compressive strength value becomes highest ‘with admixture’ FA concrete and lowest for ‘without admixture’ FA concrete. It has been noticed that increasing of strength occurred between 7 to 28 days with admixture FA concrete and it continued approximately up to 90 days. The strength of FA concrete is higher than controlled concrete for 91 days. It is reported that comparatively higher strength observed with admixture FA concrete than without admixture FA concrete. It is seen that at earlier ages comparatively higher strength observed from 7 to 28 days up to one year, thereafter no significant changes. Again, there is lower compressive strength due to addition of FA at earlier ages for less content of lime, it is also observed that gaining of strength attain quickly from 7–90 days curing due to 20% FA replacement and afterwards up to 30–40% of FA. Indeed there is gaining of more strength up to 7–180 days. There are gaining about 80–90% strength of normal concrete. It has been reported that FA concrete gives lower strength at early ages than slag cement concrete. It has been presented that the increment of strength with admixture FA concrete becomes limited after 90 days. It is occurred due to completion of reaction of FA and MKPC between 90 days. It has been seen that at early age FA concrete gives higher strength than normal concrete when various type of cement mortar ratio has been used.

It is reported that the pozzolanic reaction between calcium hydroxide and FA leads to increases the compressive strength at later ages for FA concrete, however seen that pozzolanic reaction started due to the suspension of glassy layer on the outside part of FA. It has reported that FA provides higher compressive strength than cement due to high content of silicon oxide. There is also increment of strength at initial periods due to inclusion of such type of FA which increases the rate of C3A production. It has been presented that strength development occurred due to high rate of C3A produced by inclusion of high content of silicon oxide. It has been described that C-S-H gel formed for the more hydration materials due to high temperatures which increases compressive strength from 7 to 28 days. It has been observed that with admixture FA concrete, initial strength gaining for 7–28 days and this strength gaining becomes limited up to 90 days, thereafter, strength gaining more or less becomes same and initial strength becomes higher. For without admixture FA concrete, initial strength gaining exhibits lower than with admixture FA concrete and strength increasing at later ages approximately up to 365 days which examined by this study. This study would provide the overall general engineering characteristics of various FA%, w/b ratio and effects of admixture on FA concrete.

References

ACI (1979) *ACI Manual of Concrete Practice*, American Concrete Institute [online] https://books.google.co.in/booksid=HTGHnQEACAAJ.

Alasali, M. and Malhotra, V. (1991) 'Role of concrete incorporating high volumes of fly ash in controlling expansion due to alkali aggregate reaction', *ACI Mater. J.*, Vol. 88, No. 2, pp.159–163, American Concrete Institute (ACI), ISSN: 0889-325X [online] https://www.concrete.org/publications/acimaterialsjournal.aspx.

Alonso, S. and Palomo, A. (2001) 'Alkaline activation of metakaolin and calcium hydroxide mixtures: influence of temperature, activator concentration and solids ratio', *J. Mater. Lett. Res.*, Vol. 47, Nos. 1–2, pp.55–62.

ASTM-C618-8a (2009) *Standard Specification for Coal Fly Ash and Raw or Calcinied Natural Pozzolan for Use in Concrete*, ASTM International, USA.

Bendapudi, S.C.K. (2011) 'Contribution of fly ash to the properties of mortar and concrete', *Int. J. Earth Sci. Eng.*, Vol. 4, No. 6 SPL, p.1017e1023.

Bleszynski, R. and Thomas, M. (1998) 'Microstructural studies of alkali silica reaction in fly ash concrete immersed in alkaline solutions', *Adv. Cem. Based Mater.*, March, Vol. 7, No. 2, pp.66–78.

British Standards Institution (BSI) (1997a) *BS 5328: Part 1, Guide to Specifying Concrete*.

British Standards Institution (BSI) (1997b) *BS 8110: Part I, Structural Use of Concrete: Code of Practice for Design and Construction*.

Cao, C., Sun, W. and Qin, H. (2000) 'The analysis on strength and fly ash effect of roller compacted concrete with high volume fly ash', *Cem. Concr. Res.*, January, Vol. 30, No. 1, pp.71–75.

Chancey, R. (2008) *Characterization of Crystalline and Amorphous Phases and Respective Reactivities in a Class F Fly Ash*, PhD dissertation, pp.887–890, The University of Texas at Austin, TX.

Chindaprasirt, P., Homwuttiwong, S. and Sirivivatnanon, V. (2004) 'Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar', *Cem. Concr. Res.*, Vol. 34, No. 7, pp.1087–1092, Elsevier, ISSN: 0008-8846.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T. (2007) 'Effect of fly ash fineness on microstructure of blended cement paste', *Constr. Build. Mater.*, July, Vol. 21, No. 7, pp.1534–1541.

Chousidis, N., Ioannou, I., Rakanta, E., Koutsodontis, C. and Batis, G. (2016) 'Effect of fly ash chemical composition on the reinforcement corrosion, thermal diffusion and strength of blended cement concretes', *Construction and Building Materials*, 15 November, Vol. 126, pp.86–97 [online] https://doi.org/10.1016/j.conbuildmat.2016.09.024.

Christy, C.F. and Tensing, D. (2010) 'Effect of class-F fly ash as partial replacement with cement with cement and fine aggregate in mortar', *Indian Journal of Engineering & Material Sciences*, Vol. 17, pp.140–144 [online] http://nopr.niscpr.res.in/bitstream/123456789/8614/1/IJEMS%2017%282%29%20140-144.pdf.

Diamond, S. (1981) 'Effects of two Danish fly ashes on alkali contents of pore solutions of cement-fly ash pastes', *Cem. Concr. Res.*, May, Vol. 11, No. 3, pp.383–394.

Dinakar, P., Kali, P.S. and Sahoo, U.C. (2013) 'Design of self-compacting concrete with ground granulated blast furnace slag', *Mater. Des.*, Vol. 43, No. 1, pp.161–169.

Dunstan, E. (1980) 'A possible method for identifying fly ashes that will improve the sulfate resistance of concretes', *Cem. Concr. Aggreg.*, Vol. 2, No. 1, pp.20–30 [online] https://www.astm.org/cca10175j.html.

Durdzinski, P.T., Snellings, R., Dunant, C.F., Haha, M.B. and Scrivener, K.L. (2015) 'Fly ash as an assemblage of model Ca-Mg-Naealuminosilicate glasses', *Cem. Concr. Res.*, Vol. 78, No. Part B, pp.263–272.

Erdogdu, K. and Turker, P. (1998) 'Effects of fly ash particle size on strength of Portland cement fly ash mortars', *Cem. Concr. Res.*, September, Vol. 28, pp.1217–1222 [online] https://www.osti.gov/biblio/665155-effects-fly-ash-particle-size-strength-portland-cement-fly-ash-mortars.

George, S. and Sofi, A. (2017) 'Enhancement of fly ash concrete by hydrated lime and steel fibres', *Material Today – Proceeding*, Vol. 4, pp.9807–9811.

Ghosh, S.N., Sarkar, S.L. and Harsh, S. (1993) 'Mineral admixtures in cement and concrete', in *Progress in Cement and Concrete*, p.565, ABI Books, New Delhi [online] https://www.abebooks.com/9788185522043/Mineral-Admixtures-Cement-Concrete-Ghosh-8185522049/plp.

Golewski, G.L. (2018a) 'Effect of curing time on the fracture toughness of fly ash concrete composites', *Composite Structures*, 1 February, Vol. 185, pp.105–112 [online] https://www.sciencedirect.com/science/article/pii/S026382231731961X.

Golewski, G.L. (2018b) 'Green concrete composite incorporating fly ash with high strength and fracture toughness', *Journal of Cleaner Production*, 20 January, Vol. 172, pp.218–226 [online] https://www.sciencedirect.com/science/article/pii/S0959652617323582.

Hemlatha, T. and Ramaswamy, A. (2017) 'A review on fly ash characteristics – towards promoting high volume utilization in developing sustainable concrete', 20 March, Vol. 147, pp.546–559 [online] https://www.sciencedirect.com/science/article/pii/S0959652617301294?via%3Dihub.

Hemmings, R.T. and Berry, E.E. (1988) 'On the glass in coal fly ashes: recent advances', in *MRS Symposium*, p.3, Pittsburg, USA [online] https://www.cambridge.org/core/journals/mrs-online-proceedings-library-archive/article/abs/on-the-glass-in-coal-fly-ashes-recent-advances/4A82EBCDE024CD85639DDC7B5BEDEFD8.

IS-1489 (2000) *IS 1489 (Part I): 1991 Portland-Pozzolana Cement Specification*, Amendment No. 3, Indian Standards, India.

Itskos, G., Itskos, S. and Koukouzas, N. (2010) 'Size fraction characterization of highlycalcareousfly ash', *Fuel Process. Technol.*, November, Vol. 91, No. 11, pp.1558–1563 [online] https://www.sciencedirect.com/science/article/pii/S0378382010001980?via%3Dihub.

Joshi, R.C. and Lohtia, R.P. (1997) *Fly Ash in Concrete Production, Properties and Uses*, Gordon and Breach Science Publishers, Netherlands.

Karthik, A., Sudalaimani, K. and Kumar, C.T.V. (2017) 'Investigation on mechanical properties of fly ash-ground granulated blast furnace slag based self curing bio-geoplymer concrete', *Construction and Building Materials*, 15 September, Vol. 149, pp.338–349 [online] https://www.sciencedirect.com/science/article/pii/S0950061817310279?via%3Dihub.

Khodair, Y. and Bommareddy, B. (2017) 'Self-consolidating concrete using recycled concrete aggregate and high volume of fly ash, and slag', *Construction and Building Materials*, Vol. 153, pp.307–316, DOI: 10.1016/j.conbuildmat.2017.07.063 [online] https://ur.booksc.me/book/65967261/f155de.

Kumar, S., Kumar, R. and Mehrotra, S.P. (2010) 'Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash based geopolymer', *J. Mater. Sci. Res.*, Vol. 45, No. 3, pp.607–615.

Langley, W., Carette, C. and Malhotra, V. (1989) 'Structural concrete incorporating high volumes of ASTM class F fly ash', *ACI Mater. J.*, Vol. 86, No. 5, pp.507–514 [online] https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/2130.

Liao, W., Ma, H., Sun, H., Huang, Y. and Wang, Y. (2017) 'Potential large-volume beneficial use of low grade fly ash in magnesia-phosphate cement based materials', *Fuel*, Vol. 209, pp.490–497 [online] https://en.x-mol.com/paper/article/1414469539338588160.

Mahalingam, B., Nagamani, K., Kannan, L.S., Mohammed, K., Hannefa and Bahurudeen, A. (2016) 'Assessment of hardened characteristics of raw fly ash blended self-compacting concrete', *Perspectives in Science*, Vol. 8, pp.709–711 [online] https://core.ac.uk/download/pdf/82513754.pdf.

Malhotra, V. (1986) 'Superplasticized fly ash concrete for structural applications', *Journal of Energy Engineering*, Vol. 117, No. 2, American Society of Civil Engineers, ISSN: 0733-9402 [online] https://ascelibrary.org/journal/jleed9; https://trid.trb.org/view/358781.

Malhotra, V.M. (1990) 'Durability of concrete incorporating high-volume of lowcalcium (ASTM class F) fly ash', *Cem. Concr. Compos.*, Vol. 12, No. 4, pp.271–277 [online] https://www.sciencedirect.com/science/article/pii/095894659090006J.

Medhat, H. and Michail, D. (2000) 'The effect of fly ash composition on the expansion of concrete due to alkali silica reaction', *Cem. Concr. Res.*, Vol. 30, pp.1063–1072 [online] https://www.academia.edu/16752598/The_effect_of_fly_ash_composition_on_the_expansion_of_concrete_due_to_alkali_silica_reaction.

Mehta, A. and Siddique, R. (2017) 'Properties of low-calcium fly ash based geopolymar concrete incorporating OPC as partial replacement of fly ash', *Construction and Building Materials*, 30 September, Vol. 150, pp.792–807 [online] https://www.sciencedirect.com/science/article/pii/S0950061817312084.

Mehta, P. (1985) 'Influence of fly ash characteristics on the strength of Portland-fly ash mixtures', *Cem. Concr. Res.*, July, Vol. 15, No. 4, pp.669–674 [online] https://www.sciencedirect.com/science/article/pii/0008884685900675?via%3Dihub.

Mehta, P. (1998) 'Role of pozzolanic and cementitious materials in sustainable development of the concrete industry', in *Proceedings of the 6th CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ACI SP-178, pp.1–20.

Moffatt, E.G., Thomas, M.D.A. and Fahim, A. (2017) 'Performance of high-volume fly ash concrete in marine environment', *Cement and Concrete Research*, December, Vol. 102, pp.127–135 [online] https://www.sciencedirect.com/science/article/pii/S0008884617306166.

Nadesan, M.S. and Dinakar, P. (2017) 'Structural concrete using sintered fly ash lightweight aggregate: a review', *Construction and Building Materials*, 15 November, Vol. 154, pp.928–944 [online] https://www.sciencedirect.com/science/article/pii/S0950061817315970.

Nawaz, A., Julnipitawong, P., Krammart, P. and Tangtermisrikul, S. (2016) 'Effect and limitation of free lime content in cement-fly ash mixtures', *Construction and Building Materials*, 15 January, Vol. 102, Part 1, pp.515–530 [online] https://www.sciencedirect.com/science/article/pii/S095006181530595X?via%3Dihub.

Odler, I. (2009) *Special Inorganic Cements, E and FN SPON*, Taylor and Francis Group, London.

Papadakis, V. (1999) 'Effect of fly ash on Portland cement systems, part I: low calcium fly ash', *Cem. Concr. Res.*, Vol. 29, pp.1727–1736 [online] https://doi.org/10.1201/9781482271942.

Poon, C., Wong, Y. and Lam, L. (1997) 'The influence of different curing conditions on the pore structure and related properties of fly-ash cement pastes and mortars', *Constr. Build. Mater.*, Vol. 11, pp.383–393, DOI :10.1016/S0950-0618(97)00061-5.

Rafieizonooz, M., Mirza, J., Salim, M.R., Hussin, M.W. and Khankhaje, E. (2016) 'Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement', *Construction and Building Materials*, Vol. 116, pp.15–24, DOI: 10.1016/j.conbuildmat.2016.04.080.

Rashad, A.M. (2015) 'A brief on high – volume class F fly ash as cement replacement – a guide for civil engineer', *International Journal of Sustainable Built Environment*, December, Vol. 4, No. 2, pp.278–306 [online] https://doi.org/10.1016/j.ijsbe.2015.10.002.

RILEM TC 73-SBC (1988) 'Final report on siliceous by-products for use in concrete', *Materials and Structures*, 1 January, Vol. 21, No. 121, pp.69–80, RILEM Publications SARL, ISSN: 1359-5997 [online] https://www.rilem.net/publication/publication/227?id_papier=5620

Saha, A.K. (2017) 'Effect of class F fly ash on the durability properties of concrete', *Sustainable Environment Research*, January, Vol. 28, No. 1, pp.25–31 [online] https://doi.org/10.1016/j.serj.2017.09.001.

Sakai, E., Miyahara, S., Ohsawa, S., Lee, S. and Daimon, M. (2005) 'Hydration of fly ash cement', *Cem. Concr. Res.*, June, Vol. 35, No. 6, pp.1135–1140 [online] https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1041.6581&rep=rep1&type=pdf.

Shehab, H.K., Eisa, A.S. and Wahba, A.M. (2016) 'Mechanical properties of fly ash based geopolymer concrete with full and partial cement replacement', *Construction and Building Materials*, Vol. 126, pp.560–565 [online] https://doi.org/10.1016/j.conbuildmat.2016.09.059.

Siddique, R. (2004) 'Performance characteristics of high-volume class F fly ash concrete', *Cem. Concr. Res.*, March, Vol. 34, No. 3, pp.487–493.

Siddique, R. and Klaus, J. (2009) 'Influence of metakaolin on the properties of mortar and concrete: a review', *Appl. Clay Sci.*, March, Vol. 43, Nos. 3–4, pp.392–400 [online] https://doi.org/10.1016/j.clay.2008.11.007.

Siddique, R., Kapoor, K., Kadri, E-H. and Bennacer, R. (2012) 'Effect of polyester fibred on the compressive strength and abrasion resistance of HVFA concrete', *Constr. Build. Mater.*, Vol. 29, pp.270–278 [online] https://doi.org/10.1016/j.conbuildmat.2011.09.011.

Silva, S.R.D. and Andrade, J.J.D.O. (2017) 'Investigation of mechanical properties and carbonation of concretes with construction and demolition waste and fly ash', *Construction and Building Materials*, Vol. 153, pp.704–715 [online] https://doi.org/10.1016/j.conbuildmat.2017.07.143.

Slanicka, S. (1991) 'The influence of fly ash fineness on the strength of concrete', *Cem. Concr. Res.*, March–May, Vol. 21, Nos. 2–3, pp.285–296 [online] https://doi.org/10.1016/0008-8846(91)90010-F.

Smith, I. (1967) 'Design of fly ash concretes', in *Proc. Inst. Civil Eng.*, p.769e790.

Smith, R. (1988) 'Is the available alkali test a good durability predictor for fly ash concrete incorporating reactive aggregate', in *MRS Symposium*, pp.249–256, Pittsburg, USA.

Somna, K. and Bumrongjaroen, W. (2011) 'Effect of external and internal calcium in fly ash on geopolymer formation', in *Developments in Strategic Materials and Computational Design II: Ceramic Engineering and Science Proceedings*, Vol. 32, pp.1–16.

Sua-iam, G. and Makul, N. (2015) 'Utilization of coal- and biomass-fired ash in the production of self-consolidating concrete: a literature review', *J. Clean. Prod.*, Vol. 100, p.59–76 [online] https://doi.org/10.1016/j.jclepro.2015.03.038.

Suryavanshi, A.K., Scantlebury, J.D. and Lyon, S.B. (1996) 'Mechanism of Friedel's salt formation in cements rich in tri-calcium aluminate', *Cem. Concr. Res.*, Vol. 26, No. 5, pp.717–727.

Temuujin, J. and Van Riessen, A. (2009) 'Effect of fly ash preliminary calcination on the properties of geopolymer', *J. Hazard. Mater.*, 30 May, Vol. 164, Nos. 2–3, pp.634–639 [online] https://www.sciencedirect.com/science/article/pii/S0304389408012478?via%3Dihub.

Tkaczewska, E. (2014) 'Effect of size fraction and glass structure of siliceous fly ashes on fly ash cement hydration', *J. Ind. Eng. Chem.*, 25 January, Vol. 20, No. 1, pp.315–321 [online] https://www.sciencedirect.com/science/article/abs/pii/S1226086X13001366?via%3Dihub.

Tsimas, S. and Moutsatsou-Tsima, A. (2005) 'High-calcium fly ash as the fourth constituent in concrete: problems, solutions and perspectives', *J. Cem. Concr. Compos. Res.*, Vol. 27, No. 2, pp.231–237.

Vakhshouri, B. and Nejadi, S. (2016) 'Mix design of light-weight self-compacting concrete', *Case Stud. Constr. Mater.*, Vol. 4, pp.1–14 [online] http://dx.doi.org/10.1016/j.cscm.2015.10.002.

Ward, C.R. and French, D. (2005) *Relation between Coal and Fly Ash Mineralogy, Based on Quantitative X-ray Diffraction Methods*, World of Coal Ash (WOCA), Lexington, Kentucky, USA.

Wesche, K. (1991) *Fly Ash in Concrete Properties and Performance, E & FN SPON*, RILEM, London [online] http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=106306.

Wild, S., Khatib, J.M. and Jones, A. (1996) 'Relative strength, pozzolanic activity and cementhydration in super plasticized metakaolin concrete', *Cem. Concr. Res.*, October, Vol. 26, No. 10, pp.1537–1544 [online] https://www.sciencedirect.com/science/article/pii/0008884696001482?via%3Dihub.

Yip, C.K., Lukey, G.C. and Van Deventer, J.S.J. (2005) 'The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation', *J. Cem. Concr. Res.*, Vol. 35, No. 9, pp.1688–1697.

Yu, J., Lu, C., Leung, C.K.Y. and Li, G. (2017) 'Mechanical properties of green structural concrete with ultrahigh-volume fly ash', *Construction and Building Materials*, Vol. 147, pp.510–518 [online] https://doi.org/10.1016/j.conbuildmat.2017.04.188.

Zeng, Q., Li, K., Fen-Chong, T. and Dangla, P. (2012) 'Determination of cement hydration and pozzolanic reaction extents for fly-ash cement pastes', *Constr. Build. Mater.*, February, Vol. 27, No. 1, pp.560–569 [online] https://www.sciencedirect.com/science/article/pii/S0950061811003618?via%3Dihub

Zhao, H., Sun, W., Wu, X. and Gao, B. (2015) 'The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures', *J. Clean. Prod.*, Vol. 95, p.66e74 [online] https://doi.org/10.1016/j.jclepro.2015.02.050.