Analytical Study of Angular Fly Ash Aggregates in Lightweight Concrete: Strength Development Properties

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Abstract — This study investigates the performance of angular fly ash aggregates (AFAA) as a sustainable alternative to conventional coarse aggregates in lightweight concrete applications. Experimental analysis evaluated various proportions of AFAA (0%, 25%, 50%, 75%, and 100%) as replacements for natural aggregates, with compressive strength measurements conducted at 7, 14, 21, and 28 days of curing. Results demonstrate that concrete containing up to 50% AFAA achieved satisfactory compressive strength development, with the optimal blend (50% natural aggregate and 50% AFAA) reaching acceptable target strength at 28 days. A regression-based mathematical model was developed to predict compressive strength evolution over time, showing high correlation (R^2 values between 0.914-0.992) across all mixture proportions. Comparative analysis with existing strength prediction models confirms the reliability of the proposed equations. Beyond mechanical performance, AFAA incorporation offers significant environmental benefits by reducing natural resource extraction impacts including habitat destruction, deforestation, soil erosion, and water contamination. The findings suggest that appropriately proportioned AFAA can serve as a viable alternative in lightweight concrete production, aligning with sustainable construction practices while maintaining adequate structural performance.

Keywords: Angular Fly Ash Aggregates, Lightweight Concrete, Compressive Strength, Regression-Based Model, Sustainable Construction, Strength Development, Waste Utilization, Environmental Impact, Curing Age, Coarse Aggregate Replacement

I. INTRODUCTION

A. General:

In any case, there are various uses where the high specific gravity of the normal weight aggregate is an adverse characteristic. In uses where lightweight aggregate concrete is essential, the normal-weight aggregates are partly or completely substituted with low specific gravity or lightweight aggregates. A huge portion of the lightweight aggregate that is consumed for lightweight concrete is manufactured by certain methods.

One significant environmental issue linked to natural aggregate extraction is habitat destruction. The process often involves clearing large areas of land, which leads to the destruction and fragmentation of natural habitats. This has severe consequences for local ecosystems, as it causes the loss of biodiversity and disrupts the ecological balance that supports various plant and animal species.

Another concern is the impact on land use and deforestation. Quarrying activities require the removal of vegetation and forests, resulting in deforestation and the loss of valuable carbon sinks. The clearance of land can also contribute to soil erosion and alter hydrological patterns, affecting the natural flow of water and exacerbating the risk of floods.

Water quality and quantity are also affected by aggregate extraction. The process typically involves using significant amounts of water for washing and processing the aggregates. This water can become contaminated with sediment, pollutants, and chemicals used in the extraction process, leading to a deterioration in water quality and negatively impacting aquatic ecosystems. Moreover, excessive extraction can deplete local water sources, causing water scarcity in surrounding areas.

Fly ash's cementitious characteristics are a result of these mineral components. Fly ash is widely used in the making of concrete as a partial substitute for Portland cement. The workability, longevity, and strength of concrete can be improved by combining fly ash with cement. Due to its pozzolanic qualities, fly ash can combine with calcium hydroxide and water to create new cementitious compounds.

This not only reduces the need for cement but also promotes the utilization of a waste product, making concrete production more sustainable.

In addition to its cementitious properties, fly ash offers other benefits in construction applications. It improves the permeability and cohesiveness of concrete, reduces the heat of hydration, lowers permeability, and enhances resistance to sulfate and chloride attacks. These characteristics make it a valuable additive in various construction projects.

B. Utilizing fly ash as a sustainable alternative to natural aggregate offers numerous significant benefits:

- Improved Durability and Performance: Fly ash possesses beneficial properties that enhance the durability and performance of construction materials. When used as an aggregate in concrete, fly ash contributes to improved workability, increased strength, reduced permeability, and enhanced resistance to sulfate and chloride attacks. These characteristics lead to longer-lasting and more sustainable structures.
- Lower Construction Costs: Fly ash is often cheaper than natural aggregate due to its abundance as a byproduct. Its utilization as a substitute can help reduce construction costs, making projects more economically viable. This cost advantage encourages the adoption of fly ash as a sustainable alternative in construction and infrastructure development.
- Positive Environmental Impact: By incorporating fly ash into construction materials, we reduce the need for landfill space to dispose of this byproduct. This, in turn, helps reduce the potential environmental risks associated with fly ash disposal, such as leaching of contaminants into soil and water systems. Moreover, the utilization of

fly ash in construction contributes to a lower carbon footprint, as it reduces the demand for traditional resource-intensive materials.

II. Literature Survey

A. *General:*

The building industry is paying close attention to lightweight concrete because of its many benefits, including decreased dead load, improved thermal insulation, and increased fire resistance. Researchers have looked into substituting non-traditional coarse aggregates for conventional coarse aggregates in lightweight concrete. The performance of lightweight concrete using fly ash pellets in place of coarse particles is the main topic of this research study. In order to evaluate the impact of fly ash pellet incorporation on the properties and features of lightweight concrete, the review looks at a number of studies that have been done on the subject.

Reddy, N. & Reddy, CH. (2017) The characteristics of concrete built using fly ash aggregates were investigated by the study's authors. The concrete specimens' compressive strength, water absorption, and density were the main subjects of the study. According to the findings, fly ash aggregates could be successfully added to concrete, providing acceptable compressive strength and better water absorption properties.

Reddy, M. V. S., et. al., (2016) In this work, the replacement of coarse aggregate in lightweight concrete with fly ash pellets was explored. The researchers looked at the concrete's compressive strength, density, and water absorption. The results showed that fly ash pellets could successfully replace coarse particles in lightweight concrete, resulting in comparable compressive strength and lower density.

Priyadharshini, P., Ganesh, M. G., & Santhi, A. S. (2011) Cold-bonded fly ash aggregates were the subject of an experimental investigation by the authors, which concentrated on their compressive strength and other mechanical characteristics. The study looked at the effects of several variables, including aggregate size, binder content, and curing conditions, on the characteristics of cold-bonded fly ash aggregates. The findings shed light on the viability and prospective uses of these aggregates in the building industry.

Kockal, N. U., & Ozturan, T. (2011) The durability features of lightweight concretes using lightweight fly ash particles were the focus of this investigation. The researchers looked at how well lightweight concrete withstood various environmental elements including sulphate assault, carbonation, and freeze-thaw cycles. The research showed how crucial it is to choose the right lightweight fly ash particles and optimise concrete mixes in order to guarantee the longevity of lightweight concrete.

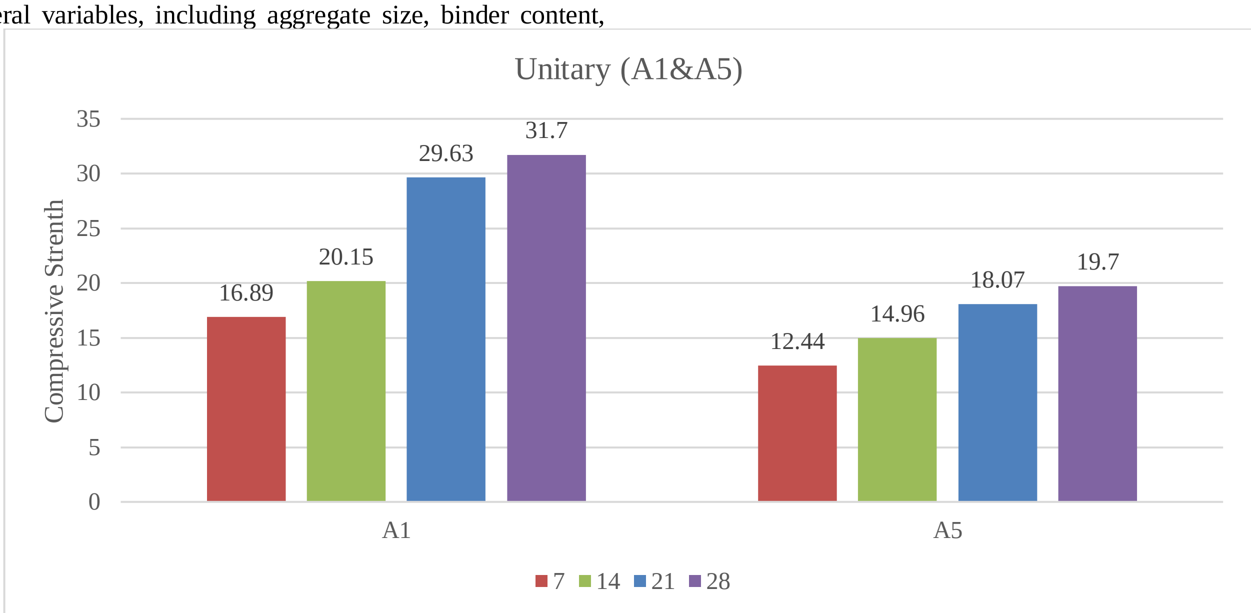
Kockal, N. U., & Ozturan, T. (2010) The behavior of lightweight concretes was examined in relation to the effects of lightweight fly ash aggregate qualities. these looked at several aggregate qualities, including particle size, shape, and density, and assessed how these affected the mechanical and durability aspects of lightweight concrete. The study gave information on how to use fly ash aggregates to optimize lightweight concrete compositions.

B. *All mix combinations' compressive strength at 7, 14, 21, and 28 days*

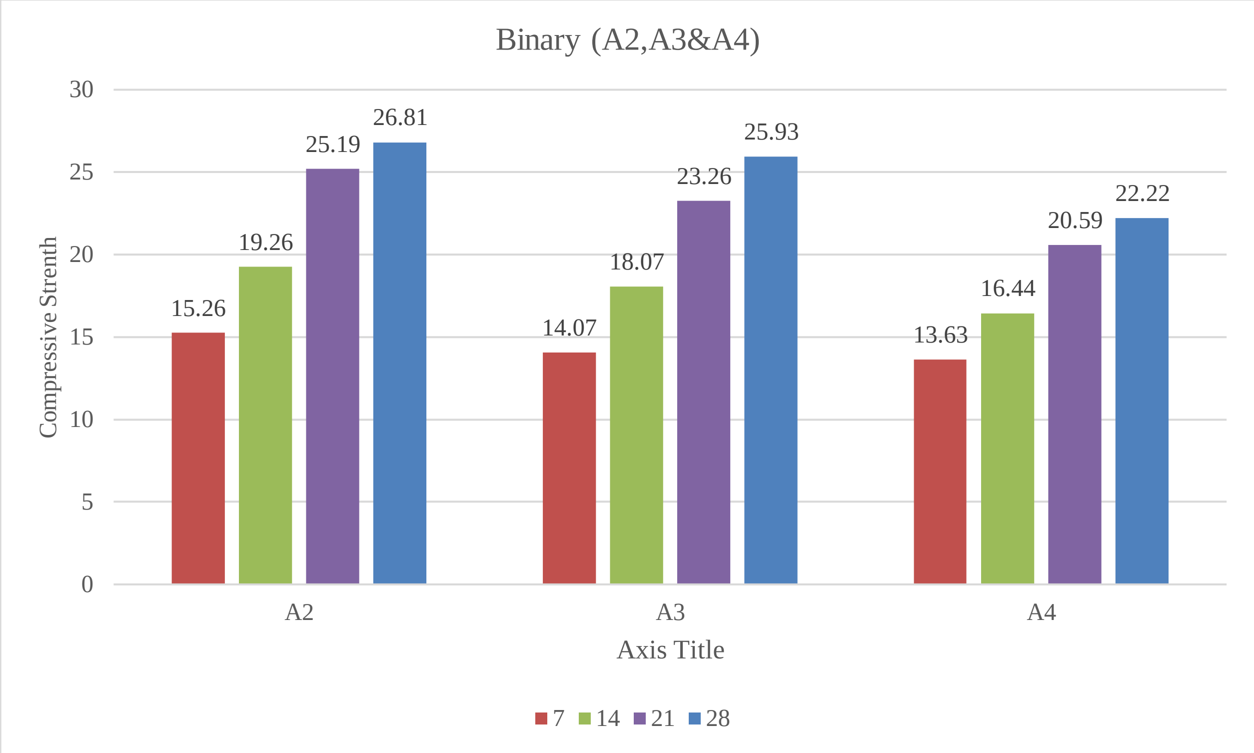
Figures 8(a) and (b), respectively, show the findings of the compressive strength of recycled concrete aggregate with samples A1, A2, A3, A4, and A5. Nearly all the mixes attain the desired value of compressive strength and demonstrate strength development with age.

Serial no.	Natural Aggregate & angular fly ash aggregate	Compressive Strength (N/mm2)			
		7 days	14 days	21 days	28 days
A1	0	16.89	20.15	29.63	31.70
A2	25	15.26	19.26	25.19	26.81
A3	50	14.07	18.07	23.26	25.93
A4	75	13.63	16.44	20.59	22.22
A5	100	12.44	14.96	18.07	19.70

Table 6.3: Compressive strength of all mix combinations at 7, 14, 21, and 28 days



A_1 & A_5(Unitary)



A_2, A_3 & A_4 (Binary)

Fig. 6.2 Compressive strength of concrete with various percentage combinations of angular fly ash aggregate at different curing ages.

In the current work, a regression-based model is created for the estimation of the compressive strength of concrete containing various percentages of angular flyash aggregate at various ages (Fc(d)). The 28th-day compressive strength (Fc(28)) and normalised compressive strength calculated using the 28th-day strength [8] are used to produce the model equation. In order to derive equations for Fc(d)/Fc(28), which are based on experimental findings, regression analysis of the best-fitted curve is used.

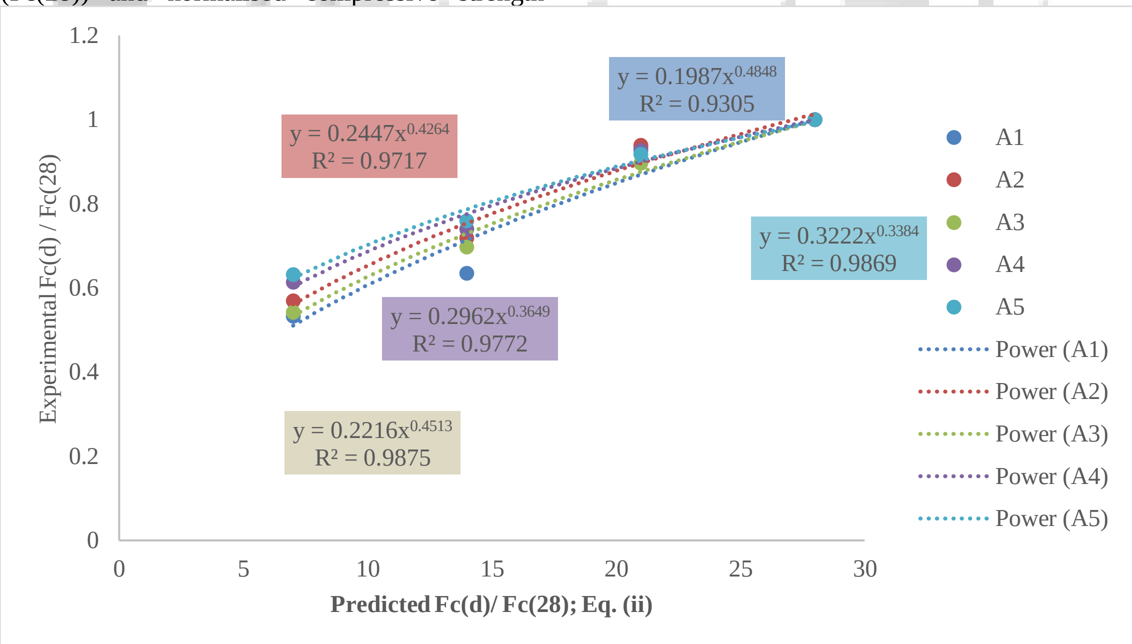


Fig. 6.3: Compressive strength normalizes at 28days as a function of curing age in days for A_1, A_2, A_3, A_4, & A_5

A relationship between the ratio of compressive strength experimental data at any age, d (in days, Fc(d)), to 28th days compressive strength Fc (28), versus curing time (in days), is plotted as shown in Fig.8 to derive the strength evaluation model for various samples. Five well-fitted curve power curve were generated by regression to formulated the generalized equation in terms of compressive strength evaluation as;

$$F_{c(d)}/F_{c(28)}=a_1t^{b1} \qquad \text{(i)}$$

where, t is the curing time, a_1 and b_1 are constants.

Because of higher R^2 values, we can say constants a_1 and b_1 are proposing the compressive strength evaluation and they are rewritten as Eqs. for different samples A_1, A_2, A_3, A_4, and A_5, respectively.

$F_{c(d)}/F_{c(28)} = 0.265d^{0.395}$ $R^2 = 0.948$ (ii)

$F_{c(d)}/F_{c(28)} = 0.226d^{0.446}$ $R^2 = 0.992$ (iii)

$F_{c(d)}/F_{c(28)} = 0.263d^{0.403}$ $R^2 = 0.932$ (iv)

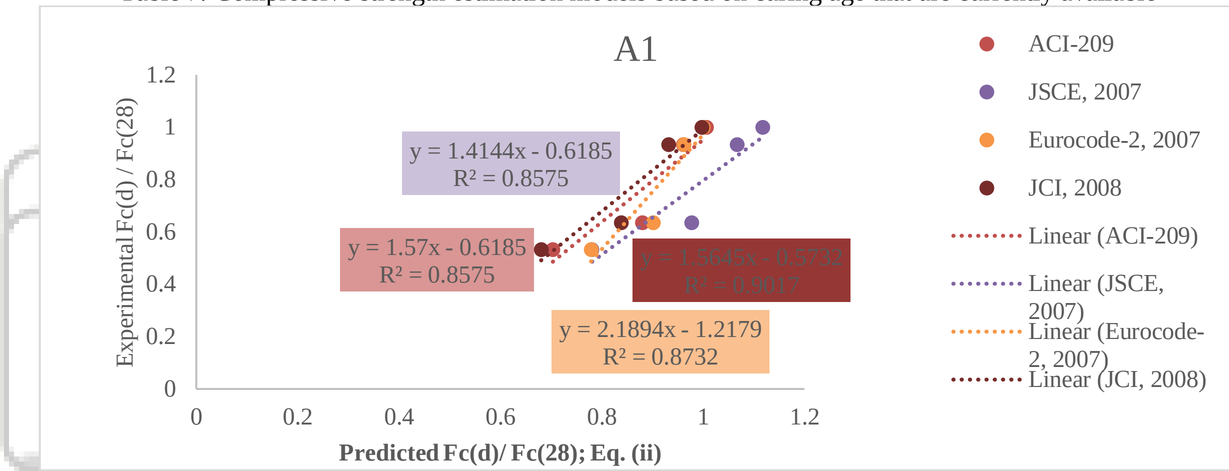
$F_{c(d)}/F_{c(28)} = 0.264d^{0.400}$ $R^2 = 0.914$ (v)

$F_{c(d)}/F_{c(28)} = 0.218d^{0.444}$ $R^2 = 0.991$ (vi)

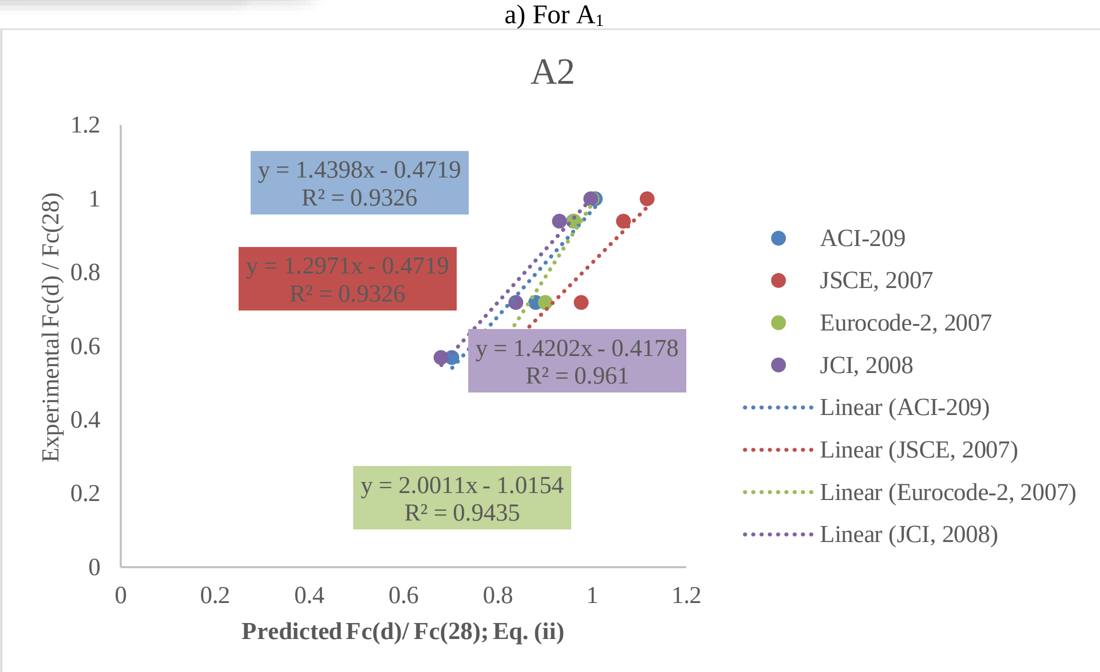
The estimation models for compressive strength evaluation based on curing time and 28th-day compressive strength provided in various standard codes around the world are listed in Table 7. The graph in Figure 10 (a), (b), (c), (d), and (e) compares the outcomes of suggested estimated models to current estimated equations. A higher R2 value indicates that geopolymer concrete behaves similarly to concrete in terms of strength development with curing time.

S.No.	Estimating model	Reference
(a)	$\frac{F_c(d)}{Fc(28)} = \frac{d}{4 + 0.85d}$	ACI-209, 1992 [27]
(b)	$\frac{F_c(d)}{F_c(28)} = 1 \cdot 11 \frac{d}{4 \cdot 5 + 0.85d}$	JSCE, 2007 [28]
(c)	$\frac{F_c(d)}{F_c(28)} = \exp\left(0.25\left(1 - \sqrt{\frac{28}{d}}\right)\right)$	Eurocode-2, 2007 [29]
(d)	$\frac{F_c(d)}{F_c(28)} = 0 \cdot 2289Ln(d) + 0 \cdot 235$	JCI, 2008 [30]

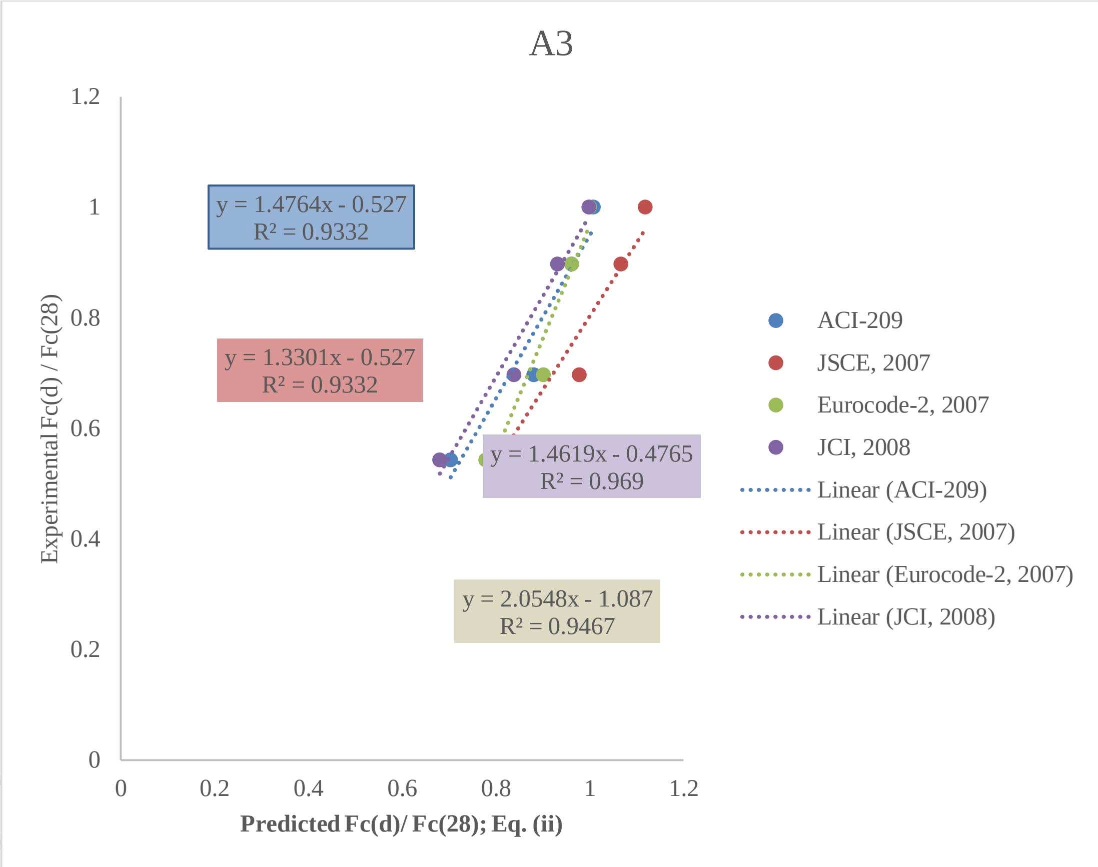
Table 7. Compressive strength estimation models based on curing age that are currently available



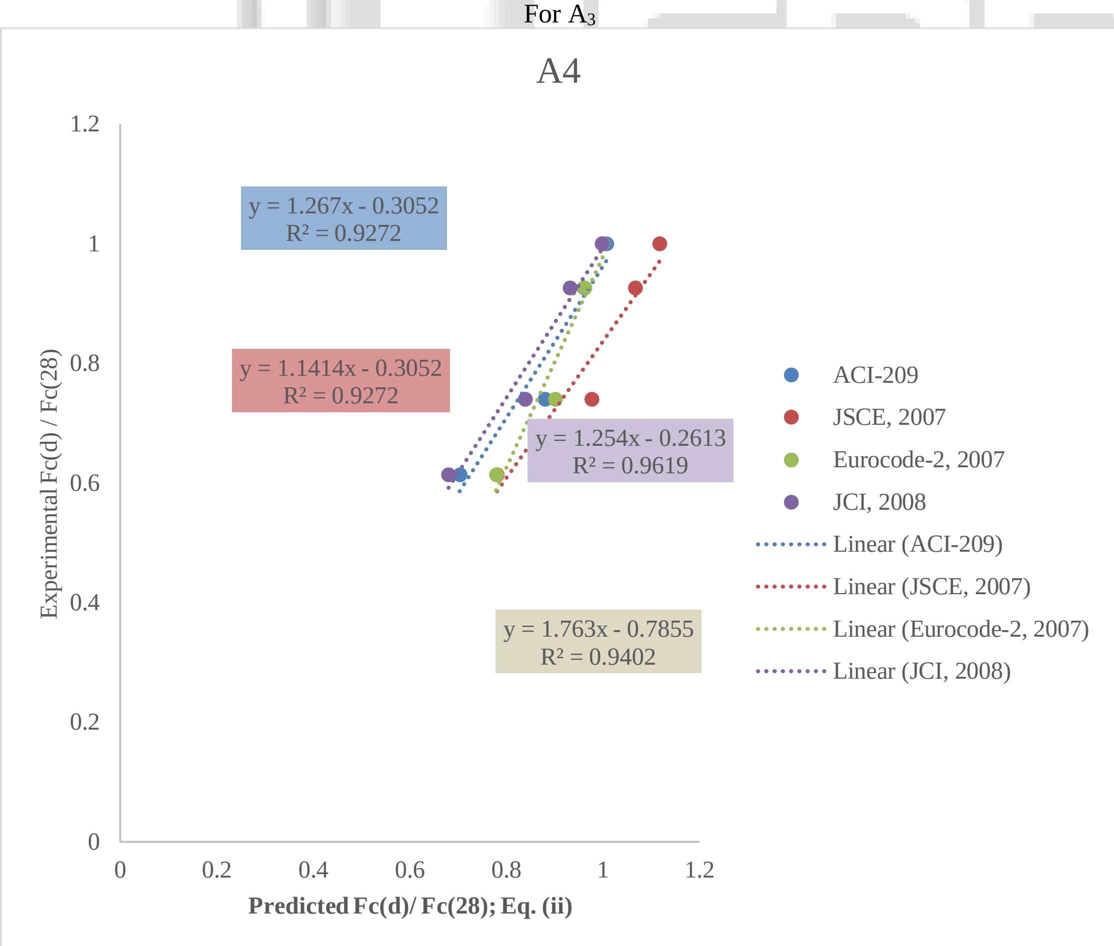
a) For A_1



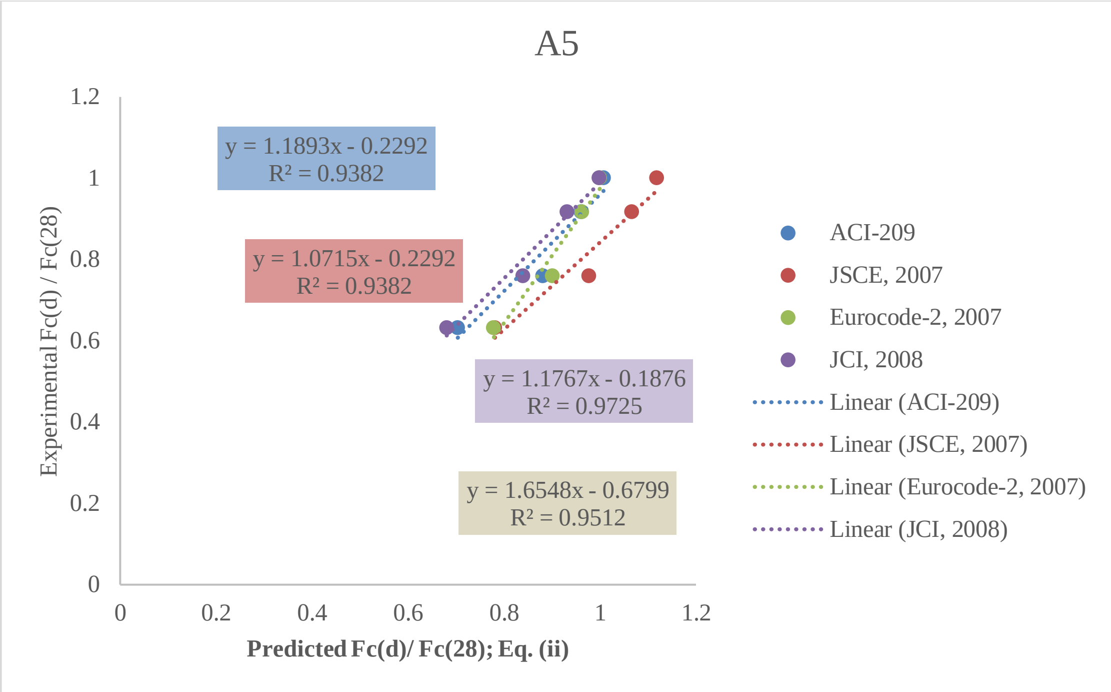
b) For A_2



For A_3

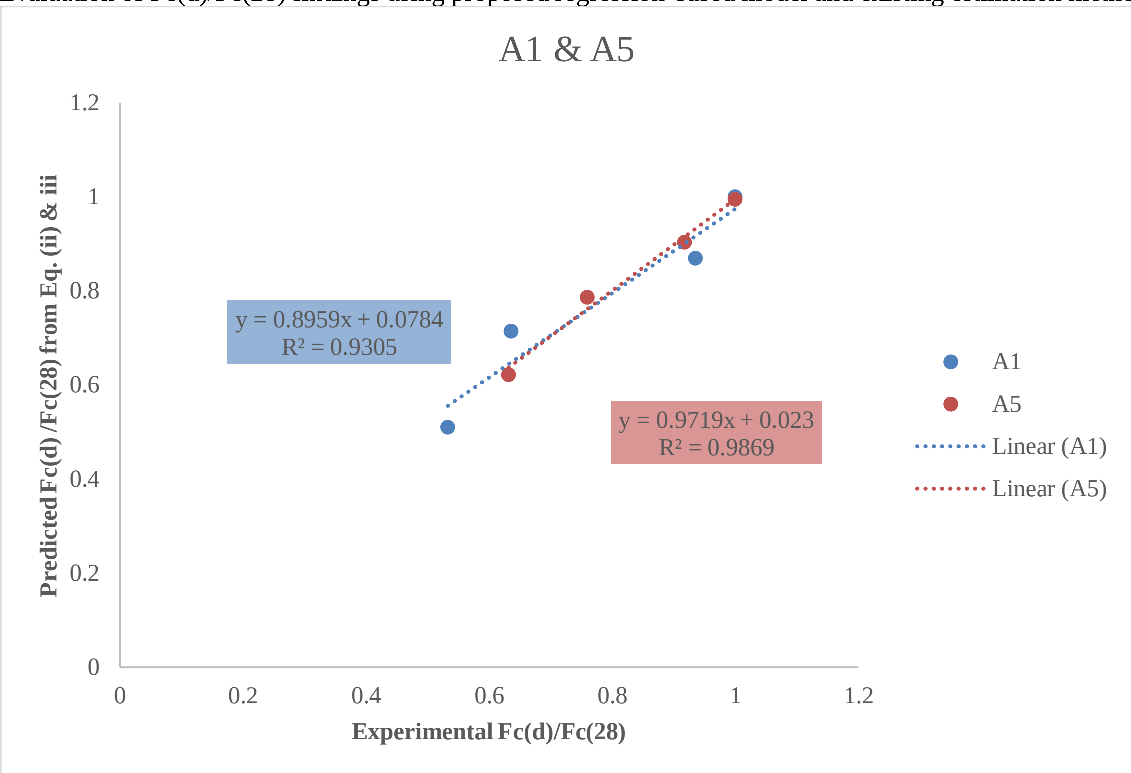


d) For A_4

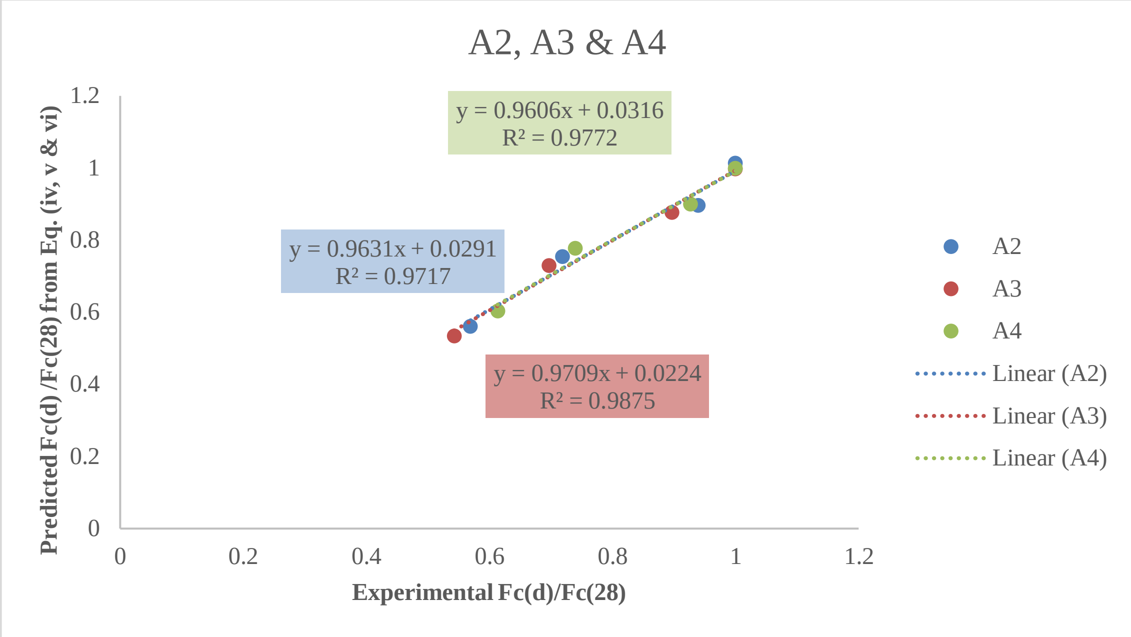


e) For A_5

Fig. 6.4. Evaluation of Fc(d)/Fc(28) findings using proposed regression-based model and existing estimation methodologies.



A_1 & A_5(Unitary)



A_2, A_3 & A_4 (Binary)

Comparison of experimental Fc(d)/Fc(28) values for various angular flyash aggregates of coarse aggregate in concrete with values from proposed models is shown in Fig. 6.5.

Equations (ii), (iii), (iv), and (v) are plotted in Fig. 11 (a) and (b) in relation to experimental compressive strength for various blends of angular flyash aggregate concrete, including unitary (A1 and A5) and binary (A2, A3, and A4 blends. In relation to the variable Angular Flyash Aggregate, the higher values of R2 demonstrate the applicability of regression-based compressive strength evaluation equations on concrete.

III. Conclusions

Experimental data on compressive strength at different curing durations were utilized to develop a regression-based model. Additionally, the empirical model's outcomes for concrete were compared with existing predictive models to evaluate compressive strength at different ages of curing. Based on the analysis of the experimental findings, the following conclusions can be drawn:

Utilizing 50% angular flyash aggregate as coarse aggregate in concrete demonstrated favourable results in terms of compressive strength. Sample A3, which combined natural aggregate (50%) and angular flyash aggregate (50%), achieved the target compressive strength within 28 days.

The proposed model proved to be reliable for predicting compressive strength in geopolymer concrete.

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