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Design And Simulation of Concrete Beams by Using Fly Ash as a Partial Replacement for Cement

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ABSTRACT

Concrete is one of the most widely used construction materials, but its high demand comes at a significant environmental cost due to the pollution caused by cement production. This research explores a practical and sustainable solution by replacing part of the cement with fly ash and studying its effects on concrete's performance. Among the different mixes tested, concrete with 15% fly ash delivered the best results, achieving a flexural strength of 2.557 MPa—outperforming mixes with 0% and 20% fly ash. It also became easier to work with, as the slump increased from 64 mm to 71 mm with higher fly ash content, improving placement and handling. Crack resistance was also enhanced, with the 15% fly ash mix showing the shallowest crack depth at just 101 mm. This is because fly ash fills tiny gaps in the concrete and reacts with leftover materials, creating a stronger, more durable structure. On the structural side, when this mix was used in building models in ETABS, it showed better resistance to lateral forces, with reduced story displacements in both directions. While there was a slight drop in stiffness, the overall performance of the material improved significantly. These findings highlight how using 15% fly ash in concrete strikes a balance between strength, workability, and sustainability, offering a simple yet impactful way to build greener, more efficient structures.

1. Introduction

Concrete is the heart of modern construction, known for its strength, versatility, and ability to shape the built environment. But behind its widespread use lies a serious challenge: Traditional concrete production relies heavily on cement, which isn't great for the environment because it releases a lot of carbon dioxide when it's made. The manufacturing process of cement releases approximately 0.9 pounds of CO_2 for every pound of cement (Portland Cement Association). This has driven researchers to search for alternatives that reduce the environmental impact of concrete while maintaining its strength and durability. One solution that has gained attention is the use of fly ash (FA), a byproduct of coal combustion in power plants. This is cool because it means we can use less cement, which means less carbon dioxide going into the atmosphere as a by-product of burning coal, fly ash is the residue that is left over after burning coal (Naik et al., 2014). Fly ash is abundant, cost-effective, and has the potential to improve concrete. Studies show that adding fly ash to concrete can enhance its workability, improve durability, and even increase its flexural strength, an essential property for load-bearing elements like beams. What's more, addition of FA as a partial replacement to the concrete may decrease the depth of crack in both mixtures. Applying FA could have the effect of decreasing the depth of fracture spread. (Raj, B. S., & Rao, M. K. 2023). These qualities make it a strong contender for more sustainable construction practices. However, figuring out the best way to use fly ash in concrete beams isn't straightforward. It takes careful testing to find the right balance between reducing cement content and maintaining performance. Advanced tools like ETABS make this task easier by simulating how fly ash concrete beams perform under different loads.

This research dives into how varying levels of fly ash affect the strength, durability, and behavior of concrete beams. By combining real-world testing with ETABS simulations, it aims to reveal how fly ash can be used to its fullest potential. It will also look at how changing the shape of beams can make them even stronger and more sustainable. The goal is to create smarter, greener, and more efficient concrete designs that benefit both the environment and the construction industry.

2. Material Properties and Methods

2.1 Material Properties

The process of making fly ash beams requires careful planning and execution to meet the desired standards, the necessary materials fly ash, coarse aggregate, fine aggregate, cement, and water are gathered. The first step is too dry mix these materials in proportions to ensure everything is evenly blended. After that, water is added, and the wet mixing begins, creating a smooth, workable mix. This mixture is poured into molds of 150 x 150 x 500 mm, and a 50-second vibration step helps settle and compact the materials properly. After setting it for 24 hours, the beams are carefully removed from the molds and submerged in water for curing, a crucial step that lasts 14 or 28 days to help them gain strength. Once the curing is complete, the beams are taken out, towel-dried, and tested immediately to avoid losing strength. Flexural strength tests are done using a Universal Testing Machine (UTM) with center-point loading, and three specimens from each batch are tested to ensure accurate results. After finding the optimal fly ash content, compressive strength tests are conducted, and the data is used in ETABS to simulate and validate the results. In ETABS, the experimental findings analyze factors like story displacement and stiffness. Combining hands-on testing and advanced simulations ensures that the results are reliable and insightful, paving the way for better use of fly ash in construction.

2.1.1 Fly Ash

Fly ash is a waste material produced after combustion of coal. It is abundantly available in large quantities at the thermal power plants. Class F fly ash is used in this research which is obtained from Rawalpindi. The different percentages of fly ash used are 10%, 15%, and 20%.

2.1.2 Coarse Aggregate:

Coarse Aggregate will be obtained locally from Khairpur. The maximum coarse aggregate size used is 25mm, as prescribed for standard practice C31 according to ASTM C293-02 for flexure strength or modulus of Rupture of concrete using center point loading.

Ordinary Portland cement was used. Cement and fine aggregate or sand were obtained locally from Khairpur.

2.2 Properties of Fly Ash beams

2.2.1 Workability

A conventional metal cone is filled with concrete in three levels, and each layer is compacted using a tamping rod. The concrete's vertical settlement, or slump, is then measured when the cone is removed. The purpose of the test in this study was to ascertain how different fly ash quantities affect the mix's workability.

2.2.2 Flexural Strength or Modulus of Rupture

This property determines the property of withstanding deformation under bending and flexural loads. The flexural strength or modulus of rupture can be determined by following the procedure of ASTM C293-02 by using center point loading.

$$R = \frac{3\,PL}{2bd^2}$$

Where R is MOR, in psi, or MPa, P is the maximum applied load that the testing apparatus indicates, lbf, or N; L is the span length, in, or mm; b is the average width of the specimen, in., or mm; and d is the average depth of the specimen, in, or mm, at the fracture.

2.2.3 Crack Depth Analysis

Crack depth analysis provides insight into the failure mechanisms of beams under applied loads by examining the depth and propagation of cracks. Concrete beams were incrementally loaded until visible cracks formed, and their depths were measured using crack depth gauges or microscopic imaging. The reason behind this test is to evaluate the role of FA in increasing crack resistance and enhancing the durability and stability of the beams.

2.3 Utilizing ETABS

In this study, ETABS was employed to evaluate the structural behavior of beams designed with varying proportions of fly ash, focusing specifically on story displacement and story stiffness. In this study, a 15-storey symmetrical building is taken.

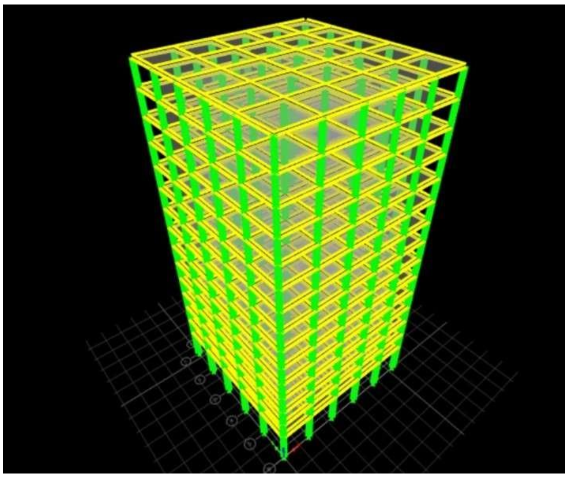

Fig 1: (a) 3D view of building

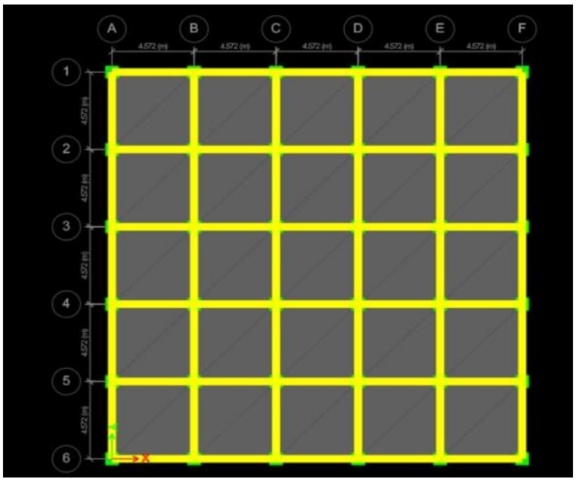

Fig 2: (b) Plan of building

3. Results and Discussion

3.1 Slump Cone Test

Four batches of concrete were prepared with percentages of fly ash being 0%,10%,15%, and 20%. It is found that the usage of fly ash increases the workability of concrete. The role of spherical form of fly ash through its ball bearing influence permits improved mix workability (N Ghazali et al. 2021). The variation in slump pattern shows more workability when a larger amount of fly ash is used, which can be observed in Table 1 and fig 3.

Table 1: Slump Test Results

S NO:	Fly Ash %	Slump (mm)
1	0%	47
2	10%	55
3	15%	64
4	20%	71

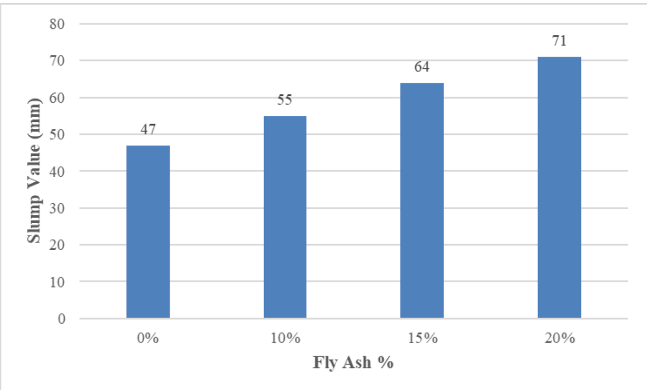

Fig 3: Graph of Slump Test

3.2 Flexural Strength Test

A total of 12 beams are tested for their flexural strength using centre point loading with the help of a universal testing machine. It is observed that flexural strength is found to be maximum at 15% fly ash. The flexural strength or MOR is found by following the procedure of ASTM C293- 02 by using center point loading.

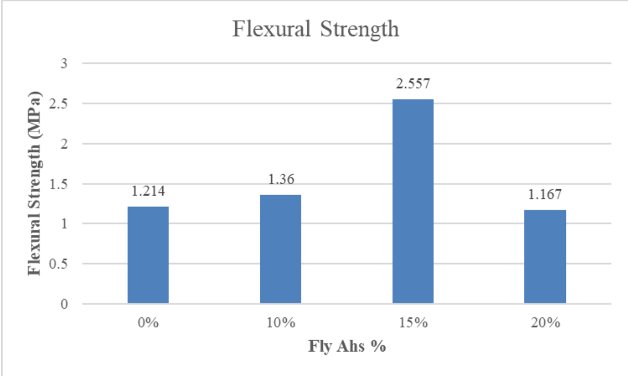

Fig 4: Graph of Flexural Strength Test Results

3.3 Crack Depth Analysis

Crack depths of all 12 beams were observed and measured via tape. The average depth was taken for each batch, and results were obtained. The results of crack depth are minimum at 15% FA and are best understood via graphical representation as shown in Fig 5.

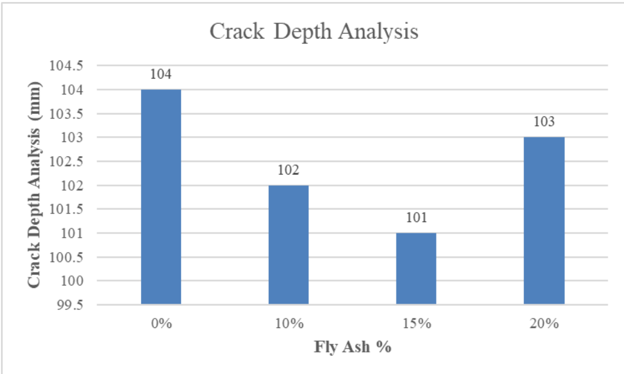

Fig 5: Graph of Crack Depth Analysis

3.4 Results Obtained from ETABS

3.4.1 Story displacement in X-direction

In this study, the performance of concrete with an optimum FA of 15% was compared to that of conventional concrete using ETABS. The findings indicate that the usage of fly ash significantly improves structural behaviour by reducing story displacement in the x-direction. Thus, fly ash concrete demonstrates better performance in resisting lateral loads, making it a more sustainable and effective alternative to conventional concrete in structural applications.

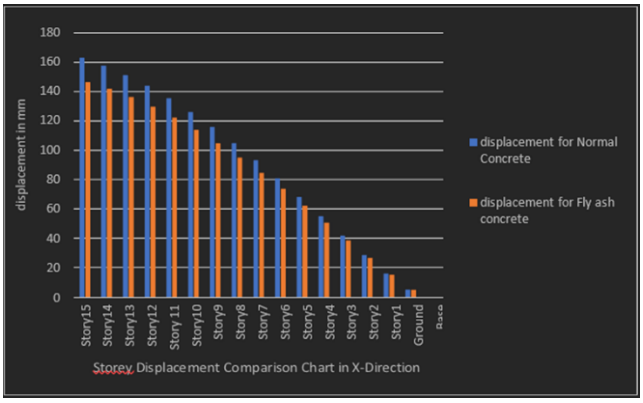

Fig 6: Graph of Comparison Chart of Story Displacement in X-direction

3.4.2 Story displacement in Y-direction

The results of story displacement in the other direction were analysed using ETABS, comparing concrete with 15% FA to conventional concrete. The findings reveal that fly ash concrete exhibits significantly reduced displacement in the y-direction, demonstrating improved stiffness and resistance to lateral loads. These results confirm that incorporating 15% FA not only improves the behavior of concrete under lateral forces but also supports the usage of sustainable materials in construction.

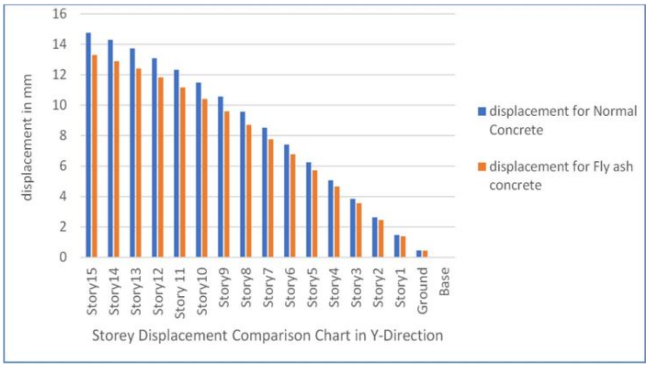

Fig 7: Graph of Comparison Chart of Story Displacement in Y-direction

3.4.3 Story Stiffness in X-direction

The analysis of story stiffness in the x-direction was conducted using ETABS, comparing conventional concrete with concrete containing 15% fly ash. The findings demonstrate that the inclusion of fly ash significantly improves story stiffness, indicating improved resistance to lateral forces.

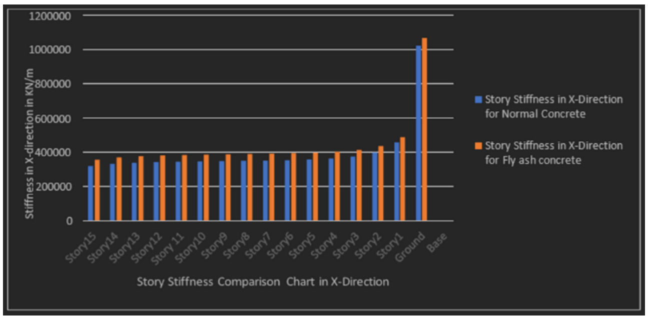

Fig 8: Graph of Comparison Chart of Story Stiffness in X-direction

4. Conclusion

Based on the results from experiments, observations, and ETABS simulations, incorporating 15% fly ash in concrete beams emerges as the ideal choice for balancing strength, workability, and durability. Beams with this mix achieved the highest flexural strength of 2.557 MPa, demonstrated excellent resistance to cracking with a reduced crack depth of 101 mm, and maintained moderate workability with a slump value of 64 mm—striking the perfect balance between ease of placement and stability. Simulations further confirmed the superior performance of 15% fly ash beams, showing reduced lateral displacement and increased stiffness, making them more resilient under load. These findings highlight the potential of 15% fly ash concrete as a sustainable, efficient, and reliable option for modern construction needs.

Acknowledgment

Not available.

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