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Effect of Thar Coal Fly Ash on Compressive and Tensile Strength of Concrete

Munesh Meghwar*
Department of Civil Engineering, Mehran University of Engineering and Technology, Pakistan
Email: munesh99@edu.bme.hu
ORCID iD: https://orcid.org/0009-0002-9797-6976
*Corresponding Author

Fareed Ahmad Memon
Department of Civil Engineering, Mehran University of Engineering and Technology, Pakistan
Email: fareed.memon@teacher.muet.edu.pk
ORCID iD: https://orcid.org/0000-0003-3027-1760

Shankar Lal Meghwar
Department of Civil Engineering, Mehran University of Engineering and Technology, Pakistan
Email: shanker.lal@faculty.muet.edu.pk
ORCID iD: https://orcid.org/0000-0002-9299-588X

Adarsh Dodai
Department of Civil Engineering, Mehran University of Engineering and Technology, Pakistan
Email: adarsh.dodai100@gmail.com
ORCID iD: https://orcid.org/0009-0000-7267-9719

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Abstract: This study's subject is the effectiveness of substituting Thar Coal Fly Ash (TCFA) for ordinary Portland cement, also known as OPC. Tharparkar, Pakistan, possesses the world’s third largest coal reserves, with deposited coal fuel of 175 billion tons and capable of providing energy for over 200 years. Thar Coal is a lignite type that produces 7-10% of by-products in ashes; among them, Fly Ash is a significant waste. Reusing this waste as a partial cement replacement offers an environmentally friendly solution. This study prepared concrete specimens with varying proportions of TCFA (0%, 10%, 20%, and 30% by mass) as cement substitutes. Compressive strength tests were conducted on 36 cubes (100mm x 100mm x 100mm) with different fly ash percentages at a proportion to water to cement of 0.52. Ages 7, 14, and 28 days for curing were considered. The findings demonstrate that a higher TCFA component enhances the workability of the concrete. At all curing ages, the strength in compression at a 20% TCFA replacement level was greater than that of standard concrete. However, as the cement replacement was increased to 30%, there was a slight decrease in the comparative compressive strength compared to regular concrete. The tensile strength of the splitting test, performed after twenty-eight days of curing age, reveals that it surpassed conventional concrete for all replacement levels. Considering the favorable outcomes in workability, constrictive strength, durability strength, and substantial economic and environmental benefits, there is much potential for using TCFA as a cement substitute in the construction sector.

Index Terms: Concrete Replacement, Fly Ash, Compressive Strength, Supplementary Cementous Material, Thar Coal.

1. Introduction

Concrete is a versatile construction material traditionally produced by mixing cement water with aggregate (sand and gravel). Because concrete is used so extensively, its production accounts for five to eight percent of global greenhouse gas emissions. It is believed that around one tone of concrete is generated annually by each person on Earth, or nearly 10 billion tons of concrete annually [1]. Such a massive production with virgin materials raises severe concerns regarding sustainability development and environmental pollution.

Using waste materials in place of usual ingredients, such as fly ash in place of cement, in concrete offers a possible solution to reduce these effects. The idea of using fly ash to improve the mechanical properties of concrete has been supported by multiple prior research studies. However, it is of the utmost importance to recognize that fly Ash characteristics vary significantly across sources and are not always the same [2]. This variation results from the fact that different coal combustion processes yield fly ash with unique chemical characteristics, which in turn influences the characteristics of the concrete that is produced. Consequently, it is vital to evaluate fly ash's performance in concrete for each unique source in a systematic way.

As thar coal fly ash is a newly produced waste material which has never been used before and also not examined experimentally in concrete. The absence of prior research or practical usage of this specific fly ash highlights a study gap in existing literature. This gaps pertains particularly to the understanding the behavior of concrete which has thar coal fly ash as a partial replacement for cement. This study aims to address this gap by investigating the effects of Thar coal fly ash on concrete's mechanical properties.

1.1. Thar Coal Fly Ash

With 175 billion tons of coal fuel already deposited, Tharparkar can power Pakistan for at least 200 years [1, 3]. Coal found in Tharparkar is lignite type and with estimated ash content of 7-10 % approximately. Fly ash is the leading coal by-product generated due to the burning up of coal. It is an incredibly fine particulate matter (composed of fine particles of burned coal) with a nebulous texture. It is yielded in coal-fired furnaces along with flue gases. The concerto, particulate size particles, and nebulous surface of fly ash signify that it has pozzolanic and Cementous characteristics [4]. Fly ash obtained from lignite or sub-bituminous coal is very useful and has pozzolanic properties. This type of fly ash is mainly classified as C type according to ASTM-C618 classification with greater than 10% lime content.

1.2. Problem Statement

Fly ash, an unused product produced by power plants that burn coal, which uses coal as their primary energy source, is produced in large quantities. The following fly ash poses significant environmental risks requiring careful management to prevent severe consequences [2]. Conversely, the conventional use of virgin materials in concrete production leads to material depletion, undermining future generations' sustainability needs. To address these environmental risks and promote sustainability, it is imperative to focus on reusing these waste products to create more sustainable concrete. Furthermore, Thar Coal Plants' large waste generation presents additional challenges for the local population.

Although numerous research papers have explored the utilization of coal plant fly ash from other power plants in concrete production, a dearth of studies specifically investigate the optimal use of fly ash from the Thar Coal Project. Therefore, examining and utilizing the fly ash produced by the It is vital to use Thar Coal Project to partially replace cement in concrete to lessen the challenges that come with it.

1.3. Objective of Study

The main objective of this study are;

1. To determine the chemical composition of Fly Ash produced from Thar Coal
2. To evaluate the effect of Thar Coal Fly Ash on workability, compressive and tensile strength of concrete

1.4. Scope of Study

In this research, concrete was created with durability and toughness in mind. 25MPa, and DOE mix design procedure ratio achieved is 1:1.98:3.17 @ W/C ratio of 0.52. For this mix cumulative of 36 cubes with a standard size of 100mm x 100mm x 100mm and 12 cylinders of size 100 mm x 400mm were cast. A total of 4 mixes of different percentages of TCFA of 0, 10, 20, and 30% of cement were prepared. For each mix, 12 cubes and three cylinders were prepared. Three3 cubes of each mix Compressive strength was tested at 7-, 14-, and 28-day curing age. Three cylinders of each mix were tested for tensile strength at a curing age of 28 days only. The Slump Cone test found the workability for each mix. The Compressive and Tensile strength was tested on UTM.

2. Literature Review

2.1. Physical and Chemical Characteristics of Fly Ash

Coal fly ash is a pozzolanic material constituting over 70% of coal ash. Materially, Fly ash is a fine particulate that ranges in size from 0.5mm to 300mm and makes up more than 70% of waste coal ash that is collected by particulate control equipment [5,6]. These minuscule, powdery particulates are primarily amorphous, hollow, or solid, and spherical in shape. Coal ashes have a specific gravity that typically ranges from 2.0 to 3.1, however it can vary greatly [7]. Fly ashes fall into one of two categories: silty sand or sandy silt, depending on the distribution of particle sizes.

All fly ash contains substantial amounts of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and calcium oxide (CaO), the primary minerals in coal strata. It's classified into Class C and Class F for industrial use, especially in cement industries, as per ASTM C618 standards [7]. Class F ash, with >70% SiO_2+Al_2O_3+Fe_2O_3, displays pozzolanic properties, reacting with calcium hydroxide to form cementitious compounds [8]. Class C ash, containing 50-70% SiO2+Al2O3+Fe2O3, adheres to specific criteria: SO3 content ⩽ 5%, Na2O ⩽ 1.5% (optional), particle size ⩽ 34% (±5% average) retained on a 45mm sieve, and LOI ⩽ 6%, extending to ⩽ 12% for Class F based on performance [8,9].

In the context of concrete production, fly ash serves as a supplementary cementitious material (SCM). When it is in a finely distributed state, it contains alumino-silicate with different percentages of calcium content. It begins interacting with Calcium Hydroxide (Ca (OH)2) generated by the hydration of OPC when combined with water to produce calcium-silicate hydrate 11 (C-S-H) and calcium-aluminate hydrates [4]. On the other hand, in the absence of a source of calcium hydroxide, fly ash with a higher calcium content also seems to exhibit cementitious qualities when it combines with water and creates calcium-silicate-hydrate. Due to these pozzolanic processes, the amount of calcium-silicate-hydrate (C-S-H) and, to a lesser extent, calcium aluminate in the cementitious binder phase could increase the long-term strength, improve density, or decrease the permeability of the system [2].

2.2. Effect of Fly Ash on Properties of Concrete

a) Workability

Jatoi M. A. *et al.* [10] studied the partia1 rep1acement of cement with f1y ash; they found that up to 55% replacement of binder with CFA work, the ability of concrete increases. M. Thomas [11] suggested that a good quality f1y ash with a level of fineness and 1ow carbon content decreases the water demand. As a result, concrete of the same workability is achieved at smaller water content. In addition, well-proportioned fly ash concrete will be easier to work with than Portland cement concrete of the same slump.

b) Compressive Strength

With increasing the replacement level of fly ash, the early-age strength decreases. However, the long-term strength is nearly identical to that of Portland cement concrete. It is also discovered that as fly ash content rises replacement level of 50%, the ultimate strength of the concrete increases. Additionally, machine learning techniques can be used to calculate compressive strength [12].

c) Tensile Strength

The inclusion of fly ash at the early and middle stages of replacement had no appreciable impact on the correlations between the concrete's tensile strength, flexural strength, elastic modulus, and compressive strength [13]. According to A. Oner [14], the ongoing pozzolanic response that strengthens the link between paste and aggregates may significantly increase the long-term flexural and tensile strength of HVFA concrete. They further advise that because of the considerable volumes of natural fly ash flakes that serve as fine aggregate and the highly tiny pores of the interfacial zone, the modulus of elasticity of HVFA concrete may be enhanced. Concrete with 55% fly ash as cement replacement early-age tensile strength decreases by 49% [11].

3. Materials and Methodology

In order to meet the study's first objective, the chemical composition of Thar Coal Fly Ash was examined using X-Ray fluorescence at the outset of the investigation. This study is essential for categorizing fly ash and determining how it might affect the qualities of concrete. In order to achieve the second goal, a concrete mix with different proportions of Thar Coal Fly Ash (0%, 10%, 20%, and 30%) was made in order to evaluate how it affected workability in addition to compressive and tensile strength. The study employed standard curing times and specimen sizes to ensure accurate assessment of these properties, providing insights into the viability of Thar Coal Fly Ash as a cement alternative. The subsequent section elaborates on the materials and methods utilized in this investigation.

3.1. Ingredients Materials

3.1.1. Cement and Fly Ash

The cement utilized in this investigation, Ordinary Portland Cement (OPC), grade 42.5, was lump-free. The requirements provided in the ASTM standards were followed for testing the cement. The cement was found to have a specific gravity of 3.13.

This Thar Coal Power Plant, Block-II, in Tharparkar, Pakistan, provided the Fly Ash used in the experiment. The chemical characteristics of Thar Coal fly ash as determined by an X-Ray Fluorescence Test are shown in Table 1. This result revealed that the fly ash generated contains high calcium content of about 16.3% and SiO2 + Al2 O3 + Fe2 O3 = 63.16 %, greater than 50%. So, TCFA is classified as class C according to ASTM C-618 classification.

Table 1. XRF Test Result of Thar Coal Fly Ash

Oxides in Ash	Units	Oxides Content
Sodium oxide Na_2O	(%)	1.65
Magnesium oxide MgO	(%)	3.52
Aluminum oxide Al_2O_3	(%)	14.115
Silicon oxide SiO_2	(%)	37.105
Phosphorus oxide P_2O_5	(%)	0.08
Sulfur oxide SO_3	(%)	10.01
Potassium oxide K_2O	(%)	0.105
Calcium oxide CaO	(%)	15.655
Titanium oxide TiO_2	(%)	1.96
Iron oxide Fe_2O_3	(%)	16.845

3.1.2. Fine Aggregate

In this investigation, the fine aggregate was made using locally accessible Bolahari sand. The sand's specific gravity was 2.52, and its water absorption rate was 1.02%. The Sieve examination was conducted with ASTM recommendations to estimate the fine aggregate's fineness modulus (FM). The aggregate's FM was determined to be 2.11 based on the sieve analysis results shown in Table 2.

Table 2. Sieve Analysis Test Result of Fine Aggregate

S.no	Sieve sizes	Weight retained (gm)	Percentage weight retained	Cumulative wt. Retained	Cumulative percentage wt. Passing
1	4.74	275	9.167	9.167	90.833
2	2.36	310	10.33	19.497	80.503
3	1.18	430	14.33	33.827	66.173
4	600 µm	700	23.33	57.157	42.843
5	250 µm	915	30.6	87.757	12.243
6	150 µm	275	9.167	96.924	3.076
7	PAN	40	1.33	98.254	0

3.1.3. Coarse Aggregate

This study utilized coarse aggregates sourced from the Petaro Aggregate Crusher Plant, with a maximum size of 19.5mm. The aggregates displayed a water absorption rate of 0.67% and a specific gravity of 2.58. Sieve analysis was performed following ASTM guidelines to calculate the fineness modulus (FM) of the fine aggregate. The findings of the sieve analysis are provided in Table 3.

Table 3. Sieve Analysis Test Result of Coarse Aggregate

S. No	Sieve sizes	Weight retained (gm)	Percentage weight retained	Cumulative wt. Retained	Cumulative percentage wt. Passing
1	37.9	0	0	0	100
2	19.5	660	16.58	16.58	83.42
3	9.5	3165	79.5	96.08	3.92
4	4.75	155	3.89	99.97	0.03
5	pan	0	0	99.97	0

3.1.4. Water

Drinking quality water from the concrete laboratory was applied to produce the concrete.

3.2. DOE Mix Design

In this research, we design the concrete mix for compressive strength of 25 MPa and the following typical specification. DOE mix design was used for this purpose.

- Cement OPC-42.5
- Max. Aggregate size = 20mm crushed
- Fine aggregate = uncrushed 40% passing from the 600-micron sieve
- Assumed density of concrete = 2355 Kg/m3
- Considering the 5% defective rate
- Target slump 50 mm

Designed concrete specifications from DOE mix design are

- Taken ratio of ingredient = 1:1.98:3.17
- w/c-ratio = 0.5

Table 4. Ingredient Mix Proportion

Mix ID	Mix proportions (Kg/cu.m)						
	Cement			fine Aggregate	W (w/c = 0.52)	coarse aggregate	designed slump(mm)
	CFA %	CFA	Cement				
M-0	0	0	345	685	179	1095	50
M-10	10	34.5	310.5	685	179	1095	50
M-20	20	69	276	685	179	1095	50
M-30	30	103.5	241.5	685	179	1095	50

3.3. Methodology

This study investigates the performance of fly ash as a cement substitute in concrete, focusing on its impact on mechanical properties like splitting tensile strength and compressive strength. The target compressive strength for the concrete mix in this study is set at 25 MPa, considering safety aspects. The influence of fly ash on fresh concrete properties and the durability of hardened concrete varies with the mixture's composition and proportion, concrete type and size, exposure conditions, and construction practices. This variability implies that no single fly ash replacement level is universally optimal.

To explore different replacement levels, 36 concrete cubes of 100mm x 100mm x 100mm were prepared for compressive strength tests, and 12 standard cement concrete cylinders (100mm x 200mm) were created to measure splitting tensile strength. The specimens were made using various fly ash proportions, replacing 0%, 10%, 20%, and 30% of the cement by weight, with a water-to-cement ratio of 0.52. For each mixture, three cubes were tested at different curing ages of 7, 14, and 28 days, totaling 12 cubes for each fly ash percentage. The cylinders were subjected to compression strength testing after a 28-day curing period

4. Results and Discussion

4.1. Workability Test

The workability of the concrete slump test is performed on every mix design. The test result is given in the following table 5. Workability was assessed using the Slump Cone Test, adhering to the ASTM C143 standard guidelines.

Table 5. Slump Cone Test Results

S.NO	Mix I.D	Fly ash (%)	Slump Value (mm)
1	M-0	0	45
2	M-10	10	55
3	M-20	20	65
4	M-30	30	80

Table 5 displays the results of the slump test conducted at various percentages of TCFA (Thar Coal Fly Ash) replacement with cement. The maximum slump value observed was 80 mm at a 30% TCFA replacement. However, the assumed nominal design slump was 50 mm at a 0.52 water-to-cement ratio (W/C ratio). The data indicates an increasing trend of slump value in the concrete mix when TCFA replaces cement. Fig. 1 illustrates that as the TCFA percentage increases, the workability of the concrete improves. The rise in a slump is 22.22%, 44%, and 77.7% at 10%, 20%, and 30% TCFA replacements, respectively. This improvement in workability can be attributed to the reduction in cement content and, subsequently, the amount of water required for hydration. Additionally, the spherical shape of fly ash particles facilitates a balling action, reducing friction between cement and aggregates and enhancing the flowability of the concrete [13].

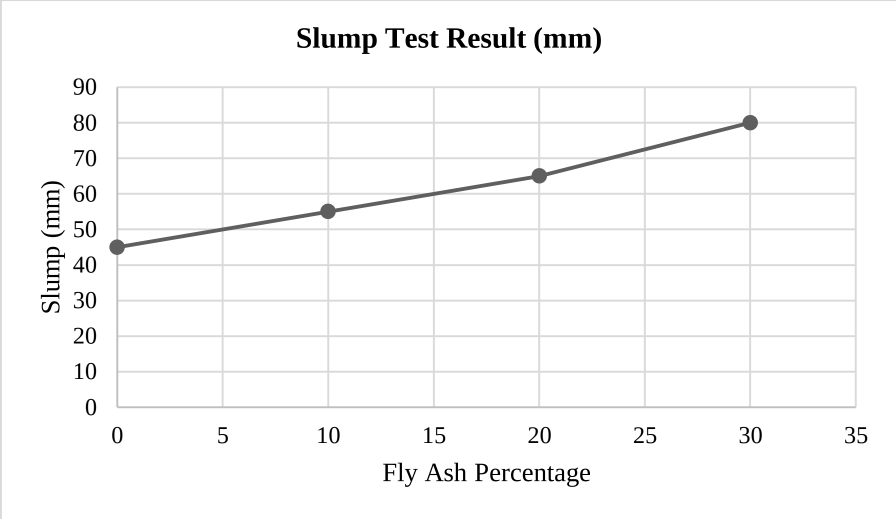

Fig. 1. Relationship between workability and fly ash replacement.

4.2. Compressive Strength Test

Compressive strength is a key indicator of hardened concrete quality, offering a comprehensive view of its characteristics. To determine this, concrete cubes measuring 100mm x 100mm are subjected to a uniform testing procedure in a Universal Testing Machine (UTM). The compressive strength is deduced from the equation

$$fc' = \frac{P}{A} \tag{1}$$

Where as

P, is the maximum load endured by the cube in UTM
A, is the cross-sectional area of specimen
fc' is the characteristic compressive strength of the concrete.

4.2.1. 7- Days Compressive Strength

The results of cube compressive strength at seven days of curing age is given below. For each percentage mix 3 standard cubes has been tested. The corresponding standard deviation is also given below table which give the variability in test results.

Table 6. 7-Days Compressive Strength Test Results

S. No	Batch ID	Fly ash (%)	Max. Load (N)	Strength (MPa)	Avg. Strength (MPa)	Standard Deviation (MPa)
1	M-0-7	0	228129	22.1	19.8	2.08
2	M-0-7		185393	17.96		
3	M-0-7		199535	19.33		
4	M-10-7	10	225961	21.89	21.3	0.70
5	M-10-7		211612	20.5		
6	M-10-7		221419	21.45		
7	M-20-7	20	255483	24.75	25	0.19
8	M-20-7		257032	24.90		
9	M-20-7		260645	25.25		
10	M-30-7	30	217393	21.06	22.71	1.36
11	M-30-7		244748	23.71		
12	M-30-7		241032	23.35		

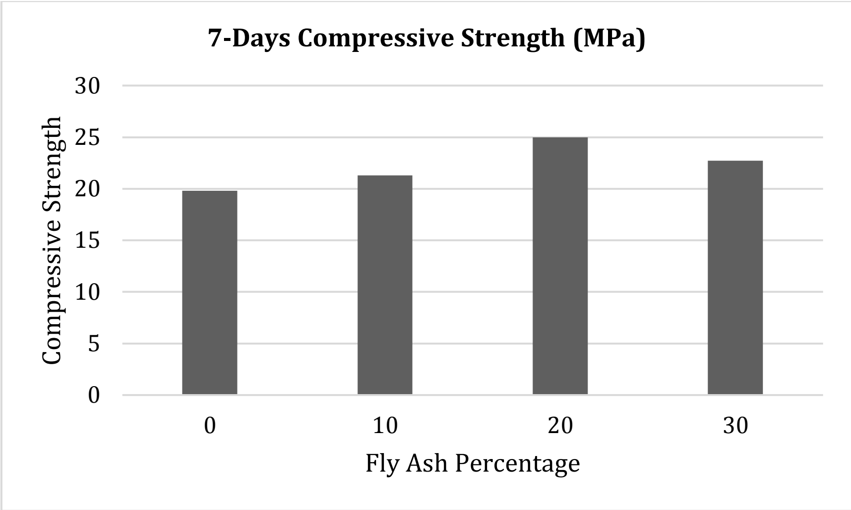

Fig. 2. Relationship between 7 days compressive strength and fly ash replacement.

The concrete mix with TCFA replacement demonstrates slightly higher compressive strength than the conventional mix. Replacing cement with TCFA at 10%, 20%, and 30% leads to respective increases in compressive strength of 7.6%, 26.3%, and 14.6% for a design mix of 1:1.98:3.17. This enhancement is likely due to the differing properties of TCFA compared to typical cement and the denser nature of the concrete with smaller fly ash grains [8,3]. However, it's important to note that this increase is limited to a certain replacement level, as exceeding 20% TCFA content results in a decline in strength. Furthermore, adding more fly ash to the mix increases the free water content and reduces strength.

4.3. 14-Days Compressive Strength

The results of cube compressive strength at seven days of curing age is given below.

Table 7. 14-Days Compressive Strength Test Results

S. No	Batch ID	Fly ash (%)	Max. Load (N)	Strength (MPa)	Avg. Strength (MPa)	Standard Deviation
1	M-0-14	0	273548	25.25	26.5	0.90
2	M-0-14		275612	26.7		
3	M-0-14		278709	27		
4	M-10-14	10	266322	25.8	27.6	1.39
5	M-10-14		276645	26.8		
6	M-10-14		281599	27.28		
7	M-20-14	20	313806	30.4	30.7	1.43
8	M-20-14		337548	32.7		
9	M-20-14		298322	28.9		
10	M-30-14	30	262193	25.4	25.93	0.40
11	M-30-14		269522	26.11		
12	M-30-14		291922	28.28		

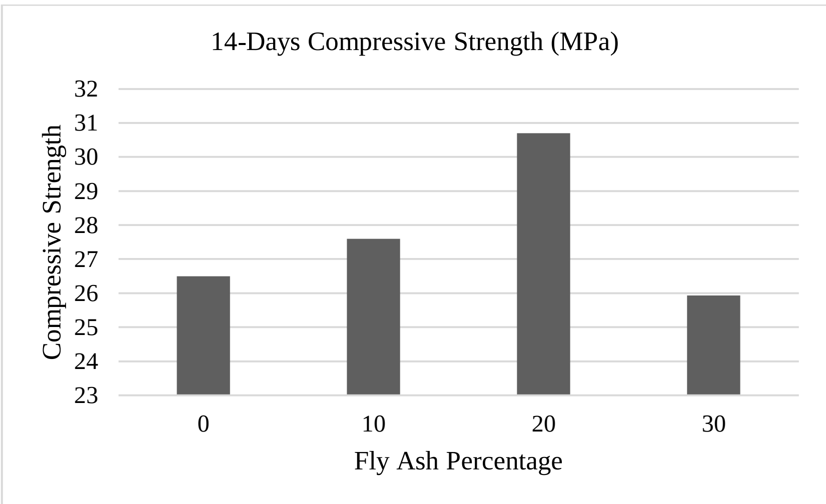

Fig. 3. Relationship between 14 days compressive strength and fly ash replacement.

Table 5 presents the compressive strength results at a 14-day curing age. This duration is typically sufficient for assessing early-age concrete strength and ensuring formwork removal. The table is accompanied by Figure 5, depicting the trend of compressive strength against the percentage of fly ash replacement. Notably, the concrete mix with fly ash replacement exhibits slightly higher compressive strength compared to the conventional mix. At a designed mix ratio of 1:1.98:3.17, the 14-day compressive strength increases by 4.2% and 15% when replacing 10% and 20% of cement with fly ash, respectively, but decreases by 2.3% at a 30% replacement. Additionally, the conventional mix demonstrates a higher strength gain rate compared to the fly ash-replaced mixes. Comparing the strengths at 14 days to those at seven days, the increase is 34%, 20.2%, 22.8%, and 14.2% for 0%, 10%, 20%, and 30% fly ash replacements, respectively, indicating a higher strength gain rate for the conventional mix.

4.4. 28-Days Compressive Strength

The results of cube compressive strength at 28 days of curing age is given below.

Table 8. 28-Days Compressive Strength Test Results

S. No	Batch ID	Fly ash (%)	Max. Load (N)	Strength (MPa)	Avg. Strength (MPa)	Standard Deviation (MPa)
1	M-0-28	0	368722	35.72	35.45	0.22
2	M-0-28		364386	35.3		
3	M-0-28		364180	35.28		
4	M-10-28	10	384619	37.26	36.6	1.06
5	M-10-28		363973	35.26		
6	M-10-28		374502	36.28		
7	M-20-28	20	401548	38.9	38.4	0.55
8	M-20-28		390193	37.8		
9	M-20-28		397419	38.5		
10	M-30-28	30	321032	31.1	32.14	0.83
11	M-30-28		326296	31.61		
12	M-30-28		348593	33.77		

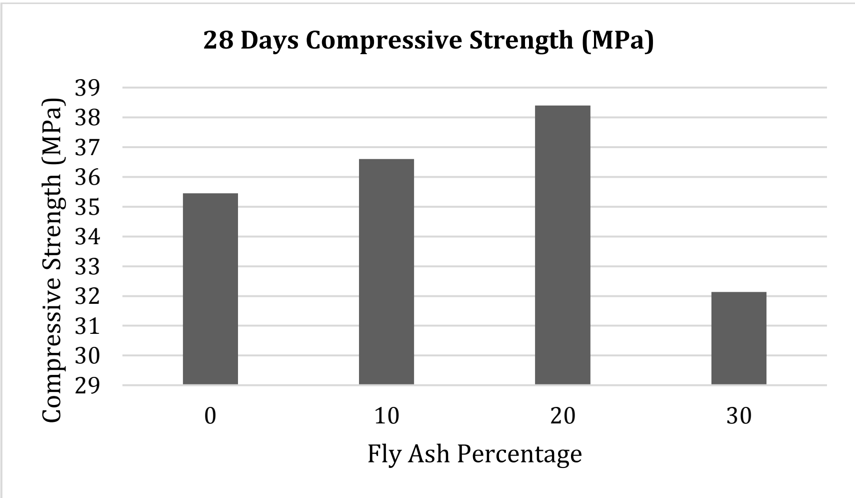

Fig. 4. Relationship between 28 days compressive strength and fly ash replacement.

Table 8 presents the compressive strength results at a 28-day curing age, which is crucial for assessing the long-term strength of structures. These results are also depicted in Figure 4. It was observed that the concrete mix with 10% and 20% TCFA (Thar Coal Fly Ash) replacements demonstrated improvements in compressive strength by approximately 3% and 8.6%, respectively, compared to the conventional mix. However, at a 30% TCFA content, the combination decreased compressive strength by approximately 8.1% compared to the conventional mix.

4.5. Impact of Varied Curing Durations (7, 14, and 28 Days)

In Fig. 5, the M-2 mix group with 20% fly ash replacement achieves the highest compressive strength at 28 days, recording 38.4 MPa, surpassing the control mix's 35.45 MPa. Conversely, the M-3 mix group, with 30% fly ash substitution, demonstrates the lowest compressive strength across all curing periods. An upward trend in strength is evident up to the 20% fly ash replacement level for all curing durations, whereas the 30% replacement level consistently results in lower compressive strengths when compared to the other groups. The 28-day curing results show that a 20% replacement achieves the highest strength, suggesting this as an optimal level for balancing early strength gain and long-term performance without compromising work schedules in construction. The variability in strength gains is attributed to the hydraulic and pozzolanic reactions of the fly ash, with long-term strength potentially improving due to ongoing pozzolanic activity and the filler effect of unreacted fly ash particles.

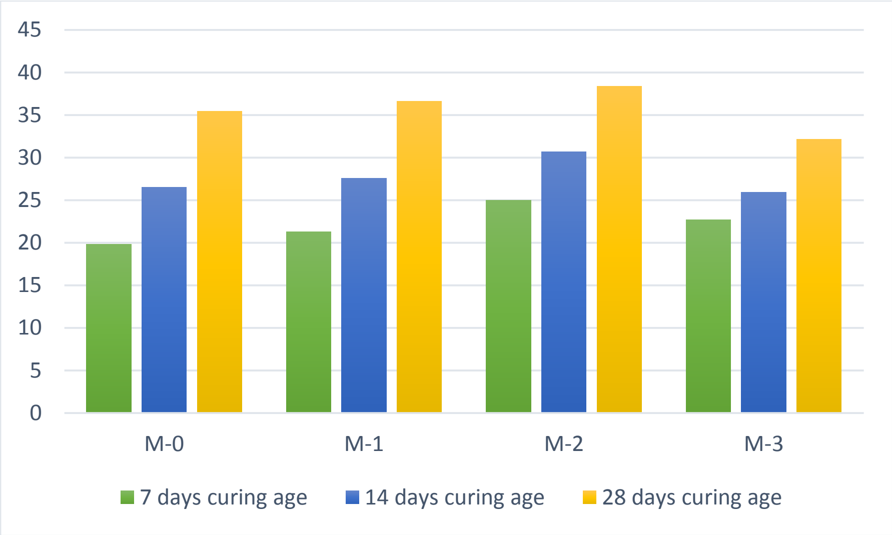

Fig. 5. Compressive Strength for Mix Groups with different curing ages (7 14 and 28 days)

4.6. Splitting Tensile Strength

The splitting tensile test offers an indirect measure of concrete's tensile strength by applying diagonal compression to a standard-sized cylinder. In this study, cylinders with dimensions of 100mm by 300mm were utilized. These were tested in a Universal Testing Machine (UTM) after a curing period of 28 days. The splitting tensile strength (fst) is calculated using following formula.

$$f_{st} = \frac{2P}{\pi dl} \tag{2}$$

Whereas,

P, is denotes the maximum load applied,
l, is the length,
d, is the diameter of the cylinder.
The results of cylinder splitting tensile strength at 28 days of curing age are below.

Table 9. 28-Days Splitting Tensile Strength Test Results

S. No	Batch ID	Fly ash (%)	Max. Load (N)	Strength (Mpa)	Avg. Strength (Mpa)	Standard Deviation (MPa)
1	M-0-28	0	30038	2.5	2.98	0.34
2	M-0-28		30565	2.94		
3	M-0-28		32805	3.5		
4	M-10-28	10	31558	2.75	3.10	0.25
5	M-10-28		36498	3.15		
6	M-10-28		56580	3.40		
7	M-20-28	20	66057	3.2	3.5	0.22
8	M-20-28		64778	3.40		
9	M-20-28		71818	3.90		
10	M-30-28	30	73878	3.75	3.62	0.11
11	M-30-28		82558	3.7		
12	M-30-28		71388	3.40		

According to Table 9's test results, the splitting tensile strength of concrete improved by 4%, 17.4%, and 21.5%, respectively, after 28 days of curing time with 10, 20, and 30% more TCFA cement than regular concrete. The continuous pozzolanic processes that strengthen the link between paste and aggregate and more dense concrete may be to blame for this rise in tensile strength [14].

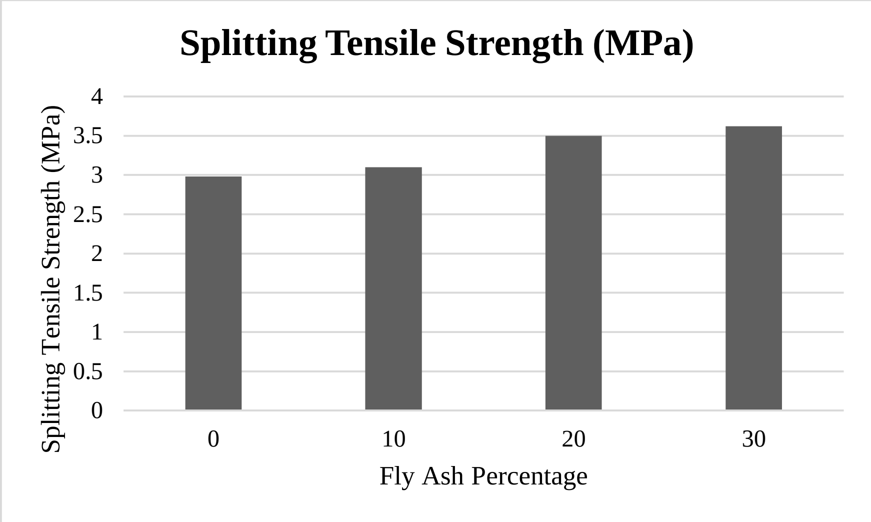

Fig. 6. Relationship between 28 days splitting tensile strength and fly ash replacement.

5. Conclusion

After analysis of test results and their comparison with conventional concrete, conclusions could be drawn.

1. The cohesiveness (workability) of concrete was enhanced by adding TCFA as a partial replacement for cement. According to test results, the proportion of TCFA material and its slump value (workability) are directly correlated.
2. The maximum value of constrictive strength occurred at 20% cement replacement with TCFA for all curing ages.
3. It was observed that cement partially replaced with 30% TCFA showed a negligible decrease in compressive strength after 28 days.
4. For optimum replacement of cement for both early and long-term strength, it is commended to use 20% TCFA. However, when slight compromises in 28-day strength are acceptable, and early strength is not crucial, replacing 30% of the cement with TCFA is advised.
5. Similarly, the tensile strength for splitting concrete at a mixed ratio of 1:1.98:3.17 increases by 21.5% with a 30% TCFA addition. Therefore, replacing some of the cement in concrete with 30% TCFA can increase the material's splitting tensile strength.

The research study will contribute to the field of sustainable construction materials by demonstrating the feasibility of using Thar Coal Fly Ash (TCFA) as a partial replacement for cement in concrete. The study has shown that a 20% replacement level optimizes compressive strength across all curing periods, marking a significant finding for material engineering and environmental sustainability.

Scientifically, the work justifies the use of TCFA by presenting empirical evidence that not only does it enhance workability but also increases the early and long-term compressive and tensile strengths of concrete. This has implications for reducing the carbon footprint of concrete production, a critical consideration in light of global environmental challenges.

Furthermore, the research opens avenues for utilizing industrial by-products in concrete, thus contributing to circular economy principles in construction practices. The economic and environmental benefits of TCFA's integration into building materials underscore its potential utility. Future studies could extend this work by exploring the long-term durability implications of TCFA-enhanced concrete in various environmental conditions.

6. Recommendations

To thoroughly recommend using TCFA as a partial replacement for cement still require detailed investigations with a broader scope. However, in this study, test results show considerable improvement in the mechanical properties of concrete. As the TCFA source has yet to be explored and a few studies are available, there is a strong need for detailed testing and analysis of mechanical properties by varying the percentage replacement at different mix proportions and W/C-ratio. In addition to mechanical properties, durability is one of the critical problems when conventional cement is replaced with fly ash. Therefore, durability properties should also be investigated to know the long-term behavior of TCFA in structural concrete.

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Authors’ Profiles

Munesh Meghwar is a freshly graduated student at the Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan. His research interests are Sustainable Civil Engineering Materials, ANN Application in Civil Engineering, Structural Health Monitoring, Recycling, and Green Building.

Dr. Fareed Ahmed Memon works as a Professor at the Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan. His research areas are Structural Engineering, Concrete Technology, Self-Compacting Geopolymer Concrete, Fiber Reinforced Concrete, Recycle, and Reuse of Waste Materials.

Dr. Shanker Lal Meghwar is currently working as a Lecturer at the Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan. His areas of interest are Structural Engineering, Concrete Technology, Self-Compacting Geopolymer Concrete, Fiber Reinforced Concrete, Recycle, and Reuse of Waste Materials. His research interest in Ergonomics, Lean Manufacturing, Six Sigma, and Quality Control.

Adarsh Dodai is an MSc. Scholar at the Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan. His research interests are Sustainable Civil Engineering Materials, Autoclaved Aerated Concrete, Material Recycling, Management, and Green Buildings.

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