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Experimental Study on Use of Fly Ash as a Partial Replacement of Cement in Concrete

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Abstract: ***Cement ranks high among the world's most popular construction materials. A major contributor to the recent spike in carbon emissions is the cement industry. Partial cement substitutes made of alternative or low - emissions binders have grown in popularity in the last several years. The inexpensive cost and large annual production of fly ash as a waste material have made it one of the most accessible options. Due to their low cost and outstanding performance, fly ash - based building materials show great potential as alternatives to cement. This article delves into the ways in which fly ash impacts the practicability, setting time, compression strength, and tensile strength of concrete. Additionally, the types and properties of fly ash were examined.***

Keywords: fly ash concrete, sustainable construction, cement alternatives, carbon emissions, building material properties

1. Introduction

Because of its strength, accessibility, and longevity, concrete is among the most used "construction materials" (Berry, 2009). The annual global production of concrete exceeds 10 billion tons (Babor et al., 2019). Three primary components—aggregate, water, and Portland cement (PC) —make up concrete. In order to make cement, a number of basic ingredients are heated to high temperatures in order to induce chemical reactions. These components include clay and limestone. Approximately 5% of the world's annual energy consumption and enormous amounts of carbon dioxide are released into the atmosphere by this process (Tafheem et al., 2011). Utilizing waste materials as an alternative to cement (Valipour et al., 2016). According to Al - Zubaid et al. (2017), using waste material in a certain ratio instead of cement may cut the cost of cement while also allowing for the manufacture of concrete with fewer environmental implications and cheaper expenses.

By using other pozzolanic materials as a cement - like binder, the quantity of cement needed to make the concrete mixture may be decreased (Golewski, 2017). The term for these substances is supplemental cementitious materials, or SCM. The extraction, mining, and processing of waste materials would also reduce emissions of pollutants if they were put to use (Tafheem et al., 2011). Green concrete may be made using SCM, such fly ash, instead of cement. In order to create environmentally friendly, high - performing, long - lasting, and cost - effective concrete, "green" concrete uses materials that are either naturally occurring or can be recycled (Valipour et al., 2016).

You may use SCM in lieu of some of the cement in concrete, and there are many different kinds to choose from. When deciding to adopt SCM, factors such as cost, proximity, availability, and durability are taken into account. If you're looking for an alternative to cement, fly ash is a great choice (Tafheem et al., 2011). It is only utilized partially as a cement replacement because of the chemical interactions it has with the water and calcium hydroxide that are generated during cement hydration. One kind of concrete is ash concrete, which uses ash in place of some of the cement. In 1930, American scientists started using ash in cement concrete. Silica, alumina, and iron make up the bulk of fly ash. Fly ash also contains calcium, potassium, sulfur, magnesium, and sodium (Tafheem et al., 2011). Researching the effects of ash on concrete's setting time, workability, compressive strength, and tensile strength when used in part as a substitute for cement was the primary objective of this research.

Fly Ash

Fly ash, as seen in Figure 1, is a solid byproduct of steel, iron, and thermal power plants (Panda et al., 2019). According to Bagheri et al. (2020), the majority of ash involves of silica, iron, aluminum, and calcium oxide. Concrete made using fly ash is stronger and more long - lasting than cement concrete because it chemically combines with hydroxide to form secondary silicate (George et al., 2012).

Making concrete from fly ash and cement prevents the harmful compounds from the ash from harming the environment. By replacing cement with fly ash, we can cut down on energy use, resource consumption, and carbon dioxide emissions. Liew et al. (2020) found that it improves workability, lowers body temperature, and decreases bleeding. According to Krishnamoorthi and Kumar (2013), it is used as a filler in concrete with the purpose of reducing total voids. Several construction firms have opted to partly substitute cement with pozzolanic elements like ash in order to densify the matrix and increase.

Types of Fly Ash

The properties of ash may fluctuate greatly from plant to another as a result of variations in coal quality. According to Nath and Sarker (2011), the composition, burning temperature, and pace of cooling of fly ash all have an impact on its physical and cementitious properties. Class F and Class C fly ash are defined by ASTM C 618 (Altwair & Kabir, 2010). Table 1 demonstrates the main difference between different Class, as shown in Altwair & Kabir (2010) and Rashad (2015).

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Difference of Ash

C FA	F FA
1) Sub - bituminous coal or lignite are burned to produce it. 2) It contains a lot of free lime 3) More than 10% of its content is calcium oxide. 4) A combination of three important oxides, ranging from 50% to 70%, namely SiO2, Al2O3, and Fe2O3. 5) Five, it is a cementitious material. 6) The larger amounts of alkali sulfate in it lead it to be typically finer than F FA.	1) It produces smoke when bituminous and anthracite coal are burned. 2) The free lime content is low. 3) Less than 10% of its content is calcium oxide. 4) By adding together the three major oxides (SiO2, Al2O3, and Fe2O3), almost 70% 5) Cementitious characteristics are rather uncommon. 6) The smaller amounts of alkali sulfate cause it to be typically larger than C FA.

Physical Properties

Cement particles are larger and more coarse than glassy, spherical "ball bearing" fly ash particles (Pitroda1 et al., 2012). According to Abushad and Sabri (2017), the size of individual fly ash particles may vary from 1 micron to 1 mm. The relative density, or specific gravity, of fly ash ranges from 1.9 to 2.8. According to Rashad (2015), the surface area (blaine fineness) ranges from 300 to 500 m2/kg. Table 2 details the physical properties of fly ash.

Physical properties of fly ash.

Properties	(Berndt, 2009)	(Sahmaran *et al.,* 2009)	(Sahmaran *et al.,* 2009)	(Kayali & Ahmed, 2013)	(Memon *et al.,* 2010)	(Marthong & Agrawal, 2012)	(Namagga & Atadero, 2009)	(Pati1 *et al.,* 2012)
Specific Gravity (g/cm3)	**2.35**	**2.27**	**2.08**	**2.13**	**2.54**	**2.13**	**2.71**	-
Blaine fineness (m2/kg)	341	306	289	310		330		340-360

Chemical Components

Fly ash's primary chemical constituents are SiO2, Fe2O3, Al2O3, and CaO. The pozzolanic action of these compounds is due to these chemical components. The chemical make - up of fly ash is shown in Table 3.

Chemical components of fly ash

Chemical Components %	(Nath & Sarker, 2011)	(Dhiyanesh *et al.,* 2013)	(Sathawane *et al.,* 2013)	(Namagga & Atadero, 2009)	(Bernd t, 2009)	(Kayali, & Ahmed, 2013)	(Onera *et al.,* 2005)	(Mukherjee *et al.,* 2012)	(Sahmaran *et al.,* 2009)	(Sahmaran *et al.,* 2009)
CaO	2.13	18.67	2.0	23.45	5.54	<1	2.10	0.59	10.07	2.21
SiO2	50.50	45.98	40	39.76	47.58	67.5	57.55	64.58	48.08	54.13
AI2O3	26.57	23.55	25	14.31	26.42	23	25.16	25.89	25.87	25.73
MgO	1.54	1.54	3.71		0.90	<1	2.5	5.27	1.46	2.12
Fe2O3	13.77	4.91	6	5.56	12.19	4.5	6.5	0.26	4.54	6.43
SO3	0.41	1.47	1.74	6.19	1.08	0.1	0.19		0.55	0.11
K2O	0.77	1.8	0.80		1.9	1.5	3.65	0.041	1.22	4.33
Na2O3	0.45	0.24	0.96		1.5	0.5	0.66	0.027	0.73	0.47
Loss on ignition (LOI)	0.65	2.32	3.0	1.66	2.21	1.0	1.672	2.5	1.1	1.44

Fresh Properties of Concrete

One definition of concrete's workability is the degree to which it can be mixed, poured, compacted, and finished with relative ease. There are a couple of common ways to test the workability of concrete: slump flow time and slump flow diameter.

Fly ash concrete, like regular concrete, is worked differently depending on the water content (Wattimena & Hardjito, 2017). Both the 2007 and 2009 studies by Sahmaran et al. carried out experiments. Figure 2 shows that the w/cm ratio decreases as the FA replacement with PC increases. This is because fly ash's smooth surface and spherical particle shape have a lubricating effect, reducing the water need of concrete. One possible explanation is because the compact design and at low replacement levels, the spherical particles of ash in cement paste and aggregates reduce friction. However, as the percentage of fly ash replacement increases, the workability of the concrete decreases due to the high surface area of the ash. The workability of fly ash concrete is greatly affected by factors such as the FA's shape and surface roughness (Sahmaran et al., 2007) and the rate at which FA replaces PC (Xu & Shi, 2018). However, according to Wattimena and Hardjito (2017), workability is not as affected by changes in the chemical composition of fly ash.

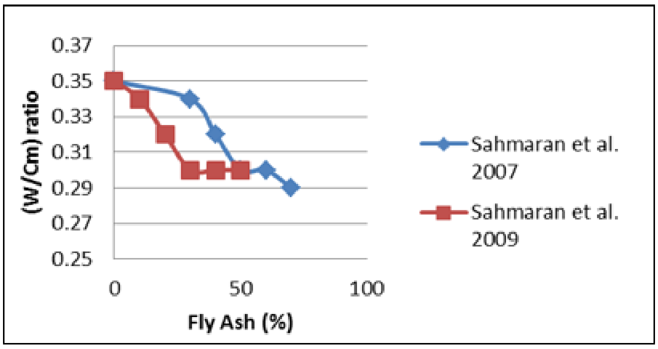

Figure 2: Effect of fly ash content on (w/cm) ratio

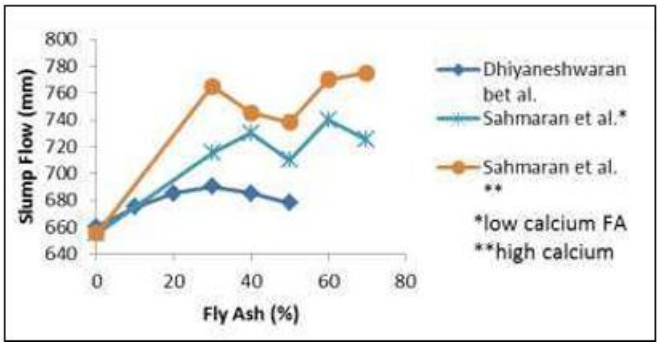

Figure 3: Effect of fly ash content on slump flow

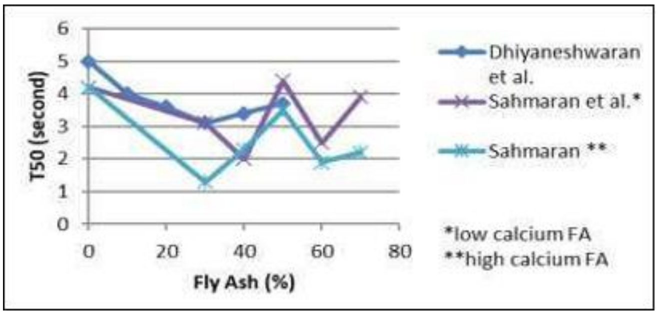

Figure 4: Effect of fly ash content on slump flow time

Setting Time

The setting time of concrete is the duration required for the material to transition from a liquid to a solid state. Among the most important components of fly ash concretes, it determines the properties of the hardened state and the amount of time that must pass between handling the material and placing and compacting it (Wattimena & Hardjito, 2017). According to Kesharwan et al. (2017), the addition of fly ash to concrete makes the curing process take longer than if no fly ash were used. An increase in the number of absorbed calcium ions frequently lengthens the setting time of fly ash concrete, which helps prevent a buildup of calcium ion concentration in the new paste during early hydration. (Kocak & Nas, 2014; Sahmaran et al., 2009; Wang, 2004). Varieties and quantities of fly ash used in the mixture determine the curing duration of fly ash concrete (Bendapudi & Saha, 2011; Wang, 2004; Ravina & Mehta, 1986; Siddique, 2008). Using fly ash of Class C and Class F causes concrete to set more slowly.

Contrarily, a rapid setting may be induced by some C FA types (Wattimena & Hardjito, 2017; Siddique, 2008). The setting time is inversely proportional to the particle size of the cement, as stated by Marthong and Agrawal (2012). Cement hydrates more quickly when its particle size decreases because a smaller particle size increases the surface area accessible for chemical interaction. This leads to the early development of hardness and strength. The effect of fly ash on concrete's setting behavior depends on a number of factors, including water content, cement type, quantity, and composition (Siddique, 2008; Sata et al., 2007).

Hardened Properties of Fly Ash

Compressive Strength

The compressive strength test is the most significant metric for producing concrete for two main reasons. To begin with, it is a crucial test for determining a great deal of other concrete qualities. Also, it's not hard to figure out. The chemical characteristics of the fly ash, especially its calcium oxide level, have a significant impact on the compressive strength of fly ash concrete. Fly ash with a high calcium content reacts more quickly, resulting in greater early age strength. Results from experiments shown that after 7 and 28 days, fly ash - containing concrete had a higher compressive strength than fly ash - free concrete (Dhiyaneshwaran et al., 2013; Nagagga & Atadero, 2009). On the other hand, Sahmaran et al. (2009) found that fly ash - containing concrete had a decreased compressive strength compared to fly ash - free concrete after 7 and 28 days. This difference might be explained by the different ratios of CaO to FA that were used. Fly ash with a CaO concentration of 2.21% was utilized in the second one, whereas fly ash with a CaO content of 18.67% and 23.45% were employed in the first one. When fly ash concrete ages, the sio2 concentration has a significant impact on its compressive strength because it forms calcium silicate hydrate by reacting with calcium hydroxide (Sata et al., 2007).

Table 4 shows that, in comparison to regular concrete, fly ash concrete's compressive strength increases substantially with time. The interaction between fly ash and calcium hydroxide (CH) starts after the cement hydration process is complete. Because of this, fly ash - containing concrete has a slower early strength rise (Shaikuthali et al., 2019). Other research, however, has shown that compressive strength increases significantly from a young age. This could be because of the pozzolanic and self - hardening properties of the high Cao content fly ash (C FA), which helps the material build strength quickly after mixing. Compressive strength decreases significantly with a high degree of replacement, as seen in Table 4. Fly ash serves as a pozzolanic component in low - volume fly ash concrete, which might explain this. Even after a long curing time, some of the fly ash in high - volume fly ash concrete doesn't react with the pozzolanic solution (Rashad, 2015). Evidence from the past suggests that the physical and chemical properties of the fly ash, as well as the quantity of cement replacement, w/c ratio, and duration, all have an impact on the compressive strength of fly ash concrete.

Compressive strength of fly ash mixed concrete.

		Compressive Strength (MPa) of fly ash concrete at days					
fly ash: cement	w/cm ratio	7	28	56	90	180	365
0: 100	0.35	23.18	39.07				
30: 70		22.08	30.92				
0: 100	0.45	29.82	46	46.66			
20: 80		26.68	48.91	49.33			
40: 60		27.9	46.35	47.46			
0: 100	According to Normal	26.7	40.2				
30: 70		30.25	45.28				
40: 60		27.75	42.00				

50: 50	consistency	25.5	39.15				
0: 100		28.77	44.				
30: 70		13.04	24.3				
40: 60	0.40	9.93	22.22				
0: 100		13.78	38.22				
30: 70		13.04	27.56				
40: 60	0.3	8.59	21.4				
0: 100		25	46	50			
35: 65		24	37	40			
45: 55		15	29	32			
55: 45		10	21	60			
65: 35		6	14	59			
0: 100	According to Normal consistency	24	57	55			
35: 65		25	51	50			
45: 55		28	48	45			
55: 45		24	41	37			
65: 35		9	32	34			
0: 100		55.9	62.2		69.9	71	74.1
30: 70	0.35	21.9	34.4		64.9	66.2	70.7
60: 40		14.9	62.2		69.9	71	74.1
70: 30		38.6	52.4		64.9	69.2	75.6
0: 100		34.5	52.3		63.2	67.2	75.6
30: 70		32	47.5		59.9	68.7	70
60: 40		22.8	39.9		52.1	62.6	65.8
70: 30	0.32	18.3	32.8		45	53.7	61.6
0: 100		79.5	97.4		110.2		
25: 75	0.24	74.6	105.9		124.5		
45: 55		56.3	89.4		107.2		
0: 100		83.5	96.8		114.5		
25: 75	0.19	74.2	102.3		123.6		
45: 55		56.4	88.5		109.2		
0: 100		19.4	26.4	29.0	31.0		32.8
10: 90		21.4	28.2	31.2	34.2		36.3
20: 80	According to Normal consistency	22.6	30.8	34.0	38.0		40.5
30: 70		25.0	34.9	40.2	44.0		46.4
40: 60		26.5	38.9	44.6	49.8		52.3
50: 50		27.2	40.0	46.3	51.4		54.8

Splitting Tensile Strength

The tensile strength of concrete dictates the size and extent of fractures in the material. The primary factor influencing tensile strength is the quality of the paste, which is determined by the properties of fine aggregates (Mehtaa & Ashishb, 2019). Although much less in size, concrete's splitting tensile strength exhibits behavior comparable to that of its compressive strength. Data from many investigations on the link between splitting tensile strength, water - to - cement mass ratio, time, and the rate of fly ash replacement of Portland cement are summarized in Table 5. Due to the pozzolanic reaction of the ashes and the fine - grained and pore - refined particles, the splitting tensile strength of fly ash concretes is higher than that of control concrete, as shown in Table 5. There is a sweet spot where the tensile strength grows with increasing fly ash concentration (up to a point), but beyond that point, it can start to drop. It is possible that the use of fly ash in low - volume fly ash concrete improves the interfacial connection between the aggregate and the paste. In high - volume fly ash concrete, on the other hand, fly ash weakens the interfacial interaction between the aggregate and the paste (Dhiyaneshwaran, 2013; Magureanu and Negrutiu, 2009). Table 5 shows that according to Siddique (2003), the splitting tensile strength of all mixes rose as they aged.

Splitting Tensile Strength of fly ash mixed concrete.

Ash: Cement	w/cm ratio	7	28	56	90
0: 100			1.72		
10: 90			1.58		
20: 80	According to Normal consistency		0.89		
30: 70			1.21		
40: 60			0.89		
0: 100				3.44	
10: 90	0.4			3.52	
20: 80				3.21	
30: 70				2.55	
0: 100				3.96	
10: 90				4.1	
20: 80				2.78	
30: 70				2.69	
40: 60	0.3			2.04	
0: 100		1.08	1.74		
10: 90		1.23	1.88		
20: 80	According to Normal consistency	1.34	2.01		
30: 70		1.47	2.06		
40: 60		1.36	1.96		
50: 50		1.28	1.84		
0: 100		2.5	3.0	3.2	3.3
10: 90		2.6	3.1	3.3	3.5
20: 80	0.49	2.6	3.2	3.4	3.6
30: 70		2.7	3.4	3.7	4.0
40: 60		2.8	3.5	3.9	4.2
50: 50		2.7	3.5	4.0	4.3

2. Conclusion

The following findings were reached after considering the topic above:

1) Although fly ash does lower the water content of concrete up to a point, if you want your concrete to be workable, you'll need more water as the FA percentage goes up.
2) Fly ash geometry and surface roughness impact fly ash concrete's workability.
3) The workability is less affected by the fly ash's chemical makeup than the setting time.
4) The physical and chemical properties of construction materials determine the optimal fly ash content.
5) 5. The values of the tensile and compressive strengths are determined by the degrees of cement replacement, the kind of FA, and the age of the material.
6) Concrete's compressive and splitting tensile strengths behave similarly.

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