EFFECT OF INDIGENOUS VOLCANIC ASH AS PARTIAL REPLACEMENT OF CEMENT ON MECHANICAL PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURE

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Abstract- This study examines the repercussions of indigenous volcanic ash (IVA) as a partial substitution of cement on the concrete's mechanical properties when exposed to elevated temperatures. The study aims to explore the potential benefits and limitations of utilizing volcanic ash in concrete mixtures for applications in high-temperature environments. The research includes varying percentages of volcanic ash replacements (10%, 20%, 30% and 40%) to assess their impact on concrete's mechanical properties. The experimental program consists of conducting compressive strength tests, splitting tensile strength tests, and strength activity index tests on concrete and mortar specimens respectively. The concrete specimens are subjected to elevated temperature conditions using a controlled heating system for 2hr. The specimens mechanical properties are evaluated and compared to those of the control specimens without volcanic ash. Lower percentages of IVA replacement (10%) show better strengths as compared to the control specimens at different temperatures. However, as the volcanic ash content increases, a gradual reduction in compressive strength and splitting tensile strength is observed with increasing temperature. The findings from this research provide valuable insights into the behavior of concrete incorporating IVA at elevated temperatures. The outcomes contribute to the broader understanding of sustainable and durable concrete production using locally available volcanic ash resources.

Keywords- Compressive strength, Elevated temperature, Indigenous volcanic ash, Splitting tensile strength

1 Introduction

The extensive worldwide utilization of concrete, reaching approximately 25 gigatonnes annually, leads to a substantial environmental impact due to its high resource consumption and significant emissions [1]. While the construction industry heavily relies on ordinary Portland cement (OPC) for concrete production, the energy-intensive nature of OPC manufacturing contributes to significant environmental impacts. With global cement production ranging from 2.8 to 4.1 billion tons annually, it is projected to double by 2030. This sector alone accounts for 8-10% of anthropogenic greenhouse gas emissions, a figure that could increase to 10-15% by 2020. To address these concerns, extensive efforts have been made to develop more sustainable and durable concrete and construction products by substituting a portion of OPC with supplementary cementitious materials (SCMs) [2]–[10]. Volcanic ash, a type of natural pozzolana, demonstrates great potential as an alternative to OPC cement in the development of concrete and blended cement. Several countries have already utilized volcanic ash as a natural pozzolana. It is economically viable and can be incorporated into concrete, cement paste, and mortars. Volcanic ash utilisation as a substitute for OPC is particularly valuable owing to its ability to reduce carbon emissions, its accessibility in the region, and its beneficial pozzolanic [11]–[14]. A natural pozzolan is defined by

ASTM C618-93 as volcanic ash, which develops during volcanic eruptions [15]. To investigate the ability of the mortar, four unique proportions of VA (0, 5, 15, and 25%) were prepared as weight replacements for the cement. A series of experiments were carried out after 28, 90, and 120 days at various temperatures (25, 200, 500, and 800 °C). The findings show that substituting cement with volcanic ash can maintain a satisfactory level of compressive, tensile, and flexural strength in mortar. Compressive strength tests at various ages and temperatures show that the mortar with 15% VA replacement has better compressive strength capabilities than other proportions [16]. The incorporation of VA up to 20% in the HSC resulted in improved resistance to chloride penetrability and degradation, as well as an increase in residual strength when exposed to a high temperature of around 800°C. When the temperature was raised above 800°C, however, the durability and strength were lowered [17]. As compared to control samples, mortar specimens with 20% VA as a replacement for cement had more substantial mechanical qualities at elevated temperatures [18]. In this study, the most optimal VA concrete mixture showed a compressive strength comparable to the controlled OPC concrete. Additionally, it exhibited lower carbon emissions and greatly improved resistance against chloride penetration. The sustainability potential index analysis indicates that the most "sustainable" alternative VA concrete has a water/binder ratio of 0.33 and a VA replacement percentage of 30%[19].The incorporation of an optimal 10% of volcanic pumice powder (VPP) as a partial substitute for cement in high-strength concrete (HSC10) revealed beneficial gains in strength qualities when compared to replacement levels of 20% and 30%. The indirect tensile strength followed the same trend as the compressive strength [14]. Mechanical tests indicated that all three OPC/VA dosages, 10%, 25%, and 40%, were equally effective. However, among OPC/VA formulations, the 10–25% dosage range demonstrated the highest effectiveness[20].

The purpose of this research is to evaluate the effectiveness of using locally available volcanic ash as a partial substitute for cement in concrete, particularly in situations of high temperatures. The goal is to develop an environmentally friendly and cost-effective concrete alternative by substituting a part of ordinary OPC with natural pozzolanic ingredients. The study focuses on investigating the effect of this natural pozzolanic ingredient, IVA, on the concrete's mechanical properties at high temperatures. The research aims to validate the suitability and commercial viability of using IVA as a partial replacement for cement based on its effects on the mechanical properties of concrete under high-temperature conditions.

2 Experimental Program

Locally available ordinary Portland cement (OPC) is used in sample preparation. The physical properties of IVA and OPC cement are illustrated in Table 1, and the chemistry of OPC cement is noted in Table 2. The chemical composition of IVA and OPC cement are illustrated in Table 1. The physical properties of IVA and OPC cement are shown in Table 2. Table 3 illustrates the physical properties of both fine and coarse aggregates. The IVA used in this research was procured from Chilas (Gini), where it is readily available.

Table 1 Chemical Content of IVA & OPC

Oxides	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**k_2O**	**Na_2O**	**LSF**	**SM**	**Am**	**LOI**
IVA	52.9	19.15	9.3	7.41	4.55	0.06	0.42	3.61	4.21	1.84	2.06	1.3
OPC	21.5	6	3.75	62	2.8	2.75	1	0.2	…	…	…	0.6

Table 2 Physical properties of IVA & OPC

Name of Property	**IVA**	**OPC**
Specific Gravity	2.67	3.07
Consistency of cement (%)	25.55	29.7
Initial setting time in minutes	175	115
Final setting time in minutes	250	243
Soundness	No Expansion	No Expansion

Table 3 Physical properties of F.A and C.A

Name of Property	(F.A)	(C.A)
Specific gravity	2.69	2.66
Absorption Capacity (%)	1.29	0.9
Fineness Modulus	2.66	

3 Research Methodology

3.1 Mix Design of Concrete

To investigate the mechanical properties of concrete. A total of five mix proportions were used. The different mix proportions are shown in Table 1. IVA0% stands for control mix containing 0% IVA, IVA10% mix containing 10% IVA, IVA20% mix containing 20% IVA, IVA 30% mix containing 30% IVA and IVA40% mix containing 40% IVA.

Table 4 Mix Design of Concrete

Concrete mix Composition					
Mixes	OPC (kg/m^{3})	IVA (kg/m^{3})	Water (L/m3)	F.A (kg/m^{3})	C.A (kg/m^{3})
IVA0%	320	0	160	640	1280
IVA10%	288	32	160	640	1280
IVA20%	256	64	160	640	1280
IVA30%	224	96	160	640	1280
IVA40%	192	128	160	640	1280

3.2 Mixing Procedure

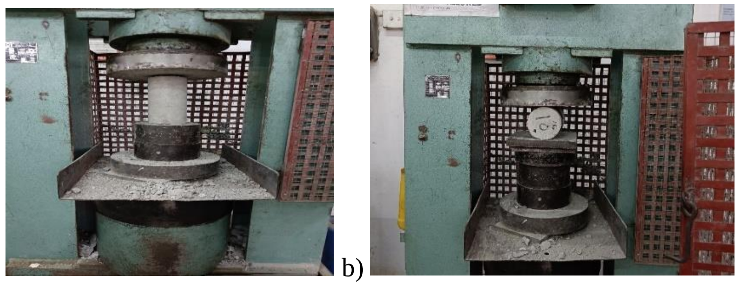
The tilting drum type electric concrete mixer was used for the homogenous mixing of concrete. Firstly, for one minute, the dry mixing of sand and coarse aggregate was done in the mixer. After that, cement, IVA if required, and water were added to the mixer. The ingredients were mixed in a mixer that revolved at a rate of 30 revolution/minute. The mixing process was limited to 3 minutes.

3.3 Specimen Preparation

The mortar cubes of size 50mmx50mmx50mm were prepared in accordance with ASTM C109 [21], having a mix ratio of 1:2.75 and a water to cement ratio of 0.484. 20% IVA is replaced with cement by weight in the mortar mix. The 100mm x 200mm concrete cylinders are made with a mix ratio of 1:2:4 and a water-to-cement ratio of 0.50. The percentages of 10%, 20%, 30%, and 40% IVA are replaced with cement by weight in the concrete mixes.

3.4 Heating of Concrete

The present research focuses on examining the thermal behaviour of concrete when a portion of cement is replaced with IVA. The replacement proportions of IVA with cement are 0%, 10%, 20%, 30%, and 40%. In order to investigate this, a series of concrete mixes were prepared and subjected to elevated temperatures in a furnace. Specifically, one set of concrete samples was heated to 150°C for a duration of 2 hours, while another set was exposed to temperatures of 450°C and 750°C for the same amount of time [22]. The concrete samples were allowed to cool down to room temperature after the heating process. This experimental procedure will enable the researchers to analyse and evaluate the thermal performance and behaviour of the concrete mixes at different temperatures.

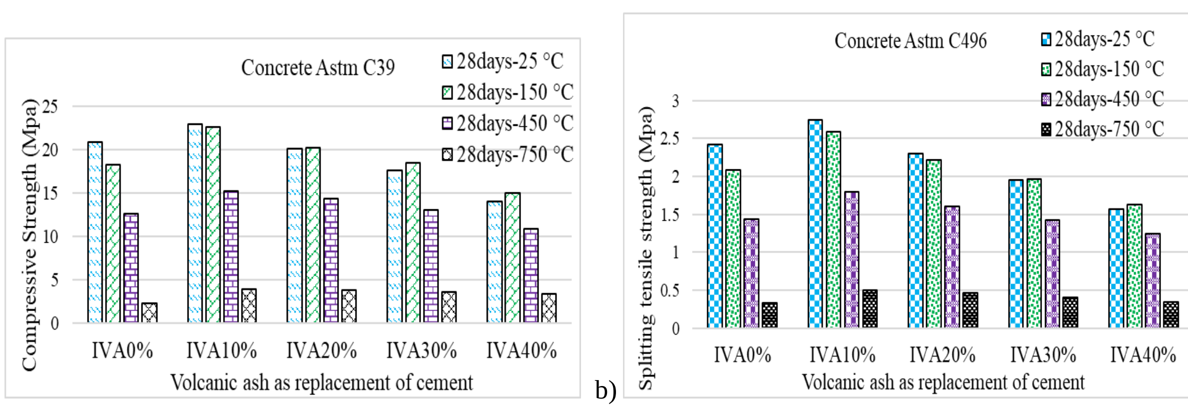


a) b)

Figure 1 Testing, a. casting Compression test of cylinder, and b. Splitting tensile test

3.5 Compressive Strength

The compressive test of the specimens is conducted on cylinders of size 100mmx200mm at 28 days after exposure to different temperatures, i.e., 25°C, 150°C, 450°C, and 750°C. Figure 2a shows the relationship between the effect of different temperatures and the compressive strength of concrete for different percentages (0%, 10%, 20%, 30%, and 40%) of IVA replacement with cement. The replacement of 10% IVA with OPC cement in the specimens shows higher compressive strength compared to the control specimens after exposure to different temperatures, i.e., 25°C, 150°C, 450°C, and 750°C. At 25°C (room temperature), an increase in the compressive strength of the specimen occurs at 10% replacement of IVA with cement as compared to the control mix. It may be due to the chemical reaction of SiO_2 in IVA with CH. As a result, the amount of CH decreased and CSH (calcium silicate hydrate) increased, which improved the compressive strength of concrete. Further increase of IVA from 20% to 40% decrease in compressive strength of concrete occurs. It may be because of substituting cement with IVA, reduces the cement content in the mix [23], [24]. At 150°C, the compressive strength of some concrete mixes containing IVA increased as compared to its compressive strength at 25 °C, may be due to the formation of tobermorite. Tobermorite is a mineral formed when a chemical reaction takes place between unhydrated particles of IVA and lime at an elevated temperature [25]. The compressive strength of all mixes decreases when the temperature rises to 450 °C [26]. This decrease may be due to roughening of the pore structure of concrete. At 750 °C, all the mixes show severe loss in compressive strength, which may be due to the dissociation of CSH gel [24].



a) b)

Figure 2 Results, a. Compressive strength test, and b. Splitting tensile strength test

3.6 Splitting Tensile Strength

The splitting tensile strength of concrete is performed on the cylinder of size 100mmx200mm at 28 days after exposure to different elevated temperatures, i.e., 25°C, 150°C, 450°C, and 750°C. Figure 2b shows the relationship between the effect of different temperatures and the splitting tensile strength of concrete for different percentages (0%, 10%, 20%, 30%, and 40%) of IVA replacement with cement. The effect of elevated temperatures on Splitting Tensile Strength shows a comparable trend with compressive strength. After exposure to various temperatures, i.e., 25°C, 150°C, 450°C, and 750°C, the replacement of 10% IVA with OPC cement shows higher Splitting Tensile Strength compared to the control specimens. At 25°C (room temperature), the specimen's Splitting Tensile Strength increases when 10% IVA is replaced with cement compared to the control mix. It could be due to the chemical reaction of SiO_2 in IVA with CH [23], [24]. As a result, the amount of CH reduced while CSH increased, improving the Splitting Tensile Strength of concrete. As IVA increases from 20% to 40%, the splitting tensile strength of concrete decreases. It could be because replacing cement with IVA, decreases the cement content of the mix. At 150°C, the splitting tensile strength of a concrete mix containing IVA increased as compared to its splitting tensile strength at 25°, may be due to the formation of tobermorite. Tobermorite is a mineral that forms when unhydrated particles of IVA and lime react chemically at high temperatures. The splitting tensile strength of all mixes decreases as the temperature rises to 450 °C. This decrease may be due to roughening of the pore structure of concrete. At 750 °C, all the mixes show severe loss in splitting tensile strength, which may be due to the dissociation of CSH gel [24].

4 Discussion

In comparison to conventional concrete, IVA concrete has higher fire resistance and residual thermal characteristics. IVA concrete should be utilized in places that are more prone to catching fire to improve the structure's sustainability and lifespan. To protect the structural integrity of buildings and mitigate potential damage, it is recommended to use IVA concrete in several critical areas. These include firewalls, fire barriers, furnaces, tunnels, underground parking, kitchen areas, etc. By utilizing IVA concrete in these applications, the risk of direct structural damage can be effectively mitigated.

5 Conclusion

The study's findings lead to several key conclusions:

1. The strength activity index of mortar containing 20% IVA is 90.6% at 7 days and 93.9% at 28 days, exceeding the minimum threshold of 75% specified in ASTM C618.
2. At various elevated temperatures, the optimal amount of IVA for cement replacement is determined to be 10%. At this dosage, the compressive strength of concrete exhibits a better performance in terms of compressive strength as compared to the control specimen.
3. The loss in compressive strength of mix IVA10% was 0%, 1.5%, 33.7%, and 82.9%, while the loss in compressive strength of mix IVA0% was 0%, 12.4%, 39.6%, and 89.2% at various temperatures, i.e., 25°C, 150°C, 450°C, and 750°C respectively.
4. The splitting tensile strength accompanied the same trend as the compressive strength at 10% replacement of IVA with cement at various elevated temperatures. The loss in splitting tensile strength of mix IVA10% was 0%, 5.5%, 34.3%, and 81.8%, while the loss in splitting tensile strength of mix IVA0% was 0%, 14.1%, 40.5%, and 86.4% at various temperatures, i.e., 25°C, 150°C, 450°C, and 750°C respectively.

Recommendations

The present research investigation confirms the Viability of IVA in concrete, thereby demonstrating an efficient approach to environmental sustainability. There are some recommendations made after this investigation:

1. It may be possible to replace the cement quantity with calcined IVA at various temperature levels.
2. The combination of various locally available industrial wastes (such as fly ash, ground granulated blast furnace, etc.) can be used with IVA to produce sustainable and durable concrete.
3. It can also be suggested to study the durability characteristics of each concrete mix.

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