Experimental testing of concrete mixes using volcanic ash for bridge construction

Talat Salama
Department of Manufacturing and Construction Management, Central Connecticut State University, New Britain, Connecticut, USA
E-mail: *talats@ccsu.edu*

Abstract. This research project evaluates the enhancement of strength and durability properties in concrete mixtures through the incorporation of volcanic ash as an admixture. Concrete used in bridge construction is prone to degradation over time, allowing water to permeate and carry chlorides and other harmful substances that accelerate deterioration. To address this, alternative green construction materials are being explored to extend the lifespan of these structures without significantly increasing maintenance costs. This study compares the effects of volcanic ash and the traditional fly ash admixture on concrete's strength and durability. The results indicate that volcanic ash can significantly improve early strength, with mixes containing 20% volcanic ash showing higher initial stress values compared to those with fly ash. Both volcanic ash and fly ash mixes achieve comparable long-term strength, but volcanic ash mixes tend to perform slightly better. High proportions of volcanic ash (50% or more) result in lower strength, suggesting that optimal replacement levels (around 20-25%) provide a good balance between early and long-term strength. These findings support the use of volcanic ash as a sustainable and effective alternative to fly ash in concrete production, contributing to more durable and environmentally friendly bridge construction.

Keywords. Concrete, admixture, volcanic ash, fly-ash.

1. Introduction

The purpose of this research was to see if replacing portions of Portland cement in concrete mixtures with volcanic ash, as opposed to fly ash, improves the strength and workability of the concrete used in bridge construction. The increase in strength is expected to increase the life of the structure therefore minimizing the total life-cycle costs. Increasing the strength of concrete can minimize fractures that allow water to permeate into the concrete structures carrying chlorides and other harmful materials into the structures that result in premature deterioration and failure. According to the American Society of Civil Engineers Report Card, the US bridges and roads received a grade point average of "C" [1]. Moreover, The National Bridge Inventory (NBI) (Federal Highway Administration, 2016) stated that of more than 615,002 bridges in the United States, 47,619 bridges are in 'Poor' condition and 279,270 are in 'Fair' condition, while only 288,030 are in 'Good' condition [1]. Major decisions must be made to allocate the limited funds available for repair, rehabilitation, and replacement of these deficient bridges. An investment of nearly one trillion dollars is needed in the next five years to alleviate the problems associated with bridges and roads [2].

Increased compressive strength of concrete is inversely related to the water-cementing materials ratio that can make concrete too dry to place into forms adequately without the use of superplasticizers or other liquefiers to create a flowable product. Because fly ash particles are spherical in shape, they tend to flow and blend freely in the concrete mixtures. The addition of fly ash greatly improves the durability of concrete through control of high thermal gradients, pore refinement, depletion of cement alkalis, resistance to chloride and sulfate penetration and continued micro structural development through a long-term hydration and pozzolanic reaction [3]. There have been a number of studies and experiments on the use of fly ash as an admixture for concrete. Most of them have been performed to justify the use of fly ash as a means to reduce our consumption of natural resources by supplementing a waste byproduct into current concrete mix designs [4, 5].

An investment of nearly one trillion dollars is needed in the next five years to alleviate the problems associated with bridges and roads. Recently cracking has been observed in many bridge piers. Such cracking threatens to allow penetration of chlorides and other harmful materials within the concrete, leading to potential reinforcement corrosion. These degradation mechanisms can lead to severe deterioration, increased maintenance costs, and decreased service lives of bridge components. Concrete strength and durability are major components of this problem, and having a concrete mixture design that is sustainable is a major part of the solution. Better concrete mix designs can increase the useful life of bridges and make them more sustainable [6]. The study by Chu [7] highlights that incorporating volcanic ash into concrete reduces the overall energy required for its production, making it a sustainable alternative to traditional cement. The research by Ahmed et al. [8] demonstrates that volcanic ash significantly enhances concrete durability through pozzolanic reactions and micro-filling voids, and using 10% volcanic ash can reduce overall costs by 30%. The paper by Kupwade-Patil et al. [9] reports that replacing a certain percentage of traditional cement with volcanic ash can reduce a concrete structure's embodied energy, contributing to more sustainable construction practices.

The American Society for Testing and Materials C618 is the standard specification that governs the use of fly ash, a by-product of the combustion of powdered coal as a mineral admixture. This study will utilize this standard for volcanic ash. Concrete specifications have usually limited the admixture substitution by weight for Portland cement to a range of 15 to 25 percent maximum; with the easing of these restrictions, replacement values as high as 50 percent are successfully being used on concrete construction projects. These new concrete mixes have increased the environmental benefits of using the waste by-product, as well as enhancing the concretes' mix properties. The use of volcanic ash will also be governed by the concrete design mix standard 211 of the American Concrete Institute. The research will evaluate the concrete at different stages of the curing process.

2. Concrete Mixture Experimental Study

The experimental work studied the effect of varying several parameters on concrete strength and durability. The parameters studied were the ash types, water-to-cement ratio (w/c), cement replacement percentage, and time. Twelve concrete mixtures were designed and mixed using the mechanical concrete mixture (Figure 1). Each mix weighed about 115 lbs. to be able to produce 10 concrete cylinder specimens from each test, with a cylinder size of 4 inches in diameter by 8 inches in depth. The total number of specimens constructed and tested were 120 concrete cylinders (Figure 2). The specimens were tested using the compression testing machine.

Figure 1. Mixing Concrete using Mechanical Concrete Mixer.

Figure 2. Curing Box for the 12 Mixtures.

Tests 1, 2 and 3 were mixes that had a w/c of 0.50, and tested the replacement of 20% of cement (by weight) by the two types of ash, volcanic and fly-ash (Class F). The results are presented in Table 1 (100% cement), Table 2 (80% cement and 20% fly-ash), and Table 3 (80% cement and 20% volcanic ash). The results show that the volcanic ash mix is almost the same strength as the fly ash mix at 28 days, and more durable by 4.7% at 56 days. The results of these tests provided an incentive for more similar tests targeting the replacement percentage. Table 4 compares the average stress over time for the three tests.

The key observation is that for the concrete mix at 100% cement, the average stress increases from 14.46 MPa on day 1 to 54.84 MPa on day 56. This mix shows a consistent increase in strength over time, indicating good long-term performance. For the concrete mix with 80% cement and 20% fly-ash, the average stress increases from 7.16 MPa on day 1 to 43.96 MPa on day 56. The initial strength is lower compared to the 100% cement mix, but it shows significant improvement over time. For the concrete mix of 80% cement and 20% volcanic Ash 20%, the average stress increases from 10.47 MPa on day 1 to 46.04 MPa on day 56. This mix shows higher early strength compared to the fly ash mix and achieves comparable long-term strength. These results were encouraging to perform more tests at significantly varying replacement percentages.

Table 1. Test 1: 100% Cement with no admixtures at w/c=0.50.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	121.6	112.9	15.0	13.9	14.5
7	239.7	229.5	29.6	28.3	28.9
14	296.2	291.3	36.5	35.9	36.2
28	347.5	379.7	42.9	46.8	44.8
56	432.2	457.0	53.3	56.4	54.8

Table 2. Test 2: 80% Cement with 20% Fly-Ash at w/c=0.50.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	55.5	60.5	6.9	7.5	7.2
7	196.3	192.0	24.2	23.7	23.9
14	233.9		28.9		28.9
28	297.5	313.7	36.7	38.7	37.7
56	433.9	278.9	53.5	34.4	44.0

Table 3. Test 3: 80% Cement with 20% Volcanic-Ash at w/c=0.50.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	86.7	83.1	10.7	10.2	10.5
7	192.7	199.6	23.8	24.6	24.2
14	225.0	229.8	27.8	28.3	28.0
28	314.4	307.0	38.8	37.9	38.3
56	375.5	370.9	46.3	45.8	46.0

Table 4. Average Stress over Time for Concrete Tests 1, 2 and 3 with w/c=0.50.

Days	Test 1: 100% cement (MPa)	Test 2: 20% FA (MPa)	Test 3: 20% VA (MPa)
1	14.5	7.2	10.5
7	28.9	23.9	24.2
14	36.2	28.9	28.0
28	44.8	37.7	38.3
56	54.8	44.0	46.0

Tests 6, 7, 8, 9, 10, 11, and 12 were all mixed at higher w/c of 0.55, at varying cement replacement percentages (25%, 50% and 75%), for the two types of ashes (fly-ash and volcanic ash), where Test 12 was the control with 100% cement and no ash replacement. The results are tabulated in Table 5 (Test 6: 50% Cement with 50% Volcanic-Ash), Table 6 (Test 7: 50% Cement with 50% Fly-Ash), Table 7 (Test 8: 25% Cement with 75% Volcanic-Ash), Table 8 (Test 9: 25% Cement with 75% Fly-Ash), Table 9 (Test 10: 75% Cement with 25% Volcanic-Ash), Table 10 (Test 11: 75% Cement with 25% Fly-Ash), and Table 11 (Test 12: 100% Cement with no admixtures). Table 12 compares the average stress over time for the seven tests.

For the concrete mix of 75% cement and 25% volcanic ash, the average stress increases from 6.10 MPa on day 1 to 36.25 MPa on day 56. This mix shows good early and long-term strength, making it a viable option for structural applications. For the concrete mix of 75% cement and 25% fly-ash, the average stress increases from 5.89 MPa on day 1 to 28.90 MPa on day 56. This mix shows lower strength compared to the 25% volcanic ash mix but still performs adequately.

For the concrete mix of 50% cement and 50% volcanic ash, the average stress increases from 1.79 MPa on day 1 to 17.60 MPa on day 56. This mix has significantly lower strength, indicating that a high proportion of volcanic ash may not be suitable for high-strength applications. For concrete mix with 50% cement and 50% fly-ash, the average stress increases from 1.92 MPa on day 1 to 13.94 MPa on day 56. Similar to the 50% volcanic ash mix, this mix also shows low strength, suggesting that high fly ash content may not be ideal for early strength development.

For the concrete mix with 25% cement and 75% volcanic ash 75%, the strength development increases from 2.44 MPa on day 7 to 9.07 MPa on day 56. This mix shows very low strength, indicating that such a high proportion of volcanic ash is not suitable for structural applications. For the concrete mix with 25% cement and 75% fly ash, the strength development increases from 1.85 MPa on day 7 to 7.15 MPa on day 56. This mix also shows very low strength, similar to the high volcanic ash mix.

Table 5. Test 6: 50% Cement with 50% Volcanic-Ash at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	14.7	14.3	1.8	1.8	1.8
7	42.8	43.5	5.3	5.4	5.3
14	60.1	59.3	7.4	7.3	7.4
28	99.6	100.6	12.3	12.4	12.3
56	144.0	141.3	17.8	17.4	17.6

Table 6. Test 7: 50% Cement with 50% Fly-Ash at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	-	15.6	-	1.9	1.9

7	38.2	38.7	4.7	4.8	4.7
14	53.6	54.9	6.6	6.8	6.7
28	77.2	78.6	9.5	9.7	9.6
56	121.0	105.0	14.9	12.9	13.9

Table 7. Test 8: 25% Cement with 75% Volcanic-Ash at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	-	-	-	-	-
7	21.7	17.8	2.7	2.2	2.4
14	38.5	37.6	4.7	4.6	4.7
28	54.8	65.3	6.8	8.1	7.4
56	71.2	75.9	8.8	9.4	9.1

Table 8. Test 9: 25% Cement with 75% Fly-Ash at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	-	-	-	-	-
7	14.5	15.4	1.8	1.9	1.8
14	18.5	20.0	2.3	2.5	2.4
28	28.2	29.6	3.5	3.6	3.6
56	58.1	57.8	7.2	7.1	7.1

Table 9. Test 10: 75% Cement with 25% Volcanic-Ash at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	49.2	49.7	6.1	6.1	6.1
7	129.6	123.9	16.0	15.3	15.6
14	161.6	157.9	19.9	19.5	19.7
28	232.0	244.4	28.6	30.1	29.4
56	298.6	289.2	36.8	35.7	36.3

Table 10. Test 11: 75% Cement with 25% Fly-Ash at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	51.4	44.1	6.3	5.4	5.9
7	97.1	105.5	12.0	13.0	12.5
14	127.7	121.1	15.8	14.9	15.3
28	184.6	176.8	22.8	21.8	22.3
56	222.1	246.5	27.4	30.4	28.9

Table 11. Test 12: 100% Cement with no admixtures at w/c=0.55.

Days	Load 1 (kN)	Load 2 (kN)	Stress 1 (MPa)	Stress 2 (MPa)	Average Stress (MPa)
1	76.3	82.2	9.4	10.1	9.8
7	165.3	-	20.4	-	20.4
14	208.2	199.7	25.7	24.6	25.2
28	262.4	265.5	32.4	32.8	32.6
56	318.2	313.8	39.3	38.7	39.0

Table 12. Average Stress over Time for Seven Concrete Tests with w/c=0.55.

Days	Test 12: 100% cement (MPa)	Test 10: 25% VA (MPa)	Test 11: 25% FA (MPa)	Test 6: 50% VA (MPa)	Test 7: 50% FA (MPa)	Test 8: 75% VA (MPa)	Test 9: 75% FA (MPa)
1	9.8	6.1	5.9	1.8	1.9	-	-
7	20.4	15.6	12.5	5.3	4.7	2.4	1.8
14	25.2	19.7	15.3	7.4	6.7	4.7	2.4
28	32.6	29.4	22.3	12.3	9.6	7.4	3.6
56	39.0	36.3	28.9	17.6	13.9	9.1	7.1

3. Discussion

The graphical representation of the tests 6 through 12 (at w/c=0.55) is presented in Figure 3 which demonstrated that the mixes with volcanic ash were continuously stronger and more durable than the mixes with fly ash. Figure 4 is a graphical representation of stress versus the percentage of cement replacement by both volcanic ash and fly ash. The graph shows the improvement in strength of volcanic ash mixes as compared to fly ash mixes. Figure 4 demonstrates that there is a reduction in stress as the replacement percentage increase. The reduction is almost one-to-one for the volcanic ash mixes at day 56, while the reduction is more severe for fly ash mixes. Table 13 provides the percentage increase in strength at almost 100% for days 14 and 28, and a durability improvement of 27% at day 56.

Mixes with volcanic ash generally show higher early strength compared to those with fly ash. This is particularly evident in the mixes with 25% volcanic ash, which outperform their fly ash counterparts in early stages. Both volcanic ash and fly ash mixes achieve comparable long-term strength, but volcanic ash mixes tend to perform slightly better. For instance, the mix with 25% volcanic ash reaches an average stress of 36.3 MPa by day 56, compared to 28.9 MPa for the fly ash mix.

High proportions of either volcanic ash or fly ash (50% or more) result in significantly lower strength, indicating that such high replacement levels are not suitable for structural concrete. Mixes with 50% volcanic ash or fly ash show much lower strength development, making them less viable for high-strength applications. The analysis suggests that optimal replacement levels (around 20-25%) provide a good balance between early and long-term strength, making volcanic ash a promising sustainable material for concrete production. Mixes with 25% volcanic ash show good performance, achieving an average stress of 36.3 MPa by day 56.

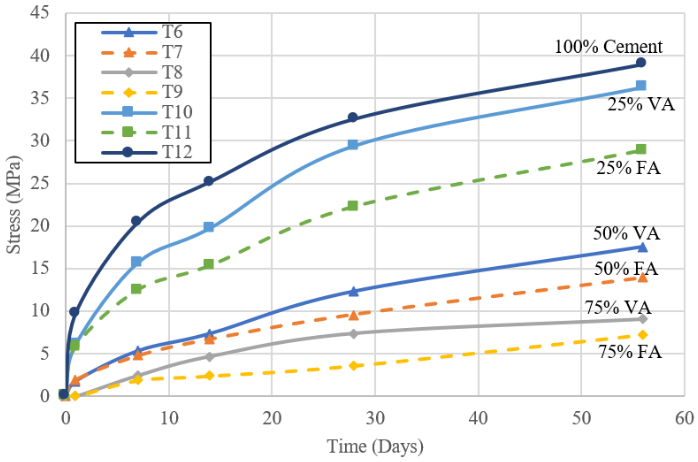

Figure 3. Graph of Stress versus Time for Concrete Tests at w/c=0.55.

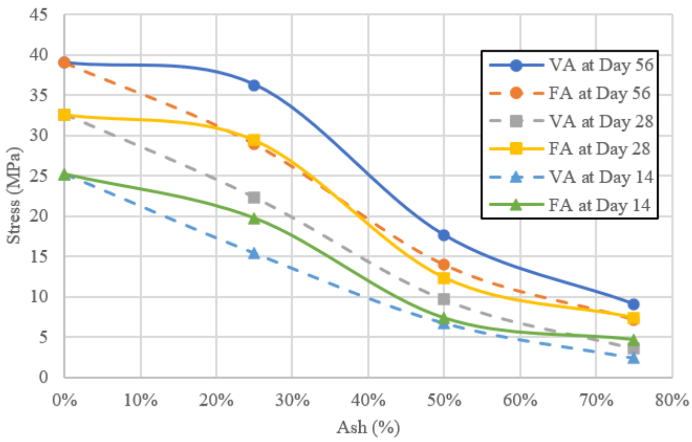

Figure 4. Strength versus Ash Percentage over Time at w/c=0.55.

Table 13. Average Stress versus Ash Content Percentage at w/c=0.55.

Ash Content	Day 56 VA	Day 56 FA	% Increase	Day 28 VA	Day 28 FA	% Increase	Day 14 VA	Day 14 FA	% Increase
0%	39.0	39.0	-	32.6	32.6	-	25.2	25.2	-
25%	36.3	28.9	25.4%	29.4	22.3	31.8%	19.7	15.3	28.4%
50%	17.6	13.9	26.3%	12.3	9.6	28.5%	7.4	6.7	10.0%
75%	9.1	7.1	26.9%	7.4	3.6	107.9%	4.7	2.4	97.9%

4. Conclusions

The study demonstrates that volcanic ash can enhance both early and long-term strength of concrete mixes, making it a viable and sustainable alternative to fly ash. The key finding is that volcanic ash mixes generally show higher early strength compared to fly ash mixes at water-to-cement ratio of 0.55. Both volcanic ash and fly ash mixes achieve comparable long-term strength, with volcanic ash mixes performing slightly better at a lower water-to-cement ratio of 0.50.

A second key finding is that high proportions of volcanic ash or fly ash (50% or more) result in significantly lower strength, indicating that such high replacement levels are not suitable for structural concrete. Optimal replacement levels (around 20-25%) provide a good balance between early and long-term strength, making volcanic ash a promising sustainable material for concrete production.

Future research should focus on further optimizing the mix proportions and exploring the environmental benefits of using volcanic ash in concrete production. This includes investigating the long-term durability and performance of volcanic ash concrete in various environmental conditions and its potential impact on reducing carbon emissions in the construction industry. Future studies could also include interviews with concrete suppliers and industry professionals to investigate volcanic ash concrete use as well as marketability for future mixture designs. The author feel it is important to focus on the economics of alternative concrete use as it would have a major impact encouraging the construction industry to use green concrete more frequently.

The experimental work of this research project showed the significant benefits of volcanic-ash concrete as compared to fly-ash concrete, both in strength and durability. The construction industry, led by the Department of Transportation, would benefit significantly to begin the switch to this new mixture design of volcanic ash concrete, as the depletion of fly ash only continues with each build and with less availability comes increase in cost.

References

[1] Federal Highway Administration, “Tables of Frequently Requested NBI Information,” Available Online: http://www.fhwa.dot.gov/bridge/britab.cfm (accessed on 1 June 2016).

[2] “Federal Highway Administration Research and Technology-Coal Fly Ash,” Publication Number: FHWA-RD-97-148. Available Online: https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/cfa53.cfm (accessed on 5 June 2016).

[3] S. L. Patil, J. N. Kale and S. Suman, “Fly ash concrete: A technical analysis for compressive strength,” *International Journal of Advanced Engineering Research and Studies*, vol. 2, no. 1, pp. 128-129, 2012.

[4] H. Quan and H. Kasami, “Experimental study on effects of type and replacement ratio of fly ash on strength and durability of concrete,” *The Open Civil Engineering Journal*, vol. 7, pp. 93-100, 2013.

[5] M. Reiner and K. Rens, “High-volume fly ash concrete: Analysis and application,” *Practice Periodical on Structural Design and Construction*, vol. 11, no. 1, pp. 58-64, 2006.

[6] R. Merritt Jr., W. S. Bonzon and J. S. Dunham, “Pearl harbor memorial bridge-signature bridge replaces its aging namesake,” *Aspire Magazine*, pp. 30-33, 2012. Available Online: http://aspirebridge.com/magazine/2012Fall/PearlHarbor.pdf (accessed on 10 March 2014).

[7] J. Chu, *Cities of the Future May be Built with Locally Available Volcanic Ash*. MIT News Office, Massachusetts Institute of Technology, Boston, Massachusetts, USA, 2018.

[8] J. Ahmad, F. Althoey, M. A. Abuhussain, A. F. Deifalla, Y. O. Ozkılıç and C. Rahmawati, “Durability and Microstructure Analysis of Concrete Made with Volcanic Ash: A Review (Part II),” *Journal Science and Engineering of Composite Materials*, vol. 30, no. 1, pp. 20220211, 2023.

[9] K. Kupwade-Patil, C. De Wolf, S. Chin, J. Ochsendorf, A. E. Hajiah, A. Al-Mumin and O. Buyukozturk, “Impact of Embodied Energy on Materials/Buildings with Partial Replacement of Ordinary Portland Cement (OPC) by Natural Pozzolanic Volcanic Ash,” *Journal of Cleaner Production*, Vol. 177, p. 547-554, 2018.