A Comparison between Natural Pozzolana and Fly Ash Replacements on the Mechanical Properties of Concrete

Mervat O. Aburumman
Tajarub Research & Development, Doha, Qatar
mervat.ruman@tajarub.org

Malak M. Al-diseet
Tajarub Research & Development, Doha, Qatar
malak.aldiseet@tajarub.org

Mohamed O. Mohsen
Department of Civil and Architectural Engineering, Qatar University;
Tajarub Research & Development, Doha, Qatar
200202128@student.qu.edu.qa, mohamed.mohsen@tajarub.org

Mu'tasim Abdel-Jaber
Al-Ahliyya Amman University, Amman, Jordan
m.abdeljaber@ammanu.edu.jo

Khalid Kamal A A Naji
Department of Civil &Architectural Engineering, Qatar University, Doha, Qatar
knaji@qu.edu.qa

Ala Abu Taqa
Department of Civil Engineering, Munib and Angela Masri Faculty of Engineering,
Aqaba University of Technology, Aqaba, Jordan
aabutaqa@aut.edu.jo

Abstract

This study investigates the effect of Natural Pozzolana (NP) and Fly Ash (FA) substitutes on concrete’s mechanical and microstructural properties. Mixes containing 10 – 50 % cement substitute ratios were prepared and tested for flexure and compressive strength after 28 days of curing. Then, qualitative microstructural analysis was performed using Scanning Electron Microscope (SEM). In terms of compressive strength, the mixes containing only 10 % replacement ratios of both NP and FA showed an improvement of 10 % compared to the plain control mix. On the other hand, all mixes containing FA could attain at least a 25 % development in their flexural strength compared to the control mix. The microstructural analysis illustrated that adding FA and NP enhances cement hydration by improving the formation of dense hydration products such as calcium silicate hydrate (C-S-H) and calcium hydroxide (C-H), which are mainly responsible for the performance of the improved mechanical properties of concrete.

Keywords: Natural Pozzolana; Cement Replacements; Strength; Fly Ash; Microstructural Analysis

1 Introduction

Supplemental Cementitious Materials (SCMs), known as pozzolanic materials, are commonly used as fillers in concrete to partially replace cement. SCMs have become popular due to growing sustainability concerns in the construction industry, the need to produce more durable and sustainable concrete, and long-term resistance to harmful chemical reactions (Uzal et al., 2010). Fly ash (FA) is the most widely utilized type of SCM, which has proven itself as the industry standard for producing high-quality and durable concrete due to its low cost and widespread availability (Golewski et al., 2018; Zabihi-Samani et al., 2018). Since the late 1980s, many studies have been conducted on the properties of concrete impregnated with FA, and many innovative outcomes have been reached. For example, different studies indicate that mechanical performances are generally better at 20-40 % replacement of cement (De Matos et al., 2019; Mehta, 2004; Atiş, 2002). Still, these levels can reach 60 % or higher (Yu et al., 2017; Huang et al., 2013). In addition, no significant reduction in concrete strength was observed at an early age, but more excellent strength gain properties appeared in the long term. It should be noted that the test results for samples treated for a short period could have been very different if the treatment period was longer (Golewski et al., 2018; Toutanji et al., 2004). Also, FA contents can significantly affect the rheological properties of concrete (Khodair et al., 2017; Bentz et al., 2013). In other words, using FA in concrete can produce an environmentally safe green material for civil engineering with structural, financial and environmental advantages.

However, finding practical natural substitutes that perform similarly to FA to improve mechanical and rheological concrete properties is essential because upcoming environmental and safety laws threaten its availability and quality. Therefore, there has been a great trend recently to use Natural Pozzolana (NP) as a natural material resulting from volcanoes with variable mineral, chemical and reactivity properties (Hossain et al., 2021; Shukla et al., 2020; Camacho et al., 2002; Ghrici et al., 2007). In addition to its abundance in different geographical locations, it is an economically viable option as a supplementary cementitious material in concrete production (Khan & Alhozaimy, 2011). Consequently, researchers recently turned to conduct experimental studies to determine the NP effect on concrete. For example, most studies found that using NP to replace approximately 20-30 % of Portland cement improved mechanical performance, particularly compressive strength, reduced chloride ion permeability by 66 %, and self-shrinkage by 40% (Ababneh & Matalkah, 2018; Hijazin et al., 2012). Also, replacing the cement by 50 % improved the concrete's resistance to alkali-silica reactions and sulfate attacks (Turanli et al., 2005). This study aims to compare concrete impregnated with FA and NP in mechanical and microstructure properties with cement replacement ratios ranging from 10 to 50 % in 10 mixes and compare them with a reference mix. The effect of these pozzolanic materials on concrete compressive and flexural strength was evaluated at 28-day. After that, a scanning electron microscope (SEM) was used to analyze the microstructure of the examined samples. Based on the strength results at 28-day, future tests will be directed towards improving and modifying these pozzolanic materials' physical properties and compositions to obtain specific and acceptable cement replacement ratios in concrete composites that give better results in the early ages and long term.

2 Experimental Program

2.1 Materials and Equipment

Cement (CEM II / B-P 42.5 N) conforming to EN 197-1: 2011, coarse aggregate (dolomite limestone) and fine aggregate (sand) used comply with ASTM C-33, in addition to natural pozzolana (ManaseerCrete) complied with ASTM C-618 class N, also, fly ash (class F), which complied with (ASTM C-618). Table 1 presents NP and FA composition and physical properties. A Polycarboxylate-ether superplasticizer (Master Glenium 51) was used in the concrete mixes preparation. The technical properties of Master Glenium 51 are shown in Table 2. A strength testing machine supplied by Controls Inc. was used for compression and flexural strength testing. Humboldt supplied a concrete mixer with an 85 L capacity. Finally, a scanning electron microscope (SEM), supplied by FEI Inc., was used for the microstructural analysis of the samples.

Table 1: Composition and Physical Properties of FA and NA

Characteristics	Sum (SiO_2,Al_2O_3, Fe_2O_3), Min%	Sulfur trioxide, Max%	Moisture Content Max%	Loss on ignition, Max%	Fineness% retained on 45 micron-sieving, Max%
Fly ash (Class F)	70	5	3	6	34
Natural pozzolana	70.5-75.5	0.2-0.8	0.4-1.2	0.8-1.2	1.7-3.3

Table 2: Technical Properties of Superplasticizer Master Glenium 51

Technical properties	
Appearance	Brown liquid
Specific gravity	1.10 ± 0.03 g/cm³
pH value	6.0 ± 1
Chloride content (%)	≤ 0.10 by mass

2.2 Concrete Mixing and Testing

The mixing of samples in this study was carried out in the proportions summarized in Table 3. To ensure that the components formed a homogeneous mix, the mixing period lasted 30 minutes. After the concrete mixing process was completed, five 100-mm cubes and five 150 mm x 150 mm x 550 mm prisms were poured from each mix in accordance with ASTM C39 and ASTM, C78, respectively. They were removed from the molds after 24 hours and cured for 28-day in a curing tank at a constant temperature of 25 °C and 90 % relative humidity. ASTM C39 and ASTM C78 were followed to conduct the compressive and flexural strength tests on the prepared samples using the strength testing machine.

Table 3: Mixtures' Compositions

Component	Batch No. / Quantity										
	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	#10	# 11
Cement (kg)	20	18	16	14	12	10	18	16	14	12	10
Fly Ash (kg)	-	2	4	6	8	10	-	-	-	-	-
Natural Pozzolana (kg)	-	-	-	-	-	-	2	4	6	8	10
Coarse Aggregate (kg)	50										
Fine Aggregate (kg)	46										
Water (kg)	10										
Superplasticizer (g)	200										

2.3 Microstructural Analysis Using Scanning Electron Microscopy (SEM)

Microstructure analysis of the fractured samples was performed at the Qatar University Central Laboratories Unit to understand better the influence of FA and NP on the strength properties. The microscope FEI-Nova Nano SEM Model was used to scan and take high-resolution images at various imaging scales.

3 Results and Discussion

3.1 Compressive and Flexural Strengths

Figures 1 and 2 present the average compressive and flexural strength results of the batches listed in Table 3. The standard deviations were also determined for each batch. The results showed different behavior of each material on compressive and flexural strength. There was a strength increase for the batches prepared with 10 and 20 % FA by 8.9 and 0.3 %, respectively, compared to the control batch. After that, there was a significant decrease in strength for batches prepared using 30, 40 and 50 % FA. Whereas NP achieved an increase of 5.6 % in compressive strength when replacing 10 % of cement and a decrease in strength at the rest of the replacement ratios, compared to the control batch, as shown in Figure 1.

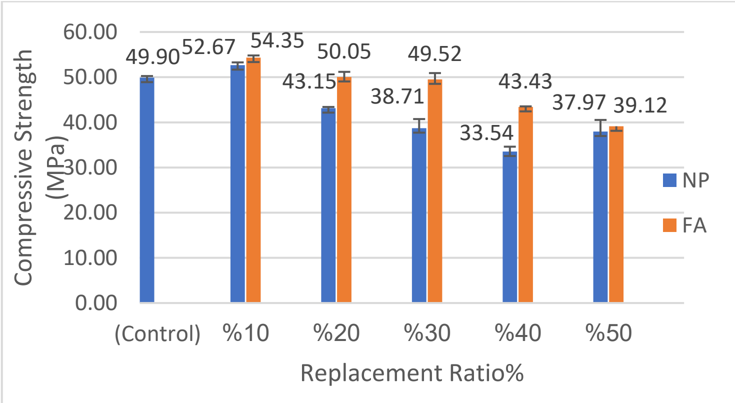

Fig. 1: Compressive Strength at 28-day

Flexural strength results were different from the above. There was an increase in strength in all batches impregnated with FA. The batches containing 10, 20, 30, 40 and 50 % of FA achieved 30.1, 26.8 %, 29.7 %, 25.1 % and 15.6 % respective increases in flexural strength compared to the control batch. In addition, in batches containing 10 % and 20 % of NP, the increase in the ratio was 35.6 % and 18.7%, respectively. This improvement in concrete strength can be attributed to the interaction between these materials and calcium hydroxide that results in the formation of re-crystallized calcium carbonate in the concrete matrix, which causes a decrease in the porosity and the transition zone in concrete.

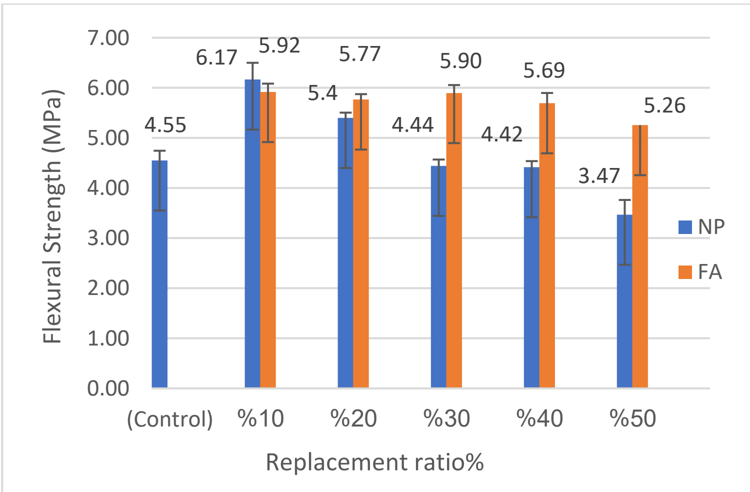

Fig. 2: Flexural Strength at 28-day

3.2 Microstructural Analysis

Figures 3 and 4 present the microstructure and morphology of randomly selected concrete mixes containing FA and NP at images of a 5, 10 and 50 µm scale. The samples were analysed after 28 days to ensure that the pozzolanic reaction with the cement stabilized and to be able to make comparisons between them.

Figure 3 shows the smooth and fine surface of FA particles, which improves the concrete surface roughness and stimulates the pozzolanic reaction. The figure also shows calcium silicate hydrate (C-S-H) covering of the FA elements, that is probably caused by the pozzolanic reaction of the FA and calcium hydroxide ($Ca(OH)_2$). It is noticeable from Figure 4 that the NP-containing sample contains fewer calcium hydroxide crystals and the concrete matrix is more porous. Samples may tend to crack early; Therefore, lower mechanical strength properties were obtained.

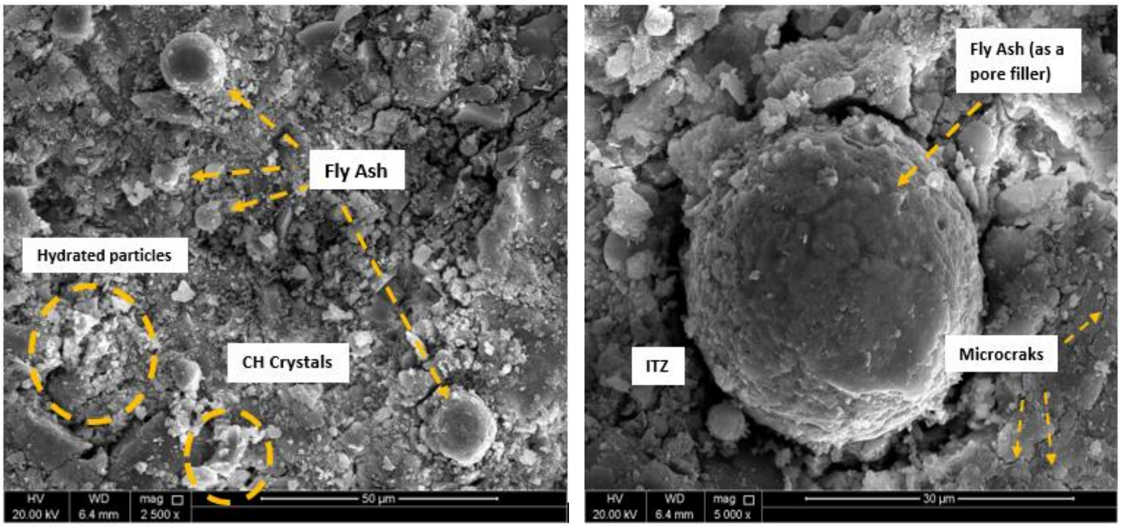

Fig. 3: SEM Micrographs of Concrete Matrix Impregnated with FA

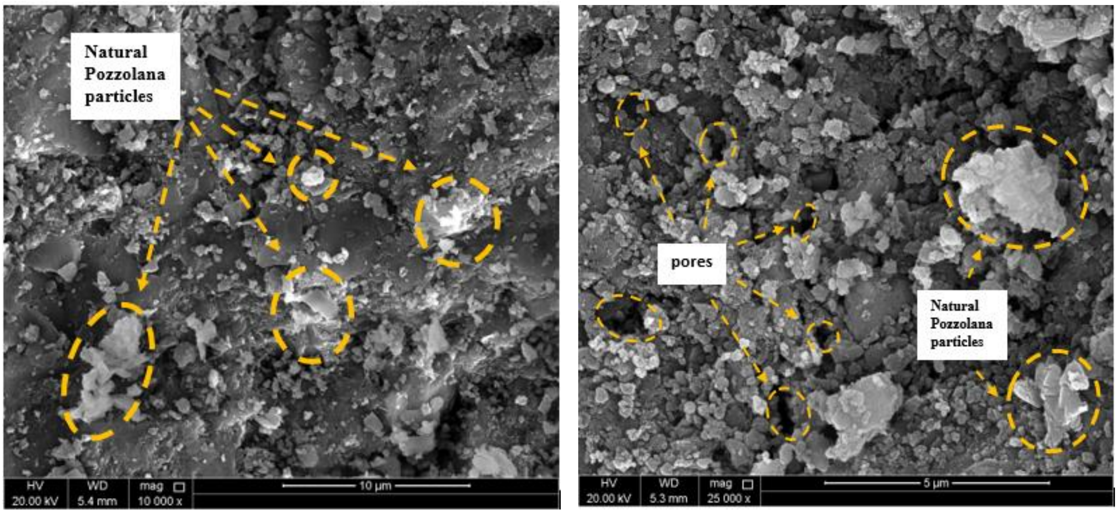

Fig. 4: SEM Micrographs of Concrete Matrix Impregnated with NP

4 Conclusions and Recommendations

The main experimental results drawn from this research are:

- Concrete impregnated with FA achieved better strength results than those containing NP.
- Incorporating FA material in concrete has good effects on mechanical properties. The batches prepared with 10 %, 20 %, 30 %, 40 % and 50% of FA increased flexural strength by 30.1 %, 26.8 %, 29.7 %, 25.1 % and 15.6%, respectively, compared to the control batch. Also, compressive strength enhancement by 8.9 % when replacing 10 % cement with FA.
- Replacing 10 % of cement with NP in concrete led to an improvement of compressive and flexural strength by 5.6 % and 35.6 %, respectively, compared to the control batch.

- Adding FA and NP promotes the cement hydration process by improving the formation of dense C-S-H and C-H crystals, primarily responsible for concrete's improved mechanical properties performance.
- Future tests should be directed towards improving and modifying the compositional and physical properties of FA and NP materials to obtain an acceptable cement replacement ratio that can improve concrete's mechanical properties, permeability and microstructure.

Acknowledgments

We express our sincere appreciation and gratitude to the Departments of Civil and Architectural Engineering at Qatar University and the Faculty of Engineering at Al-Ahliyya Amman University.

References

Ababneh, A. & Matalkah, F. (2018). Potential use of Jordanian volcanic tuffs as supplementary cementitious materials. *Case studies in construction materials, 8*, 193-202. https://creativecommons.org/licenses/by-nc-nd/4.0/

Atiş, C. D. (2002). Heat evolution of high-volume fly ash concrete. *Cement and Concrete Research, 32*(5), 751-756.

Bentz, D. P., Ferraris, C. F. & Snyder, K. A. (2013). Best practices guide for high-volume fly ash concretes: Assuring properties and performance. https://doi.org/10.1016/S0008-8846(01)00755-4

De Matos, P. R., Foiato, M. & Prudêncio Jr, L. R. (2019). Ecological, fresh state and long-term mechanical properties of high-volume fly ash high-performance self-compacting concrete. I, 282-293. https://doi.org/10.1016/j.conbuildmat.2019.01.074

Espinoza-Hijazin, G., Paul, Á. & Lopez, M. (2012). Concrete containing natural pozzolans: new challenges for internal curing. *Journal of Materials in Civil Engineering, 24*(8), 981-988. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000421

Golewski, G. L. (2018). Green concrete composite incorporating fly ash with high strength and fracture toughness, *J. Clean. Prod. 172*, 218–226. https://doi.org/10.1016/j.jclepro.2017.10.065

Ghrici, M., Kenai, S. & Said-Mansour, M. (2007). Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements. *Cement and Concrete Composites*, *29*(7), 542-549. https://doi.org/10.1016/j.cemconcomp.2007.04.009

Golewski, G. L. (2018). Evaluation of morphology and size of cracks of the Interfacial Transition Zone (ITZ) in concrete containing fly ash (FA). *Journal of hazardous materials*, *357*, 298-304. https://doi.org/10.1016/j.jhazmat.2018.06.016

Hossain, M. U. et al. (2021). Sustainable natural pozzolana concrete–A comparative study on its environmental performance against concretes with other industrial by-products. *Construction and Building Materials, 270*, 121429. https://doi.org/10.1016/j.conbuildmat.2020.121429

Khan, M. I. & Alhozaimy, A. M. (2011). Properties of natural pozzolan and its potential utilization in environmental friendly concrete. *Canadian Journal of Civil Engineering, 38*(1), 71-78. https://doi.org/10.1139/L10-112

Khodair, Y. & Bommareddy, B. (2017). Self-consolidating concrete using recycled concrete aggregate and a high volume of fly ash, and slag. *Construction and Building Materials, 153*, 307-316. https://doi.org/10.1016/j.conbuildmat.2017.07.063

Mehta, P. K. (2004, May). High-performance, high-volume fly ash concrete for sustainable development. In Proceedings of the international workshop on sustainable development and concrete technology (pp. 3-14). Ames, IA, USA: Iowa State University.

Rodrıguez-Camacho, R. E. & Uribe-Afif, R. (2002). Importance of using the natural pozzolans on concrete durability. *Cement and Concrete Research, 32*(12), 1851-1858. https://doi.org/10.1016/S0008-8846(01)00714-1

Shukla, A. et al. (2020, April). Natural Pozzolans a Comparative Study: A Review. In IOP Conference Series: Materials Science and Engineering (Vol. 804, No. 1, p. 012040). IOP Publishing. https://doi.org/10.1088/1757-899X/804/1/012040

Toutanji, H. et al. (2004). Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete. *Cement and concrete research, 34*(2), 311-319. https://doi.org/10.1016/j.cemconres.2003.08.017

Turanli, L, Uzal, B. & Bektas, F. (2005). Effect of large amounts of natural pozzolan addition on properties of blended cements. *Cement and concrete research, 35*(6), 1106-1111. https://doi.org/10.1016/j.cemconres.2004.07.022

Uzal, B. et al. (2010). Pozzolanic activity of clinoptilolite: A comparative study with silica fume, fly ash and a non-zeolitic natural pozzolan. *Cement and Concrete Research, 40*(3), 398-404. https://doi.org/10.1016/j.cemconres.2009.10.016

Yu, J. et al. (2017). Mechanical properties of green structural concrete with ultrahigh-volume fly ash. *Construction and Building Materials*, *147*, 510-518. https://doi.org/10.1016/j.conbuildmat.2017.04.188

Zabihi-Samani, M., Mokhtari, S. P. & Raji, F. (2018). Effects of Fly Ash on Mechanical Properties of Concrete. *Journal of Applied Engineering Sciences*, *8*(2). https://doi.org/10.2478/jaes-2018-0016

Cite as: Abu Rumman M., Al-Diseet M., Abdel-Jaber M., Abutaqa A., Naji K. & Mohsen M., "A Comparison between Natural Pozzolana and Fly Ash Replacements on the Mechanical Properties of Concrete", *The 2nd International Conference on Civil Infrastructure and Construction (CIC 2023)*, Doha, Qatar, 5-8 February 2023, DOI: https://doi.org/10.29117/cic.2023.0066