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Characterisation of Taal Volcanic Ash as a Potential Raw Material for the Construction Industry

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Abstract

The phreatomagmatic eruption of Taal Volcano in Batangas, Philippines, in January 2020 resulted in a massive ash plume covering a large portion of nearby provinces, including Metro Manila. This event caused damage and disruptions to various sectors, including agriculture, the environment, health, infrastructure, and aviation. The challenge of managing the vast amount of collected tephra environmental waste prompted the initiative of converting it into a useful material. This study characterizes and evaluates the quality of the collected tephra as a potential raw material for the construction industry, based on the Philippine National Standard (PNS) 07:2018, to ensure structural integrity and public safety.

Four ashfall samples from strategic locations, identified by the Philippine Institute of Volcanology and Seismology (PHIVOLCS), were obtained and analysed for specific chemical parameters using various analytical techniques. The results suggest that tephra has potential as a raw material for ground-level structures. However, further treatment is necessary to reduce the concentration of certain constituents. The material met the standard specifications for SiO_2, MgO, and SO_3. However, the levels of Al_2O_3, Fe_2O_3, total alkali, loss on ignition, and water-soluble and acid-soluble Cl^- exceeded the threshold limits set by PNS 07:2018 and EN 197-1:2000.

Keywords

Volcanic ash, construction materials, chemical analysis, oxides, waste management

1 Introduction

In January 2020, the Taal volcano, located in Batangas, Philippines, exhibited a phreatomagmatic eruption.[1] Since it is situated in the middle of a lake, the interaction of magma with water resulted in the explosive ejection of water, steam, and volcanic fragments.[2] Ashfall subsequently occurred, and the dispersion of emitted ash reached nearby provinces, such as Laguna, Cavite, Rizal, Bulacan, and Metro Manila. This phenomenon caused disruptions to various sectors, including agriculture, the environment, health, infrastructure, and aviation. The damages incurred in the agricultural sector alone were estimated at 3.150 billion pesos.[3] Addressing the problem of the vast amount of tephra waste collected from cleaning establishments, buildings, and houses blanketed by wet ash was a primary concern of the local government units and residents after the disaster. This prompted collaboration with the government agencies responsible. Given that several studies have investigated the suitability of tephra waste as an additive in the manufacture of cement, this study evaluated the volcanic ash for its potential as a raw material in cement production.[4–7] Cement, along with aggregates and water, is one of the key ingredients in making concrete. It is composed of several chemical compounds, the quantities of which dictate its characteristics. These include silica (SiO_2), lime (CaO), alumina (Al_2O_3), ferric oxide (Fe_2O_3), titania (TiO_2), magnesia (MgO), alkalis (Na_2O and K_2O), water content and carbonates, and sulphate (SO_4^{2-}). Each of these components influences the properties of the cement, such as durability, setting time, and colour, among others. Therefore, the right formulation is key to achieving the desired property of the cement.[8–10] Since the chemical and physical properties of construction materials are crucial to structural integrity, the Bureau of Product Standards Technical Committee on Cement and Lime (BPS/TC 3) has set the technical specifications for Portland cement. The Bureau of Philippine Standards – Department of Trade and Industry (BPS-DTI) approved these specifications for adoption in 2018 as the Philippine National Standard (PNS) 07:2018. In terms of chemical properties, it has specified limits for SiO_2, Al_2O_3, Fe_2O_3, MgO, loss on ignition (LOI), insoluble residue, tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), $C_3S + 4.75C_3A$, tetracalcium aluminoferrite + tricalcium aluminoferrite ($C_4AF + 2C_3A$) or $C_4AF + C_2F$, equivalent alkalis ($Na_2O + 0.658\ K_2O$), and sulphur trioxide (SO_3).[11]

This study aimed to conduct a preliminary characterisation of the Taal Volcano ashfall from strategic locations impacted by the plume caused by the January 2020 Taal Volcano eruption. Specifically, the study: (1) characterised the Taal Volcano ashfall for complete chemical analysis (SiO_2, Al_2O_3, TiO_2, Fe_2O_3, CaO, MgO, Na_2O, K_2O, loss on ignition), acid-soluble and water-soluble sulphate, and ac-

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id-soluble and water-soluble chloride; and (2) evaluated the quality of the ashfall as a potential construction material against the criteria set by PNS 07:2018 and European Standard EN 197-1:2000.[29]

2 Experimental

2.1 Sampling

Tephra samples were collected from the four strategic locations identified by PHIVOLCS. Fig. 1 shows the geographical locations (latitude and longitude) where the samples, coded as B13, B48, B73, and B78, were obtained. One location (B73) was near the centre of the volcano, while the other three locations (B13, B48, and B78) were near the periphery of the volcano.

2.2 Characterisation

Various analytical techniques were used to determine the metal oxides, and water-soluble and acid-soluble Cl^- and SO_4^{2-} in the volcanic ash samples. Gravimetric techniques were employed to analyse LOI and SiO_2. Titrimety was utilized for Al_2O_3 and acid-soluble Cl^-. Flame atomic absorption spectrophotometry was used for Na_2O, K_2O, CaO, MgO, and Fe_2O_3. Ion chromatography was applied to measure water-soluble Cl^- and water-soluble SO_4^{2-}. UV-visible spectrophotometry was used for the analysis of TiO_2 and acid-soluble SO_4^{2-}. Table 1 shows the specific methods used in the determination.

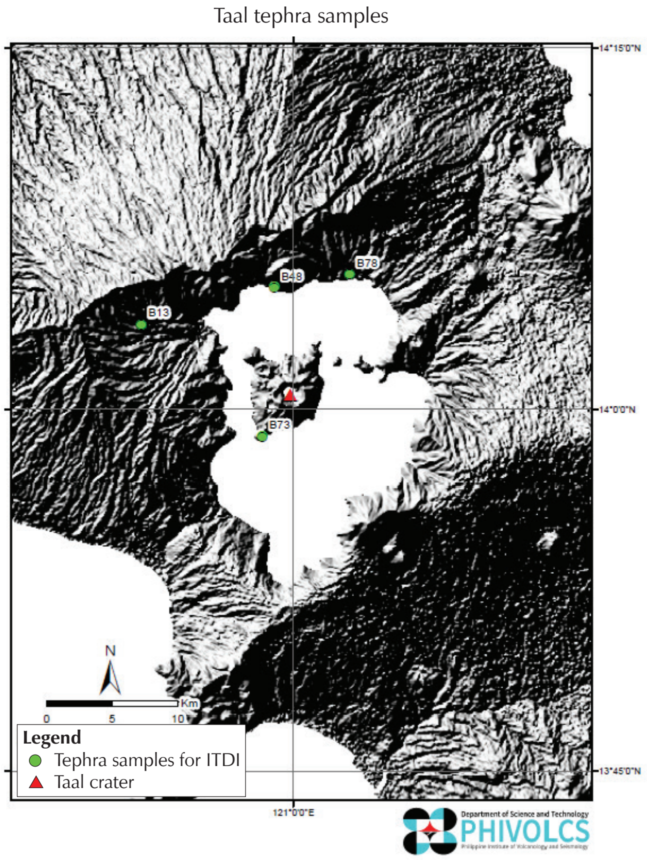

Fig. 1 – Tephra sampling sites

Table 1 – Test method for each parameter

Test parameter	Test method	Remarks (comparison against BS EN 196-2:1995[27] and 196-21:1992[28])
Silica (SiO_2)	JIS M 8853:1998[20]	Similar except that the cement is fused with Na_2CO_3 first before addition of HCl, and no NH_4Cl is used
Alumina (Al_2O_3)	ASTM C 25 – 93a[21] (modified)	Both use EDTA as titrant, but work at different pH ranges
Ferric oxide (Fe_2O_3)	JIS M 8853:1998[20]	Both use EDTA as titrant, but work at different pH ranges
Loss on ignition (LOI)	JIS M 8853:1998[20]	Similar
Titania (TiO_2)	JIS M 8853:1998[20]	
Calcium oxide (CaO)	JIS M 8853:1998[20]	Both use EDTA as titrant, but work at different pH range and use different indicators
Magnesium oxide (MgO)	JIS M 8853:1998[20]	Both use EDTA as titrant, but work at different pH range and use different indicators
Sodium oxide (Na_2O)	JIS M 8853:1998[20]	Flame atomic absorption spectrophotometer was used instead of flame photometer
Potassium oxide (K_2O)	JIS M 8853:1998[20]	Flame atomic absorption spectrophotometer was used instead of flame photometer
Acid-soluble chloride (Cl^-)	ASTM C1152/C1152M – 04[22] (modified, titrimetry)	Both use Volhard method
Water-soluble chloride (Cl^-)	ASTM C 1218/ C1218M – 99[23] (modified, ion chromatography)	
Acid-soluble sulphate (as SO_3)	CS3:2013[24]/US EPA 9038[25] (modified)	Sample preparation part is the same, but the gravimetric technique is replaced by UV-visible spectrophotometry
Water-soluble sulphate (as SO_3)	ASTM C 1580 – 15[26] (modified, ion chromatography)	

Table 2 – Measurement results for oxide analyses of tephra samples

Test parameter	Result (n = 3)				PNS 07:2018 (type II)
	B13	B48	B78	B73	
SiO_2, % w/w	51.9	50.8	50.6	50.6	20.0 min.
Al_2O_3, % w/w	13.2	17.0	15.1	15.1	6.0 max.
Fe_2O_3, %w/w	10.8	11.5	10.8	11.0	6.0 max.
LOI, %w/w	7.15	5.47	6.11	7.47	3.0 max.
TiO_2, %w/w	0.942	0.964	0.927	0.890	–
CaO, %w/w	7.91	7.99	6.79	7.79	–
MgO, %w/w	3.09	2.93	2.74	2.85	6.0 max.
Na_2O, %w/w	3.66	3.46	3.23	3.40	0.60 max.
K_2O, %w/w	1.73	1.76	1.71	1.65	
Total alkali (Na_2O + 0.658 K_2O), % w/w	4.80	4.62	4.36	4.49	

2.3 Evaluation

For most of the parameters, the quality of the ashfall as a raw material for the production of cement was evaluated using PNS 07:2018. This included SiO_2, Al_2O_3, Fe_2O_3, MgO, loss on ignition (LOI), equivalent alkalis (Na_2O + 0.658 K_2O), and acid-soluble and water-soluble SO_4^{2-} (as SO_3). Meanwhile, the acid-soluble and water-soluble Cl^- concentrations were evaluated against the requirements of EN 197-1:2000.

3 Results and discussion

3.1 Oxide analyses of tephra samples

Table 2 depicts the measurement results of the oxide analyses conducted for the tephra samples collected from the four sampling sites. SiO_2, Al_2O_3, Fe_2O_3, and CaO are the primary components of cement, as they are involved in forming the four major compounds that mainly contribute to the properties of cement, such as strength, setting time, and colour. These compounds are alite or tricalcium silicate (C_3S or 3CaO · SiO_2), belite or dicalcium silicate (C_2A or 2CaO · SiO_2), celite or tricalcium aluminate (C_3A or 3CaO · Al_2O_3) and felite or tetracalcium aluminoferrite (C_4AF or 4CaO · Al_2O_3 . Fe_2O_3). Alite and belite are the constituents mainly responsible for concrete strength, as their hydration results in the production of calcium silicate hydrate or C−S−H gel (3CaO · $2SiO_2$. $3H_2O$). Celite does not significantly contribute to the strength and is responsible for the undesirable flash setting of cement during hydration. Felite does not contribute to the strength but helps prevent unwanted sulphate attack. All the tephra samples met the 20.0 %w/w minimum requirement for SiO_2 of PNS 07:2018. However, they exceeded the 6.0 %w/w limit for both Al_2O_3 and Fe_2O_3. This could affect the hydration of the cement, potentially impacting its strength and workability.[8–10,19]

LOI refers to the mass loss of a sample upon heating at very high temperatures (*e.g.,* 1000 °C). The mass loss accounts for the water content and/or carbonation, which reduce the quality of the cement. A high loss on ignition can indicate pre-hydration and/or carbonation.[12–13] All the tephra samples indicated LOI values greater than the regulation limit of 3.0 %w/w. This was somewhat expected as the volcano is within a lake, and carbon dioxide emissions from the volcano may have oxidised to carbonates. High MgO may be detrimental to the firmness of the cement, contributing to strength reduction by altering the heat of hydration.[8,14–15] All the tephra samples were below the 6 % w/w regulation limit.

The presence of alkalis increases the pH up to 13.5, which is beneficial for protecting reinforcement steel from corrosion. However, excessive alkalis are undesirable as they react with aggregates in concrete, causing efflorescence. Efflorescence is a white or greyish crystalline deposit of salts formed on surfaces after water evaporates.[8–10,16] The tephra samples exceeded the 0.60 %w/w total alkali threshold limit.

3.2 Extractable anions analyses of tephra samples

Excessive chloride may cause corrosion of reinforcement steel bars embedded in the concrete, whereas excessive sulphate may cause expansion and subsequent cracking of the concrete. Extractable anions are categorised into water-soluble and acid-soluble. Water-soluble anions refer to the free or available anions that can be extracted by using only water. Acid-soluble anions pertain to the total extractable anions that can be extracted under extreme conditions such as an acidic medium. In normal settings, only the water-soluble anions are available for reaction with the components of the concrete and cause detrimental effects. However, under extreme conditions, other more tightly held anions may be extracted, thus acid-soluble

Table 3 – Measurement results for extractable chloride and sulphate in tephra samples

Test parameter	Result				Standard specification
	B13	B48	B78	B73	
Acid-soluble Cl^-, % w/w	0.586	0.156	0.243	0.325	≤ 0.10 % w/w (EN 197-1:2000)
Water-soluble Cl^-, % w/w	0.549	0.161	0.217	0.320	
Acid-soluble SO_4^{2-}, % w/w	1.15	1.11	1.32	1.40	3.0 % w/w (PNS 07:2018 – type II)
Water-soluble SO_4^{2-}, % w/w	2.89	1.86	2.36	2.88	

anions must also be determined.[17–18] Table 3 shows the measurement results for the extractable anions (chloride and sulphate) in the tephra samples. All the tephra samples exceeded the 0.1 % w/w chloride maximum requirement set by the European Standard (Cement – Part 1: Composition, specifications, and conformity criteria for common cements (EN 197-1:2000)). Meanwhile, all the tephra samples met the 3.0 % w/w sulphate (as SO_3) limit set by the PNS 07:2018.

In summary, it was found that the Taal volcanic ash contained most of the vital components of cement. Moreover, there were selected chemical parameters that conformed to the specifications set by relevant standards. However, as some parameters exceeded the threshold limits, careful considerations must be given to these constituents when formulating cement using the volcanic ash as a raw material.

4 Conclusion

The results suggested that Taal volcanic ash has the potential to be a raw material for the production of cement, as it contains the essential components. However, the cement to be produced is recommended for use in ground-level structures only. For other applications, further treatment is necessary to reduce the concentration of certain constituents. Based on the PNS 07:2018, the material met the standard specifications for SiO_2, MgO, and water-soluble and acid-soluble SO_4^{2-} (as SO_3). In contrast, the results for Al_2O_3, Fe_2O_3, total alkali, loss on ignition, and water-soluble and acid-soluble Cl^- exceeded the threshold limits set by the standards. These preliminary data will help the construction industry and local government units plan for the utilisation of volcanic ashfall in the event of a volcanic eruption. Furthermore, this study promotes a circular economy, wherein waste generated from natural disasters such as volcanic eruptions is converted into useful material. As a way forward, it is recommended to conduct studies on optimising cement formulation using the volcanic ash, incorporating it into actual construction, and testing the physical properties of the resulting concrete.

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List of abbreviations and symbols
Popis kratica i simbola

PNS – Philippine National Standards
PHIVOLCS – Philippine Institute of Volcanology and Seismology
BPS/TC – Bureau of Product Standards Technical Committee
BPS-DTI – Bureau of Philippine Standards – Department of Trade and Industry
JIS – Japan Industrial Standards
ASTM – American Society for Testing and Materials
CS – Construction Standard
US EPA – United States Environmental Protection Agency
EN – European Standards
BS – British Standards
LOI – loss on ignition
C_3S – tricalcium silicate
C_2S – dicalcium silicate
C_3A – tricalcium aluminate
C_4AF – tetracalcium aluminoferrite
C_3A – tricalcium aluminoferrite
C_2F – dicalcium ferrite
% w/w – percent weight *per* weight

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SAŽETAK

Karakterizacija pepela vulkana Taal kao potencijalne sirovine u građevinskoj industriji

Michael S. Lagmay,* *Admer Rey C. Dablio*, *Elyson Keith P. Encarnacion*, *Ruth L. Damian*, *Emma D. Tayag*, *Liwayway M. Piquero*, *Noel Angelo P. Kalacas*, *John Joshua L. Sergote*, *Mark Anthony M. Principe* i *Joel B. Jane*

Freatska erupcija vulkana Taal u Batangasu na Filipinima u siječnju 2020. izazvala je formiranje masivnog oblaka pepela koji je prekrio veliki dio obližnjih provincija i područje grada Manile. Ovaj događaj prouzročio je štetu i poremećaje u različitim sektorima, uključujući poljoprivredu, okoliš, zdravstvo, infrastrukturu i zrakoplovstvo. Izazov upravljanja ogromnom količinom vulkanskog pepela prikupljenom u okolišu potaknuo je inicijativu da ga se pepeo pokuša pretvoriti u korisnu sirovinu. U ovoj studiji provedena je karakterizaciju prikupljenog pepela i ocijenjena njegova kvaliteta kao potencijalne sirovine u građevinskoj industriji prema Filipinskom nacionalnom standardu PNS 07:2018, ne bi li se osigurao integritet struktura i sigurnost.

Analizirana su četiri uzorka pepela uzorkovana na lokacijama koje je strateškima ocijenio Filipinski institut za vulkanologiju i seizmologiju. Rezultati su pokazali da vulkanski pepeo ima potencijal da se primijeni kao sirovina za prizemne građevinske strukture. Međutim, potrebna je daljnja obrada kako bi se smanjila koncentracija određenih komponenata. Materijal je udovoljio standardnim specifikacijama za SiO_2, MgO i SO_3, dok su razine Al_2O_3 i Fe_2O_3, ukupni alkalitet, gubitak žarenjem, te sadržaj klorida topljivih u vodi odnosno kiselinama premašili granice postavljene standardima PNS 07:2018 i EN 197-1:2000.

Ključne riječi
Vulkanski pepeo, građevinski materijali, kemijska analiza, oksidi, upravljanje otpadom

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