

GEOCHEMICAL AND COMPACTION-BREAKAGE CHARACTERISTICS OF WEATHERED AIR-FALL TEPHRAS

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ABSTRACT

The North Island of New Zealand is a region of high volcanic activity with eruptions occurring every few years. Past events suggest that future volcanic eruptions may produce considerable amounts of air-fall tephra or tephric soil deposits (both ash and granular), which raises issues of disposal and storage. The use of such deposits in geotechnical applications is a viable solution, but it requires a full understanding of their physical, geochemical, mineralogical and mechanical properties in their fresh and weathered state. That is, when tephra deposits undergo weathering, their grains become more crushable, compromising their mechanical response. Aimed at providing useful insights, in this study, selected heterogeneous weathered tephtras from Rotorua and Auckland regions were characterized. Specifically, compaction-induced particle breakage was evaluated by means of standard Proctor compaction test and sieve analyses, while elemental and mineralogical properties were attained by X-ray Fluorescence Spectroscopy (XRF) and X-ray Diffraction (XRD) techniques. The test results confirmed that the higher the degree of weathering is, the higher the degree of particle breakage is. Yet, the degree of weathering and, thus the associated particle breakage, is linked to the quartz and feldspars contents. It was seen that reworked volcanic deposits, having high silica (quartz) content and/or low feldspars content due to their mode of deposition, were generally more weathered and showed higher particle breakage.

Keywords: air-fall tephra, degree of weathering, weathered tephra, compaction, breakage

1 INTRODUCTION

The North Island of New Zealand has witnessed volcanism of every kind, including eruptions leading to the generation of air-fall tephra deposits in the adjoining areas. The central North Island including Taupo-Rotorua regions is mainly active and explosive due to being subduction driven, whereas northern North Island being primarily magmatic is currently dormant and less explosive (Hopkins et al., 2021). Over a period of time, these undergo changes in their physical and chemical composition depending on their mode of deposition and surrounding environment, commonly known as weathering. A weathered tephra or tephric soil deposit can be commonly used as a filling material for building sites or embankments due to its abundance and local availability near the construction sites. These tephra deposits to be used should be compacted well enough to satisfy the criteria of the engineering application. As these deposits can be products of different times and eruptions (Tarawera 1300 & 1886, Lowe & Balks 2019), their material properties are bound to be different and duly influenced by mode of deposition, imposed weathering conditions and further by loading conditions. Also, as a weathered tephra is susceptible to breakage, its particle breakage should be monitored during loading condition. Accordingly, this paper addresses the material-load characteristics of different air-fall tephtras using their physical & chemical compositions and loading condition of compaction. The compaction behaviour and post compaction breakage values of studied air-fall tephtras seem to be dependent on their mode of deposition and weathering state. It is imperative to mention that breakage here is defined as the change in percentage of particle sizes post compaction and weathering as the stabilization of the erupted tephra according to the physical and chemical conditions. The degree of weathering induced upon a particular tephra is evaluated using the following tests: physical (particle size distribution by sieving and hydrometer tests), chemical – XRF and Weathering Index of Parker WIP (Parker 1970), mineralogical (XRD) and post compaction breakage levels using sieve tests.

The WIP is a chemical method used to estimate the degree of weathering. It is the most appropriate weathering index applicable to a wide range of tephra types. The WIP seems useful chemical weathering index in the sense that it permits comparison between tephra samples present at different locations, on different parent materials and on weathering profiles of different ages (Price and Velbel 2003). This method can be utilized for distinguishing differently weathered tephtras in geology and geotechnical

engineering fields. However, the shortcomings of WIP are that it requires special equipment and non-application to highly weathered materials.

The preliminary characterization of any material can provide useful insights for its applicability in a particular geotechnical application. In this study, the material characterization of air-fall deposits was performed with respect to their weathering state using physical, chemical and mechanical methods. The post compaction breakage levels were compared with the results by XRD and WIP using XRF and as a result of the analyses, the breakage level and degree of weathering were correlated indicating higher breakage in reworked deposits than non-reworked tephtras. Since the developed method can be performed with only basic laboratory tests such as sieve analysis test and compaction test, the developed equations can be useful for easy and quick evaluation of relative weathering between different tephtra types and identify breakage levels of different tephtras upon load implication.

2 MATERIAL PHYSICAL PROPERTIES AND METHODOLOGY

2.1 MATERIAL PHYSICAL PROPERTIES

The disturbed tephtras were sampled from quarry sites and roadside cuttings around Mt. Tarawera (Rotorua) and Mt. Maungataketake (Auckland) regions in the North Island of New Zealand (Fig. 1a). The tephtras have been named successively from associated eruptions: White Kaharoa Ash (WKA), Golden Kaharoa Ash (GKA), Tarawera Basalt and Kaharoa Ash (TBKA) & Rotomahana Mud (RM) from Mt. Tarawera (Rotorua) eruptions (Lowe & Balks 2019); Pupuke Basalt (PB) and Maungataketake Ash (MA) from Auckland eruptions (Lindsay et al., 2011). Table 1 and Figure 1 show their physical properties.

Table 1 – Physical properties of tephtra deposits

Tephtra Sample	Gravel (%)	Sand (%)	Fines (%)	PI (%)	Soil Classification (ASTM D2487-17e1)	G _s bulk sample (ASTM D4318-17e1)
WKA	5.0	81.2	13.8	NP	Silty Sand (SM)	2.238
GKA	0.3	77.6	22.1	NP	Silty Sand (SM)	2.325
TBKA	11.3	67.4	21.3	NP	Silty Sand (SM)	2.444
RM	0.1	35.7	64.2	11.3	Sandy Lean Clay (CL)	2.574
PB	8.9	90.7	0.4	NP	Poorly-Graded Sand (SP)	2.819
MA	0.0	48.3	51.7	3.7	Sandy Silt (ML)	2.736

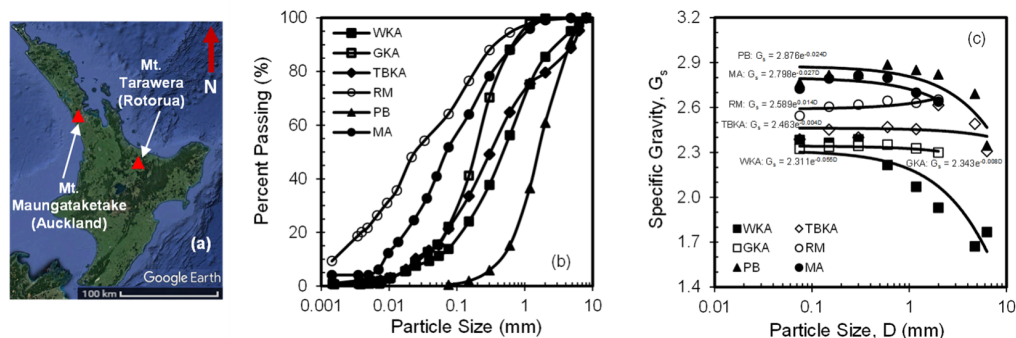


Fig. 1 – Sample locations, particle size distributions and specific gravity G_s of studied tephtra deposits

While PB constitutes uniformly graded particles; WKA, GKA & TBKA contain appreciable amount of fines making them silty sandy and RM & MA predominantly fine grained with a slight plasticity in them. The specific gravity G_s values were measured (using water pycnometer and vacuum) over the entire investigated particle sizes and a decreasing G_s trend with increase in particle size due to internal voids was observed (Wesley 2001, Cecconi et al., 2010) for all tephtras except slight deviations for RM at 4.75mm size and TBKA at 2 – 4.75mm size range (Fig. 1c). On physical observation, it was seen that TBKA and RM included basaltic and lithic fractions respectively in them in that range, which accounts for the respective higher G_s values around those sizes. For practical applications, the bulk G_s is calculated considering the entire particle size range and used further for compaction calculations.

2.2 METHODOLOGY

After the collected samples were oven-dried and pulverized, the tephtras were analysed for elemental and mineralogical compositions using XRF and XRD techniques. The equation developed by

Parker (1970) is used to estimate the degree of weathering of each sample:

$$WIP = 100 \times [(2Na_2O/0.35) + (2K_2O/0.25) + (CaO/0.70) + (MgO/0.90)] \quad (1)$$

The XRD scans for the tephra deposits show a certain hump in the 15 - 34° range, which is referred to as the amorphous or glassy phase. Using Rietveld (1969) analysis, the weight percentages of the crystalline and amorphous phases respectively were calculated using the following equation:

$$W_{Amo} = 100 - \sum(S_i \rho_i V_i^2 \mu / G) (\%) \quad (2)$$

where S_i is the scale factor, ρ_i the density, V_i the volume, μ the mass attenuation coefficient and G as the specific gravity of each crystalline phase. The tephra deposits were compacted using standard Proctor compaction, by ASTM 698-12e2, and then the particle size distribution of the samples were obtained after oven-drying. In the present study, the relative breakage defined by Hardin (1985) is used to evaluate the amount of particle crushing post compaction. The relative breakage (B_r) defined as

$$B_r = (B_t / B_p) \times 100 (\%) \quad (3)$$

where B_p is the breakage potential, which is equal to the area between the line particle size $D = 0.075mm$ and the part of the particle size distribution curve for which $D > 0.075mm$; and B_t is the total breakage, which is calculated as the difference between original breakage potential and breakage potential after compaction.

3 RESULTS AND DISCUSSIONS

3.1 GEOCHEMICAL COMPOSITIONS AND WEATHERING STATE ESTIMATION BY WIP

The major oxides and WIP of tephras were estimated by XRF (Table 2). The Rotorua tephras WKA, GKA, TBKA and RM categorize as rhyolites and dacites (higher SiO_2 & Na_2O+K_2O) and Auckland samples PB and MA as basalt and basalt andesitic (lower SiO_2 & $Na_2O + K_2O$) in the total alkalis ($Na_2O + K_2O$) vs silica (SiO_2) diagram (Fig. 2a). In addition, the higher G_s for TBKA around 2 – 4.75mm is due to the basaltic particles (TBKAc), indicating intermixing with rhyolitic (TBKAm) and dacitic (TBKAf) fractions in the sand (4.75 – 0.075mm) and finer (< 0.075mm) sized fractions. In the A (Al_2O_3) – CN ($CaO+Na_2O$) – K (K_2O) plot (Fig. 2b), the studied tephra samples lie in the slightly weathered region, indicating lesser mechanical breakdown into clayey minerals located at the upper end of the CIA plot (Nesbitt et al., 1997).

Table 2 – XRF results and calculated WIP values of all tephras

Tephra Sample	Major Oxide (Wt. %)										WIP	
	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅		LOI
WKA	75.1	0.2	12.3	1.3	0.1	0.2	1.1	3.9	3.4	0.0	2.0	5116.7
GKA	70.7	0.2	13.9	1.8	0.1	0.2	1.1	3.6	2.8	0.1	5.5	4443.0
TBKAc (2 - 8mm)	53.8	0.8	16.7	9.4	0.2	5.5	10.1	2.3	0.9	0.2	0.2	4117.2
TBKAm (0.075 - 1.18mm)	72.2	0.3	12.8	2.5	0.1	0.9	2.6	3.7	2.5	0.1	2.1	4561.8
TBKAf (<0.075mm)	68.5	0.3	12.3	2.0	0.1	0.4	1.5	3.3	3.0	0.1	8.1	4597.6
RM	68.2	0.4	14.9	3.9	0.1	1.2	2.6	2.3	2.8	0.1	3.6	4052.7
PB	45.7	2.3	11.7	13.8	0.2	13.2	8.3	2.5	0.9	0.5	0.6	4796.5
MA	57.3	1.4	12.3	8.3	0.1	5.2	6.6	2.4	1.6	0.4	4.0	4230.3

Note: TBKA shown here in three size fractions to show intermixing, WIP of TBKA is considered from the relative contributions of the three fractions

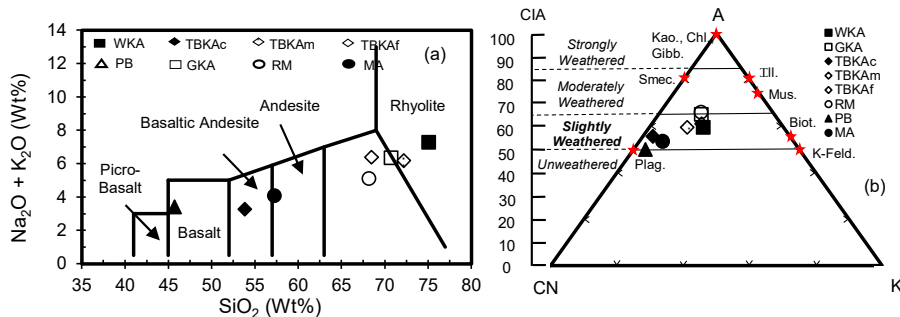


Fig. 2 – Elemental composition and weathering state by XRF

From the WIP values, the WKA is the least weathered tephra followed by PB, TBKA (m & f), GKA, MA, TBKAc and lastly RM (higher the value of WIP, lower is the degree of weathering). Fig. 3 shows the XRD scan of WKA constituting amorphous and identified crystalline phases. As seen in this figure, silica (Qz & Crs), plagioclase feldspars (Ab, Ol), alkali feldspars (Sa) and accessories (Aug, Bt) are

identified crystalline mineral phases of WKA. The relative percentages of all these constituents for each tephra are shown in Table 3. From the relative abundances of these minerals, the GKA, RM and MA are silica rich in comparison to the remaining tephtras WKA, TBKA(c, m and f) and PB. The values of WIP and wt. % of silica & feldspars are used further against post compaction breakage levels to assess the degree of weathering in the studied tephtras.

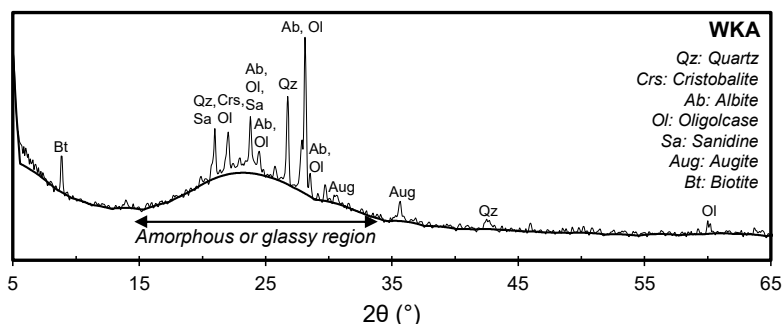


Fig. 3 – XRD scan of White Kaharoa Ash (WKA)

Table 3 – XRD - Rietveld results of all tephtras

Mineral (Wt. %)	Tephra Sample							
	WKA	GKA	TBKAc	TBKAm	TBKAf	RM	PB	MA
Glass	78.3	86.2	59.4	67.3	79.6	13.9	31.5	38.5
Quartz	3.7	3.3	1.0	7.1	5.1	26.2	1.3	26.6
Cristobalite	0.6	0.7	2.2	0.4	0.2	2.1	-	1.1
Alkali Feldspars	2.9	1.2	3.3	5.1	1.3	12.3	3.7	5.4
Plagioclase Feldspars	13.5	8.1	24.2	18.9	13.8	31.0	27.6	19.3
Accessories	1.0	0.5	9.9	1.3	-	13.2	35.8	9.2
Quartz + Cristobalite	4.3	4.1	3.2	7.5	5.3	28.4	1.3	27.7
Feldspars	16.4	9.2	27.5	24.0	15.1	43.3	31.4	24.7
Total Crystal Content	21.7	13.8	40.6	32.7	20.4	86.1	68.5	61.6

Note: The Wt.% all three fractions of TBKA are used later for breakage level vs weathering state prediction, Qz + Crs = Silica

3.2 COMPACTION CURVES AND POST-COMPACTION BREAKAGE CHARACTERISTICS

Compaction test to provide load effect was carried out with each tephra and the effect of particle breakage was analysed at the respective water contents. In addition, the sieve analysis test was performed to characterize the breakage occurring post compaction by comparing the particle size distribution before compaction with the gradation obtained after compaction. Fig. 4a - d shows the results of compaction tests. The ρ_{dmax} and w_{opt} vary from 1.32 to 1.71g/cm³ and 10.61 – 24.89% (low range) for the investigated tephtras. The low range water content is attributable to the slightly weathered nature and non-presence of highly plastic fines or clayey fractions. The tests yielded three types of compaction curves – one and a half peak (for WKA, GKA and TBKA), parabolic or single peak (for RM and MA) and gentle peak (for PB). The respective shapes are due to the role played by water levels in respective tephtras (Lee and Richard 1972). For silicate rich sand dominant tephtras such as WKA, GKA and TBKA, anti-lubrication effects at lower water contents and lubrication effects at higher water contents control density changes. The latter phenomenon also holds for low-plasticity fine grained siliceous tephtras RM and MA. On the contrary, the density of coarser basaltic lower silica PB remains unaffected by water as no effective particle contacts are generated due to the absence of fines. Fig. 4e –f show the grain size distribution curves of WKA and MA following the compaction tests. For the shown and remaining tephtras, with the same original curve and different water contents compaction curves, the differences in positions of the grain size distribution curves after compaction are very small. This meant that the amounts of particle crushing during the compaction in the tested tephtras, with the same original curve and different water contents curves, are very similar. The average of the breakages post compaction at different water contents is therefore used to define the breakage level of each tephtra. The average breakage values ranged between 1.3 – 7.6% (< 10%), with noticeably higher values for GKA, RM and MA tephtras (Fig. 4a). The measured higher breakages in these tephtras are explained w.r.t. their weathering state in section 3.3.

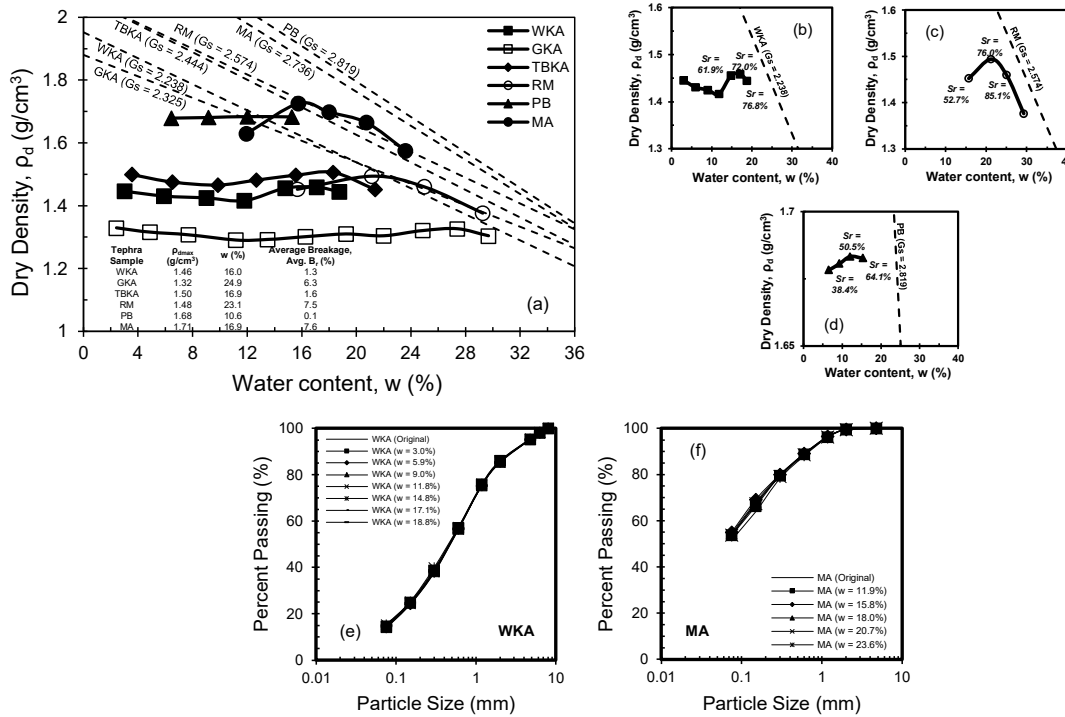


Fig. 4 – Compaction curves and post compaction breakage characteristics

3.3 CHEMICAL COMPOSITIONS AND WEATHERING MECHANISMS INFLUENCING BREAKAGE OF WEATHERED TEPHRAS

The degree of weathering of each tephra evaluated using WIP was correlated with the breakage levels post compaction and internal silica (SiO₂ = quartz + cristobalite) and feldspars minerals (Fig. 5). Silica and feldspars are essential primary components of all tephric soils, which change relative to weathering undergone by tephra (Nesbitt and Young 1997). The lower WIP values of GKA, RM and MA in comparison to PB, WKA and TBKA tephras indicates higher degree of weathering in the former samples, which also accounts for their higher breakage. The abundance of feldspars and lower silica in TBKA, GKA and WKA indicates lesser chemical weathering - internal breakdown of minerals and mechanical breakdown, which explains their less weathered nature (Table 3). It might be worthwhile to mention here that although TBKA contains physical intermixing of basaltic fractions in the 2 – 8mm range, the overall compaction load and breakage response is governed from predominant high silica sand and fine fractions (as seen from close proximity XRF values of TBKAm and TBKAf to that of WKA). On the other hand, higher silica and lower feldspar levels in RM and MA can be explained due to their depositional nature – phreatomagmatic and phreatic with inclusions from secondary lithic fragments and plastic fines in coarser and finer fractions respectively (Lowe and Balks 2019, Lindsay 2011). This also further explains weathering state of GKA, elementally similar but also silica rich and feldspar deficient in comparison to WKA, which was pulverized by the deposition of RM tephra falling directly above it. Therefore, while assessing the material - load characteristics of natural redisturbed tephra deposits of heterogeneous compositions, it might be worthwhile to look into the way of deposition (direct like WKA or reworked like GKA and RM), weathering degree value (using WIP) and the relative abundances of minerals which collectively can then help represent the degree of weathering of tephras for further usage in engineering applications. This is represented in the equations 4, 5 and 6 as follows:

$$\text{Br. (\%)} = -0.008 \times \text{WIP} + 39.14 \tag{4}$$

$$\text{Silica (\%)} = -0.026 \times \text{WIP} + 145.53 \tag{5}$$

$$\text{Feld. (\%)} = 0.021 \times \text{WIP} - 38.40 \tag{6}$$

Considering the diverse nature of air-fall tephra deposits in this study (and as expected in the field) due to processes like intermixing and weathering, these equations allows inclusion of a wider array of deposits from low silica basalts to high silica rhyolites (using their geochemical state) and enable prediction of parameters such as particle breakage upon load implication as seen during standard compaction tests.

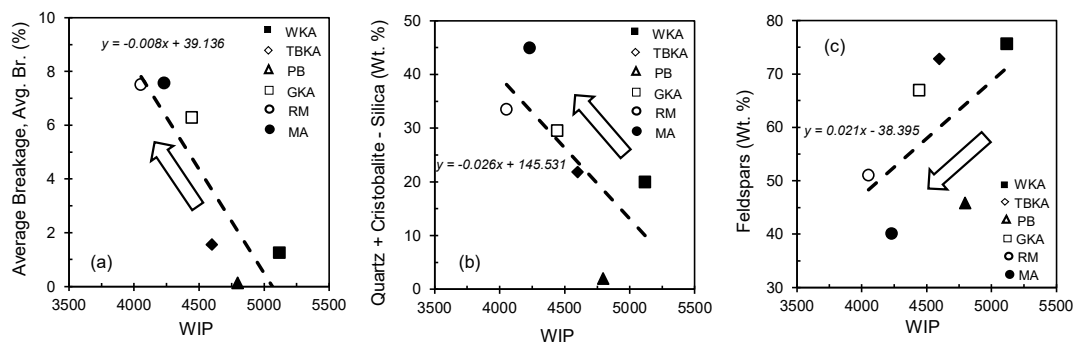


Fig. 5 – Degree of Weathering vs Breakage levels and Mineral compositions (arrows indicating higher weathering progression)

4 CONCLUSIONS

This study provided insights regarding the relationships between material (physical and chemical properties) and mechanical (compaction) characteristics of different non/slightly plastic (or slightly weathered) air-fall tephra deposits for usage as fill materials in geotechnical applications. The test results indicate that despite different grain size distributions and chemical compositions, the breakage level changes slightly with the varying water contents of a compaction test and are reportedly higher for reworked tephtras - RM, GKA and MA than non-reworked WKA, TBKA and PB tephtras. This is accountable to the relative abundances of quartz and feldspar minerals and corresponding higher degree of weathering (as collectively represented in the form of equations) in the former samples. The post compaction breakage values lie below 10%, therefore encouraging usage of these deposits as structural fills, although post-shear performance will be needed to be looked into.

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