

LOW-ALKALI ACTIVATION OF FLY ASH FOR ECO-BRICK PRODUCTION USING INDUSTRIAL AND AGRICULTURAL WASTE MATERIALS

¹Rohit K Mahadule, ²Minakshee Sawankar, ³Raju M Belekar, ⁴Virendra K Sangode

¹Department of Physics S.Chandra Mahila Mahavidyalaya Sadak Arjuni dist. Gondia

²Department of Chemistry S.Chandra Mahila Mahavidyalaya Sadak Arjuni dist. Gondia

³Department of Physics Govt. Institute of Science, Nagpur

⁴Department of Zoology, Manoharbai Patel College of Arts Commerce and Science Sadak Arjuni Dist Gondia

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ABSTRACT

The increasing generation of fly ash from coal-based thermal power plants necessitates sustainable utilization strategies. In this work, fly ash obtained from Koradi, Khaparkheda, and Adani Tirora power plants in Maharashtra was investigated for eco-brick production using alkaline activation technology. The study compared conventional NaOH–Na₂SiO₃ activation with a waste-based NaOH–aluminium foil system. Results showed that NaOH–Na₂SiO₃ activated bricks developed higher compressive strength with lower heat treatment, whereas the waste-based system required furnace curing at 250 °C and yielded moderate strength. Despite this, the waste-based approach significantly reduced chemical usage and promoted effective waste utilization. The study demonstrates the potential of fly ash-based eco-bricks as a sustainable alternative to conventional clay-fired bricks, particularly for non-load-bearing applications.

Keywords: Fly ash, Alkali activation, Geopolymer, NaOH Molarity, Na₂SiO₃/NaOH Ratio.

INTRODUCTION

Coal-based thermal power plants continue to play a dominant role in meeting India's electricity demand, and fly ash is an unavoidable by-product of this process (CEA, 2022; Jangam *et al.*, 2025). Fly ash is a finely divided particulate material produced during the combustion of pulverized coal and is collected from flue gases using electrostatic precipitators. It mainly consists of silica, alumina, iron oxides, calcium oxide, and unburnt carbon, along with trace amounts of potentially toxic elements (Yao *et al.*, 2015; Ahmaruzzaman, 2010). Depending on its chemical composition and calcium content, fly ash is broadly classified into Class F and Class C, which significantly influences its reactivity and suitability for construction applications (Kumar, 2002; Izhar and Kumar, 2021). India's heavy dependence on coal for power generation has resulted in a continuous increase in fly ash generation. According to the Central Electricity Authority, fly ash generation increased from 270.82 million tonnes during 2021–22 to approximately 340 million tonnes during 2024–25, with utilization levels nearing 98% (CEA,

2022; Energy World, 2025). Despite improved utilization, challenges related to transportation, safe disposal, and environmental impacts persist, particularly in regions with high thermal power plant density (CPCB, 2020; Bhajan Global Impact Foundation, 2024).

The Nagpur–Gondia region of Maharashtra represents one such coal-intensive zone. Power generation in this region is supported by Koradi Thermal Power Station, Khaparkheda Thermal Power Station, and Adani Tirora Thermal Power Plant (Global Energy Monitor, 2025). These plants collectively consume large quantities of coal and generate substantial volumes of fly ash, leading to concerns regarding ash pond saturation and environmental exposure (Times of India, 2025; Scroll.in, 2025). Improper handling of fly ash poses serious environmental and health risks due to airborne dispersion and leaching of toxic trace elements into soil and groundwater (Pandey and Singh, 2010; Izhar and Kumar, 2020). These concerns highlight the urgent need for environmentally sound and value-added utilization pathways. One promising solution is alkaline activation technology (AAT), which enables the conversion

*Corresponding Author: Virendra K Sangode, Department of Zoology, Manoharbai Patel College of Arts Commerce and Science Sadak Arjuni Dist Gondia, India Email: virendrasangode03@gmail.com.

of fly ash into geopolymer-based construction materials (Davidovits, 2011). Geopolymer bricks exhibit superior mechanical properties, reduced water absorption, and improved durability compared to conventional clay-fired bricks, while eliminating kiln firing and associated CO₂ emissions (Yao *et al.*, 2015; Izhar and Kumar, 2021). This study aims to develop sustainable fly ash-based eco-bricks using alkaline activation technology, with reduced dependency on commercially processed activators and increased utilization of industrial and agricultural waste materials such as stone dust and rice husk. The research evaluates the chemical and physical characteristics of fly ash from selected power plants and assesses the performance of geopolymer bricks as a low-energy alternative to conventional construction materials.

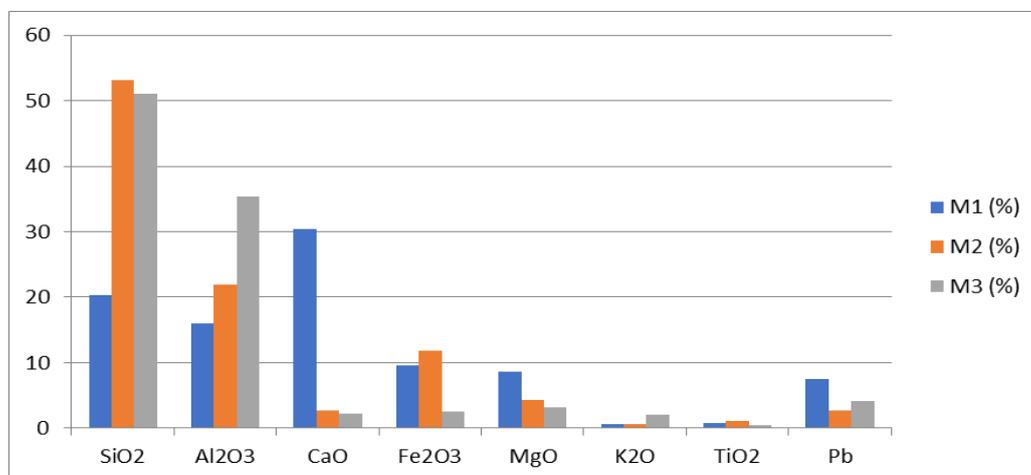
Characterization of fly ash is essential to assess its suitability for geopolymer applications (Yao *et al.*, 2015; Izhar and Kumar, 2021). Fly ash samples collected from Adani Tirora (M1), Koradi (M2), and Khaparkheda (M3)

power plants were analyzed using XRF and SEM techniques to determine their chemical and morphological properties. The results indicate significant compositional variation among the samples. Sample M1 exhibited higher CaO content, which contributed to enhanced early strength development due to calcium-assisted geopolymerization (Kumar, 2002; Davidovits, 2011). In contrast, samples M2 and M3 contained higher silica and alumina content and required additional activators such as GGBS to achieve comparable strength levels (Izhar and Kumar, 2021). Similar trends have been reported in previous studies emphasizing the role of calcium in geopolymer systems (Yao *et al.*, 2015; Ahmaruzzaman, 2010). Fly ash samples M1 (Adani Power Plant), M2 (Koradi Power Plant), and M3 (Khaparkheda Power Plant) were collected from different thermal power plants and subjected to chemical analysis using X-ray fluorescence (XRF) spectroscopy for elemental composition, and compressive strength tests for mechanical performance evaluation.

The chemical composition of the samples is as follows:

Table 1. Composition of Fly Ash Samples from Different Power Plants.

Component	M1 (%)	M2 (%)	M3 (%)
SiO ₂	20.32	53.18	51.00
Al ₂ O ₃	15.93	21.91	35.33
CaO	30.38	2.76	2.20
Fe ₂ O ₃	9.52	11.84	2.56
MgO	8.58	4.36	3.17
K ₂ O	0.56	0.65	2.11
TiO ₂	0.80	1.10	0.5
Pb	7.44	2.75	4.08
LOI	2.22	<0.01	<0.01



Graph 1. Composition of Fly Ash Samples from Different Power Plants.

The variation in composition significantly influences the binding properties of geopolymeric materials. Sample M1, with the highest calcium oxide (CaO) content (30.38%), is most suitable for eco-brick applications, providing superior early strength development. The fineness and surface area of the particles influence their pozzolanic activity, which is crucial for geopolymerization. Bricks manufactured with a mix of 60% fly ash, 25% stone dust, 10% lime, and 5% gypsum exhibited a compressive strength of 6.24 N/mm². The presence of higher CaO in M1 enhanced the early strength gain, whereas M2 and M3 required prolonged curing. Moreover, Samples M2 and M3, with higher silica and alumina content, require additional activators such as ground granulated blast furnace slag (GGBS) for enhanced performance. This analysis highlights the potential of fly ash as a sustainable construction material. M1, due to its high CaO content, is ideal for direct application in eco-brick production. M2 and M3, with higher silica and alumina content, are suitable for blended applications requiring additional activators. Future research should focus on optimizing mix proportions to enhance mechanical strength and durability. Fly ash with high calcium content (M-1) enhances geopolymerization, improving strength.

Higher silica and alumina content (M-2, M-3) requires additional activators like Ground Granulated Blast Furnace Slag (GGBS) for effective binding. Alkaline Activation Technology (AAT) is an innovative and sustainable approach for converting industrial and agricultural waste materials such as fly ash, stone dust, and rice husk into high-strength, eco-friendly construction products through chemical activation using alkaline solutions, primarily sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) (Yao *et al.*, 2015; Davidovits, 2011; Ahmaruzzaman, 2010). The technology is based on the principle of geopolymerization, wherein aluminosilicate-rich materials undergo dissolution, polycondensation, and hardening to form stable, cement-like binders with superior durability and mechanical performance (Davidovits, 2011).

Unlike conventional clay-fired bricks that require kiln firing at temperatures exceeding 1000 °C, AAT-based materials can be cured at ambient or moderately elevated temperatures (60–80 °C), resulting in substantial reductions in energy consumption and associated CO₂ emissions (Kumar, 2002; Jangam *et al.*, 2025). The typical manufacturing process involves the preparation of alkaline solutions with controlled molarities (2M–12M NaOH), followed by mixing with fly ash and supplementary waste materials, casting into molds, and curing without kiln firing before mechanical and durability evaluation (Izhar and Kumar, 2021). This approach effectively addresses the environmental challenges associated with large-scale fly ash generation in India, which reached approximately 340 million tonnes in FY 2024–25 with reported utilization levels nearing 98% (Energy World, 2025; Central Electricity Authority, 2022). Nevertheless, regions with a high concentration of coal-based thermal power plants, such as Koradi, Khaparkheda, and Tirora in Maharashtra, continue to experience localized environmental and public

health concerns due to fly ash handling and storage (Times of India, 2025; Scroll.in, 2025; Global Energy Monitor, 2025). Geopolymer bricks produced through AAT have been reported to exhibit higher compressive strength, lower water absorption, and superior resistance to chemical, fire, and sulfate attack compared to conventional masonry units (Davidovits, 2011; Kumar, 2002; Izhar and Kumar, 2021). Furthermore, the incorporation of industrial and agricultural wastes supports circular economy principles by reducing reliance on natural clay resources and Portland cement, thereby lowering the overall carbon footprint of construction materials (Jangam *et al.*, 2025; Ahmaruzzaman, 2010). Overall, AAT represents a promising pathway toward sustainable infrastructure development through waste valorization, reduced energy demand, and improved material performance. Continued research on optimized mix designs, waste-derived alkaline activators, large-scale production, and supportive regulatory frameworks is expected to further enhance the adoption of AAT-based construction materials (Pandey and Singh, 2010; Central Pollution Control Board, 2020).

MATERIALS AND METHODS

Raw Materials

Coal fly ash used in the present investigation was collected from three major coal-based thermal power plants, namely Adani Tirora Thermal Power Plant (sample M1), Koradi Thermal Power Station (sample M2), and Khaparkheda Thermal Power Station (sample M3). These plants represent significant contributors to fly ash generation in the Nagpur–Gondia region, where large-scale coal combustion continues to meet regional energy demand (Central Electricity Authority, 2022; EnergyWorld, 2025). The collected fly ash samples exhibited noticeable variation in chemical composition, particularly in calcium oxide (CaO) content, which is known to play a crucial role in geopolymerization and early strength development (Yao *et al.*, 2015; Davidovits, 2011). Based on their chemical characteristics, the fly ash samples were comparable to ASTM Class C fly ash, which possesses both pozzolanic and self-cementitious properties (Ahmaruzzaman, 2010; Kumar, 2002).

The alkaline activation system employed in the first phase of the study consisted of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), which are widely reported as effective activators for fly ash-based geopolymers (Davidovits, 2011; Izhar and Kumar, 2021). Sodium hydroxide was used in pellet form with a purity of approximately 97%, while sodium silicate solution contained 9.4% Na₂O, 30.1% SiO₂, and 60.5% H₂O, with a SiO₂/Na₂O weight ratio ranging from 3.20 to 3.30 and a specific gravity of 1.4 at 20 °C. The selection of this activator system was based on its proven ability to enhance dissolution of aluminosilicate phases and improve mechanical performance of geopolymer products (Yao *et al.*, 2015; Izhar and Kumar, 2021).

Test Variables

To evaluate the influence of alkaline concentration on geopolymer strength development, sodium hydroxide solutions of 6 M, 8 M, 10 M, 12 M, and 14 M were prepared. A constant fly ash-to-alkaline activator ratio and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2.5 were maintained throughout the experimental program. The use of multiple fly ash samples with varying CaO content enabled assessment of compositional effects on geopolymerization efficiency and compressive strength, as reported in earlier studies (Kumar, 2002; Davidovits, 2011; Izhar and Kumar, 2020).

Experimental Procedure

The sodium hydroxide solution was prepared at least 24 hours prior to mixing to ensure complete dissolution and stabilization, following standard practice recommended in geopolymer research (Davidovits, 2011). Sodium silicate solution was subsequently blended with the NaOH solution to form the alkaline activator. Fly ash was dry-mixed to obtain uniform consistency before gradual addition of the alkaline solution. The resulting mixture was thoroughly mixed to achieve a homogeneous paste, promoting effective dissolution of silica and alumina phases (Yao *et al.*, 2015). The fresh geopolymer paste was poured into moulds and compacted using vibration to eliminate entrapped air. The specimens were then cured at 70 °C for 24 hours to accelerate geopolymerization, a curing regime widely reported to enhance early strength development in fly ash-based systems (Davidovits, 2011; Izhar and Kumar, 2021). After curing, compressive strength testing was conducted using a universal testing machine at six days, following standard testing procedures.

Alternative Raw Material Composition

In response to growing concerns regarding environmental sustainability and chemical dependency, an alternative geopolymer formulation incorporating industrial and agricultural waste materials was investigated. Fly ash was combined with stone dust, rice husk, and lime to develop a composite geopolymer matrix, while sodium hydroxide alone was used as the alkaline activator. The incorporation of stone dust improved particle packing and reduced porosity, while rice husk contributed reactive silica to enhance geopolymer gel formation (Pandey and Singh, 2010; Izhar and Kumar, 2020). Lime was added in controlled proportions to promote calcium-based reaction products, accelerating early strength development (Kumar, 2002). NaOH molarities ranging from 6 M to 12 M were evaluated to study their effect on compressive strength. The dry constituents were thoroughly mixed, followed by gradual addition of the NaOH solution under controlled stirring conditions to ensure uniform activation. The prepared slurry was cast into moulds and subjected to furnace curing at 250 °C, followed by ambient curing for six days. This curing approach was adopted to compensate for the absence of sodium silicate and to enhance reaction kinetics in the waste-rich system (Davidovits, 2011). Compressive strength testing was carried out after completion of the curing cycle. The comparative analysis of both activation routes enabled assessment of performance, sustainability, and material efficiency, aligning with recent research emphasizing reduced chemical usage and enhanced waste valorization in geopolymer systems (Jangam *et al.*, 2025; Izhar and Kumar, 2021).



Figure 1. (120rpm) magnetic stirring for homogenous mixing.

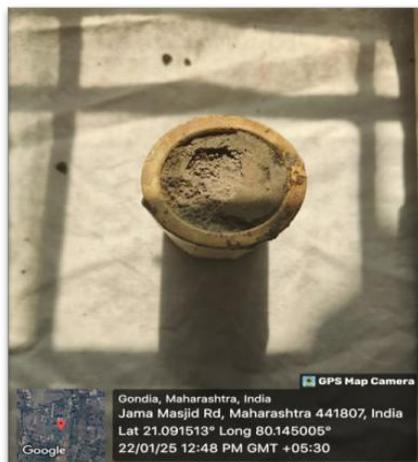


Figure 2. Slurry collected after furnace curing .

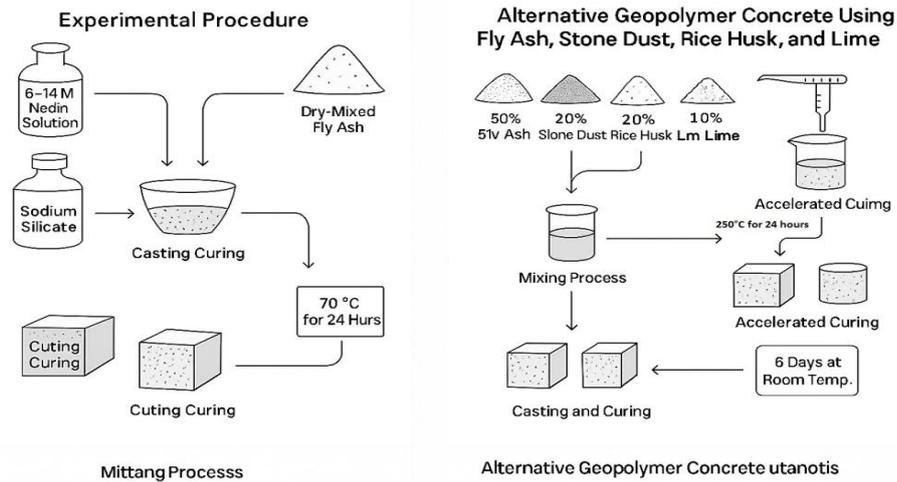


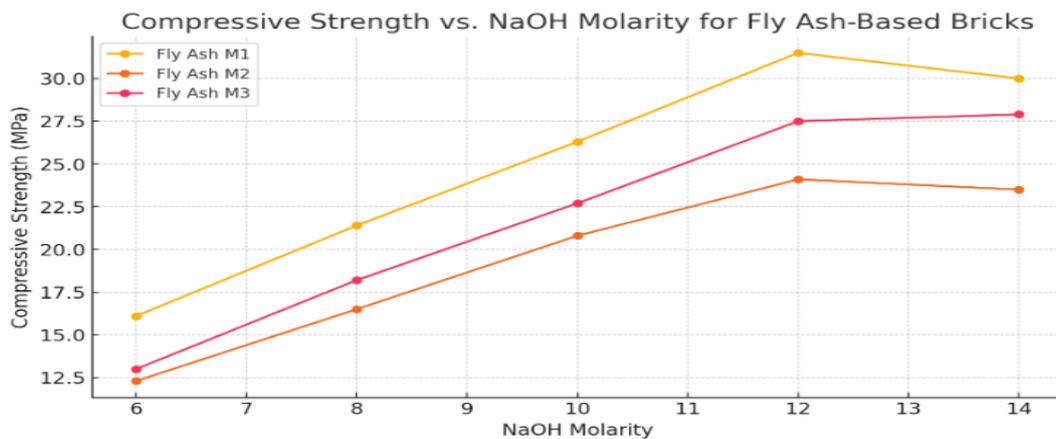
Figure 3. Diagrammatic representation of Experimental Procedure.

RESULTS AND DISCUSSION

The compositions of the test samples and their corresponding compressive strength values for different NaOH molarities are summarized in Table 1.A) Composition and Compressive Strength Data PART-A The results indicate that fly ash samples with higher CaO content (M-1 and M-2) exhibited significantly better compressive strength.

Table 2. Compressive Strength vs. NaOH Molarity for Different Fly Ash Samples.

NaOH (Molarity)	Fly Ash/Alkaline Ratio	Na ₂ SiO ₃ /NaOH Ratio	M1 (%)	M2 (%)	M3 (%)
6M	2.5	2.5	16.1	12.3	13.0
8M	2.5	2.5	21.4	16.5	18.2
10M	2.5	2.5	26.3	20.8	22.7
12M	2.5	2.5	31.5	24.1	27.5
14M	2.5	2.5	30.0	23.5	27.9

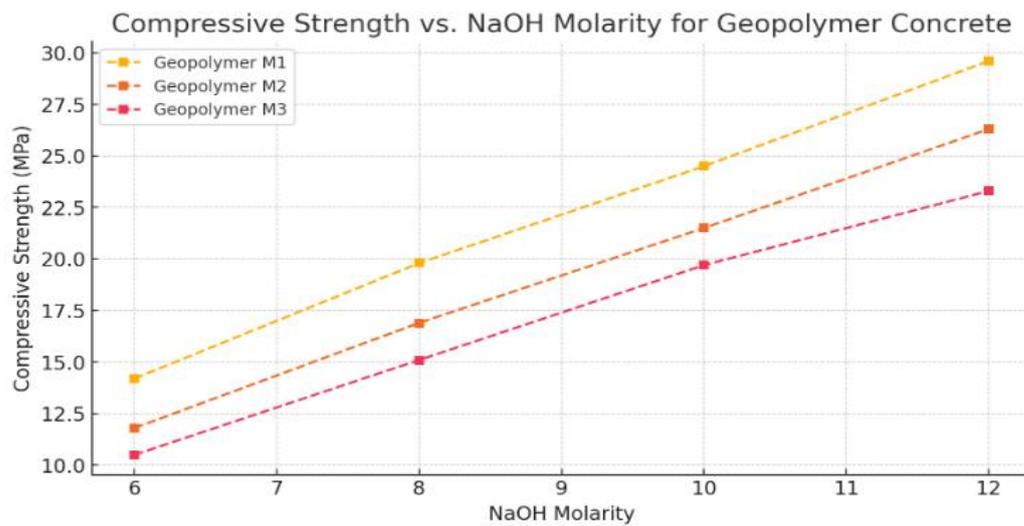


Graph 2. Compressive Strength vs. NaOH Molarity for Different Fly Ash Samples.

The result shows that compressive strength increased with NaOH molarity up to 12M, with M-1 and M-2 (higher CaO content) demonstrating the highest strength values.

Table3. Compressive Strength vs. NaOH Molarity for Different Fly Ash Samples.

NaOH (Molarity)	Fly Ash (%)	Stone (%)	Dust (%)	Rice (%)	Husk (%)	Lime (%)	M1 Strength (MPa)	M2 Strength (MPa)	M3 Strength (MPa)
6M	50	20		20		10	14.2	11.8	10.5
8M	50	20		20		10	19.8	16.9	15.1
10M	50	20		20		10	24.5	21.5	19.7
12M	50	20		20		10	29.6	26.3	23.3



Graph 3. Compressive Strength vs. NaOH Molarity for Different Fly Ash Samples.

The compressive strength increases with increasing NaOH molarity, indicating a stronger geopolymerization reaction at higher alkalinity. Among all samples, M1 (12M NaOH) achieved the highest compressive strength (29.6 MPa), suggesting that this formulation is optimal for structural applications. The higher percentage of CaO in the M2 sample could be a contributing factor, as calcium enhances geopolymer matrix densification.

CONCLUSION

The results indicate that fly ash specimens activated using a conventional alkaline system comprising sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) achieved higher compressive strength due to enhanced geopolymer gel formation and improved matrix densification. These mixes required comparatively less thermal treatment, as satisfactory strength development was attained without prolonged high-temperature curing. However, the use of sodium silicate significantly increased material cost and chemical dependency. In contrast, the waste-based activation approach employing sodium hydroxide and

aluminium foil waste resulted in moderate strength development and required furnace curing at 250°C to achieve acceptable performance. Although the compressive strength obtained was lower than that of NaOH–Na₂SiO₃ activated specimens, this method substantially reduced the use of commercially processed alkaline activators and increased waste utilization. The findings highlight a clear trade-off between mechanical performance and sustainability, demonstrating that waste-based alkaline activation can serve as a cost-effective and environmentally responsible alternative for eco-brick production in non-structural applications.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

FUNDING

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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