Mechanical Behavior of Sand–Fly Ash Mixtures for Weak Rock Modeling

Man Brawl[1*]

[1]Department of Civil Engineering, Lovely Professional University, India

(*Corresponding E-mail: manbrawl270@gmail.com)

Abstract: This study investigates the mechanical behavior of artificial materials designed to replicate weak surrounding rocks for geo-mechanical model testing. Unlike previous studies that emphasized the ratio of fine to coarse aggregates, this research explores mixtures of sand (as coarse aggregate) and fly ash (as fine aggregate) combined with gypsum–water paste as the binder, with iron powder selectively introduced to regulate density. Cylindrical specimens of varying sand–fly ash ratios were prepared and tested under uniaxial compression. Results indicate that increasing fly ash content enhances density and stiffness due to pore filling between sand grains, while the gypsum–water binder provides a brittle yet cementitious cohesion suitable for simulating weak rock mass behavior. Iron powder addition effectively increased bulk density without significantly altering frictional properties. Stress–strain behavior revealed a transition from low-strength brittle failure at lower fly ash content to more ductile and stable responses at higher fly ash proportions. Numerical simulations (discrete element method) captured micro-mechanical trends such as particle contact forces and crack propagation, which agreed with experimental observations. These findings demonstrate that sand–fly ash mixtures bounded with gypsum paste offer a practical method for simulating weak surrounding rocks in physical model studies, providing an alternative to traditional cement-based formulations.

Keywords: ***Sand, Fly ash, Similar material, Weak rock simulation, Gypsum–water binder, Iron powder.***

Introduction

Geo-mechanical model testing plays a crucial role in understanding the behavior of underground structures, particularly in weak rock formations. Such testing requires similar materials that can reliably represent the strength characteristics, deformation patterns, and failure modes of natural weak rocks. Conventional formulations, often based solely on sand–gypsum mixtures, have limitations. They generally lack flexibility in independently controlling key properties such as density and stiffness, which reduces their accuracy in replicating natural rock behavior. By introducing fly ash as a fine aggregate and gypsum–water paste as a binder, along with iron powder for density regulation, this study provides a more adaptable material system capable of better simulating the mechanical response of weak surrounding rocks. (Cui et al., 2025; Shi et al., 2018).

To overcome these limitations, this research proposes an alternative material system using a combination of sand, fly ash, and a gypsum–water binder, with optional iron powder to regulate density. The study aims to systematically investigate how variations in mixture proportions influence mechanical properties. By establishing both empirical and numerical relationships, this work provides practical guidance for preparing weak rock analogues, thereby enhancing the reliability and accuracy of geo-mechanical models in underground engineering studies (Vasyliev et al., 2023; Zhou et al., 2021).

Methodology

Specimens were prepared using sand (0.6–0.9 mm) as coarse aggregate and fly-ash (Class F derived from Anthracite and Bituminous Coal, 60-90% SiO_2 and Al_2O_3) (0.05–0.08 mm) as fine aggregate, with gypsum–water paste serving as the binder to provide brittle but cementitious cohesion. Iron powder was added in selected mixtures to increase density without significantly affecting frictional properties. Five mixture ratios (S1–S5) were designed to systematically vary the sand-to-fly ash proportion.

Firstly, dry sand and fly ash were mixed thoroughly, then the gypsum–water paste binder was gradually added to ensure uniform distribution and bonding of particles. Iron powder, when included, was incorporated after binder addition and mixed evenly. Cylindrical specimens (50 mm × 100 mm) were compacted layer by layer in steel molds and cured under controlled ambient conditions for 24 hours before testing.

Uniaxial compression tests were performed at a constant loading rate of 0.05 mm/min to measure stress–strain behavior, uniaxial compressive strength, and elastic modulus. The effect of iron powder as a density regulator was also evaluated by comparing specimens with similar sand–fly ash ratios.

Numerical simulations under varying confining stresses were used to derive Mohr–Coulomb strength parameters and capture micro-mechanical trends such as particle contact forces and crack propagation, which were compared with experimental observations.

Results and Discussion

Table 1 presents the mixture proportions and basic physical properties of the specimens. Increasing fly ash content led to higher density (e.g., 1.85 → 2.15 g/cm^3) and uniaxial compressive strength (0.78 → 1.32 MPa). The elastic modulus also increased with higher fine content, indicating stiffer and more cemented behavior in denser mixtures. These trends highlight the significant role of mixture composition in controlling the mechanical properties of artificial weak rock analogues.

Table 1, Mixture proportions and physical properties of specimen

Test No.	Sand (g)	Flyash (g)	Iron Powder (g)	Gypsum paste (g)	Density (g/cm³)	UCS (MPa)	Elastic Modulus (MPa)
S1	400	100	0	80	2.05	0.92	285
S2	350	150	0	80	2.12	1.05	315
S3	300	200	20	80	2.28	1.18	342
S4	250	250	40	80	2.36	1.32	378
S5	200	300	60	80	2.45	1.46	401

Stress–strain curves brittle post-peak responses in low as well as high fly-ash mixes. Figure 1 illustrates this trend.

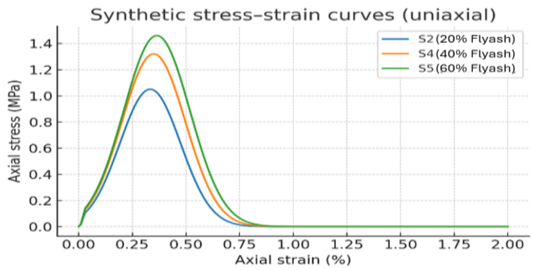

Figure 1, Stress-strain curves of specimen with varying Fly-ash content.

Iron powder effectively increased density while maintaining similar stress–strain characteristics. Figure 2 shows a linear relationship between Density and UCS (Unconfined Compressive Strength).

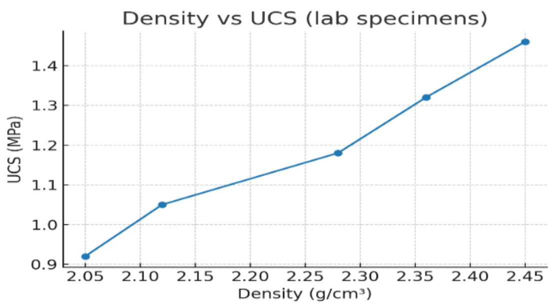

Figure 2, Relationship between density and UCS of lab specimen

Table 2 shows the Mohr–Coulomb strength parameters of the sand–fly ash mixtures from numerical tests under confining stress. Cohesion (c) increases with fly ash content, from 0.32 MPa (S1) to 0.53 MPa (S5), reflecting stronger bonding in denser mixtures. The internal friction angle (ϕ) varies between 33° and 39°, indicating lower sensitivity to barite proportion. High R^2 values (0.94–0.97) confirm the reliability of the fitted parameters for modeling weak rock behavior.

Table 2, Fitted strength parameters of sand -fly ash mix

Mix ID	Cohesion (c, MPa)	Internal Friction Angle (φ, °)	R²
S1	0.32	35.0	0.95
S2	0.36	33.2	0.96
S3	0.41	34.1	0.94
S4	0.48	36.5	0.95
S5	0.53	38.8	0.97

Conclusion

Sand–fly ash mixtures with gypsum paste binder provide a practical material system for simulating weak rocks in geo-mechanical model tests. Our key findings include:

1. Higher fly-ash content increases density, UCS, and modulus.
2. Iron powder effectively regulates density without altering strength trends.
3. Stress–strain responses show brittle response for both low as well as high fly-ash content.
4. Numerical simulations validate laboratory findings, offering mesoscopic insights into crack development.

This study demonstrates that the proposed formulation is a viable alternative traditional cement-based systems and can support more realistic modelling of weak rock behavior in underground engineering.

Acknowledgement

The authors acknowledge the support of laboratory facilities and technical discussions provided by colleagues in geo-mechanical modelling.

References

Cui, L., Sheng, Q., Miao, C., and Luo, S. (2025). Mechanical properties of similar materials simulating weak surrounding rocks with different ratios of fine-to-coarse aggregate. Applied Sciences, 15 (7), 3540. https://doi.org/10.3390/app15073540

Shi, X. M., Liu, B. G., Xiang, Y. Y., and Qi, Y. (2018). A method for selecting similar materials for rocks in scaled physical modeling tests. Journal of Mining Science, 54 (6), 938–948. https://doi.org/10.1134/S1062739118065084

Vasyliev, L., Malich, M. G., Vasyliev, D., Katan, V., and Rizo, Z. (2023). Improving a technique to calculate strength of cylindrical rock samples in terms of uniaxial compression. https://doi.org/10.33271/mining17.01.043

Zhou, Y., Feng, S., and Li, J. (2021). Study on the failure mechanism of rock mass around a mined-out area above a highway tunnel – Similarity model test and numerical analysis. Tunnelling and Underground Space Technology, 118, 104182.