Optimization of Fly Ash Dosage in Silty Soil through Geotechnical and Microstructural Characterization

Sushmeeta Rani Lal[1], Vatsala Sharma[2], Kritika Kaushal[3], Smriti Raj[4], Priyanka Shakya[5], Amit Kumar[6]

[1]Assistant Professor, Department of Civil Engineering, Government Engineering College Buxar, Bihar, India, Email: - sushmeeta007@gmail.com
[2]Assistant Professor, Department of Electronics and Communication Engineering, Government Engineering College Buxar, Bihar, India, Email:- vatsalasharma01@gmail.com
[3]Assistant Professor, Department of Civil Engineering, Bakhtiyarpur College of Engineering, Bakhtiyarpur, Bihar, India, Email: kritika08@bcebakhtiyarpur.ac.in
[4]Assistant Professor, Department of Civil Engineering, Gaya College of Engineering, Email: - smritiraj11@gmail.com
[5]Assistant Professor, Department of Electronics and Communication Engineering, Government Engineering College Buxar, Bihar, India, Email:- priyankashakya33@gmail.com
[6]Assistant Professor, Department of Electronics and Communication Engineering, Government Engineering College Buxar, Bihar, India, Email:- kamit9281@gmail.com

Abstract
Sustainable recycling of industrial by-products for soil improvement is a viable solution for geotechnical engineering and waste disposal problem. The coal fly ash which is a byproduct from water powered plants is used in this study to study the engineering and microstructure properties of fly ash reinforced silty soil. Fly ash was mixed with a soil in 20%, 30%, 40% and 45% dry contents by weight and the blended mixtures were characterised by grain size distribution method, Standard Proctor compaction method and shear strength tests. The results revealed that fly ash has a significant effect on the behaviour of soil and 40% fly ash content showed the best performance. This dosage provided the good compaction properties and peak shear strength for the stabilised soil. Scanning electron microscopy (SEM) analysis was performed to gain insight into the mechanisms responsible for these benefits. Results showed denser soil matrix under optimum fly ash content, [13] SEM micrographs obtained at each mixing period indicated diagenesis from particles coalescence to improved particle interlocking and bonding between the siliceous soil particles with less pore spaces at maximum fly ash content. The correlation between geotechnical and microstructural observations substantiates the effectiveness of fly ash in enhancing the performance of silty soil. The results indicate that 40% fly ash is the optimum dosage for stabilisation and emphasise the potential of using fly ash as a sustainable and economical material for ground improvement applications.

Keywords: Silty soil; Fly ash; Soil stabilization; Shear strength; Compaction characteristics; Scanning Electron Microscopy (SEM); Microstructural analysis.

1. Introduction

Silty soils are widely encountered in civil engineering and generally characterised by moderate to poor engineering properties that can adversely affect the performance of foundations, embankments, pavement subgrades and retaining structures. They are relatively weak, compressible and sensitive to moisture change and therefore often require stabilisation before construction. Conventional stabilisation techniques are mostly based on lime and cement. However, the growing environmental issues and the demand for sustainable construction practices have prompted the investigation of alternative materials from industrial by-products. A finely divided waste produced when coal is burnt in thermal plants is called fly ash.
The use of fly ash as soil stabiliser has received considerable attention due to its availability, low cost and environmental benefits.

According to reports, fly ash can enhance the engineering performance of fine-grained soils through improved particle packing, reduction in void ratios, and increased resistance to shear deformation. Noaman et al. [1] studied the fly ash has been found to be an effective and sustainable soil stabiliser for improving the key geotechnical properties including strength, density, permeability and bearing capacity. While Athanasopoulou [2] investigated the hybrid use of lime and fly ash, which has been popularly known as a successful method for improving the strength, stiffness and durability of highway subgrade soils. Mill tailings, fly ash and slag have exhibited great potential as sustainable mine paste backfill materials for improved mechanical performance as reported by Behera et al. [3]. Deepak et al. [4] the incorporation of fly ash to enhance substantially the engineering characteristics of clay soils by increasing strength, compaction behaviour and overall stability. Edil et al. [5] studied the stabilization of soft fine-grained soils with fly ash has proven effective in increasing bearing capacity and improving soil durability.

Ghazali et al. [6] revealed that owing to its pozzolanic properties and widespread availability, fly ash is now a crucial component of many construction projects. Inkham et al.[7] studied that lime-based stabilizers can effectively immobilize cadmium in contaminated soils by reducing its exchangeable and bioavailable forms. Romero et al [8] studied through the microstructural investigation techniques the understanding of soil behaviour by linking pore-scale features with macroscopic engineering properties. Scholars like Ringrose [9] studied that quantitative micromorphological analysis serves as an effective tool for characterizing soil fabric and pore networks. Chen et al. [10] highlighted the significance of SEM-based studies which indicates that the incorporation of appropriate admixtures can improve cement stabilization efficiency by modifying soil fabric. Ma et al. [11] focussed on X-ray micro-computed tomography studies which revealed that pore structure parameters, including porosity, pore size distribution, and connectivity, are key factors governing soil aggregate stability and strength. Pires et al. [12] revealed that micromorphological analysis are also used to characterize structure modifications of soil samples. Murphy et al. [13] stressed that the dense behavior of soils can be closely monitored by SEM analysis.

In this study, fly ash was used to stabilise silty soil at 20, 30, 40, and 45% by dry weight of soil. Laboratory tests were performed to evaluate the engineering performance of the stabilised mixtures including grain size distribution analysis, Standard Proctor compaction tests and shear strength. SEM analysis was also carried out to study the microstructural changes due to fly ash incorporation and to relate these changes with the observed geotechnical behaviour. The research was aimed at finding out the optimum fly ash content and developing relationship between microstructural development and engineering performance. The results help to develop sustainable ground improvement techniques by the effective use of fly ash in geotechnical engineering applications.

2. Methodology

The soil used in this study was collected from the bank of Subarnarekha River, Ranchi, Jharkhand, India shown in Fig. 1. Representative bulk samples from the near-surface deposit were air-dried and prepared for laboratory testing. Fly ash collected from Bokaro Thermal Power Plant, Jharkhand was used as stabilising additive as shown in Fig. 2. To determine the effect of fly ash content on the engineering behaviour of the soil, the soil was mixed with fly ash in different proportions of 20%, 30%, 40% and 45% by dry weight of soil. The prepared mixtures were thoroughly homogenised to ensure uniform distribution of fly ash in the soil matrix.

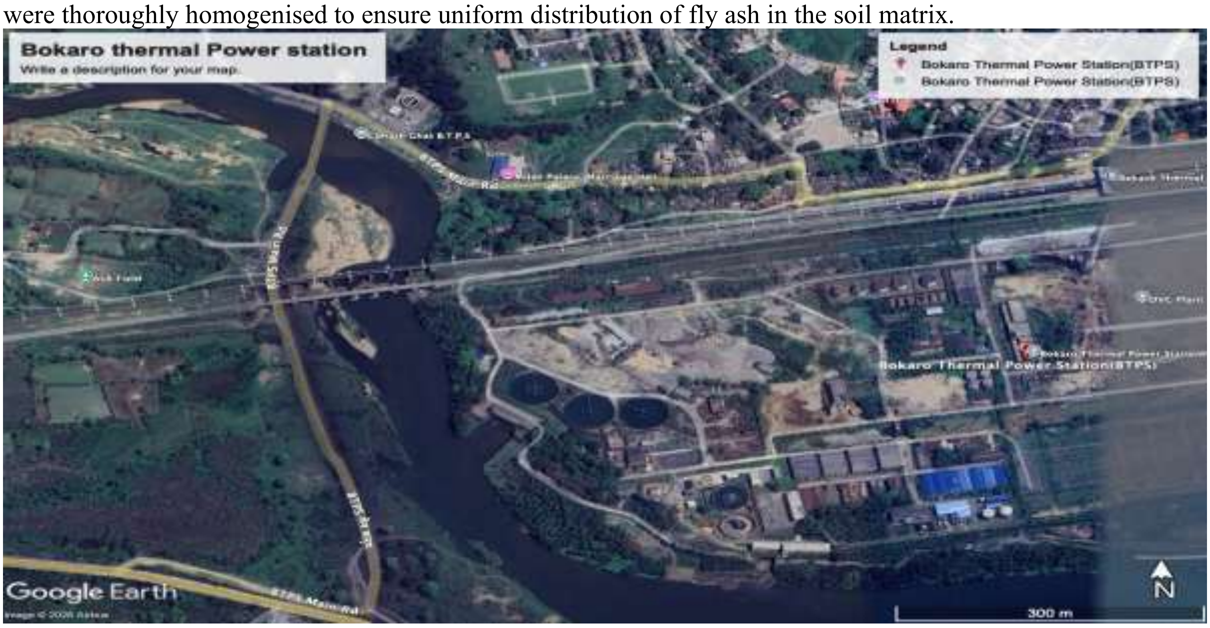

Figure 1. Sampling site of fly ash used in the study

Figure 2. Sampling site of the silty soil used in study

The physical, compaction, strength, and microstructural characteristics of untreated and fly ash-treated soil samples were assessed by a thorough experimental investigation. To investigate the gradation and particle size properties of soil-fly ash mixes, Grain Size Distribution (GSD) tests were performed. To find each mix's Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), standard Proctor compaction tests were carried out. In order to analyse shear strength behaviour, laboratory shear tests were conducted to determine how fly ash inclusion affected the soil's strength characteristics. In order to examine the microstructural alterations caused by fly ash stabilisation and connect the observed alterations to the outcomes of geotechnical tests, a few specimens were also examined using scanning electron microscopy (SEM). The specifics of every laboratory test performed, together with the corresponding IS code specifications, are listed in Table 1.

Table1. Experimental Framework for the present study

Test performed	IS code
Grain size distribution	IS 2720 (PART 4): 1985
Standard Proctor test	IS 2720 (PART 7): 1980
Direct Shear test	IS 2720 (PART 13): 1986
Scanning electron Microscope analysis	ASTM E986

3. Results

3.1 Grain size distribution test results

The untreated soil was made up of 0.50% gravel, 34.94% sand and 64.56% silt and clay fractions, which showed that it was fine-grained silty soil. The fines fraction increased with the addition of fly ash, while the sand and gravel content decreased. The soil-fly ash mixture with 20% fly ash had 0.40% gravel, 27.96% sand and 71.64% silt and clay. The mixtures containing 30%, 40% and 45% fly ash gave gravel contents of 0.34%, 0.30% and 0.28%, sand contents of 24.47%, 20.95% and 19.21% and silt and clay contents of 75.19%, 78.75% and 80.52% respectively. The increase in finer fraction with the increase in fly ash content can be attributed to the predominantly silt-sized nature of fly ash particles that changed the overall gradation of the soil matrix. The results of grain size distribution for untreated and fly ash treated soil mixtures are summarised in table. Results of grain size analysis indicate that the soil gradation shifted towards finer particle distribution with the increase of fly ash content. This is reflected in the increase of the silt and clay fraction from 64.56% in the untreated soil to 80.52% at 45% fly ash content. This trend is in accordance with the fine particle nature of fly ash and suggests better void filling and particle packing in the soil matrix which can contribute towards the improved compaction and shear strength characteristics observed in the stabilised mixtures.

Table 2. Grain size analysis of the Mixtures

Parameter	**Virgin soil**	**Virgin soil + 20% fly ash**	**Virgin soil + 30% fly ash**	**Virgin soil + 40% fly ash**	**Virgin soil + 45% fly ash**
Percentage of Gravel, (%)	0.50	0.40	0.34	0.30	0.28
Percentage of Sand, (%)	34.94	27.96	24.47	20.95	19.21
Percentage of silt and clay, (%)	64.56	71.64	75.19	78.75	80.52

The most favourable engineering performance was achieved at 40% fly ash content, indicating an optimum balance between particle-size modification and soil skeleton stability.

3.2 Standard Proctor tests

The compaction characteristics of the virgin and fly ash-treated soil mixtures were evaluated using the Standard Proctor test, and the results are presented in Table 3. The untreated silty soil exhibited a Maximum Dry Density (MDD) of 1.47 g/cc and an Optimum Moisture Content (OMC) of 13.04%. The addition of fly ash resulted in a progressive increase in both MDD and OMC. At fly ash contents of 20%, 30%, 40%, and 45%, the MDD values increased to 1.589, 1.78, 1.87, and 1.98 g/cc, respectively, while the corresponding OMC values increased to 14.02%, 16.81%, 19.06%, and 22.89%.

Table 3. Standard proctor tests results

Fly ash content (%)	Maximum dry density(g/cc)	Optimum moisture content (%)
0, (virgin soil)	1.47	13.04

20	1.589	14.02
30	1.78	16.81
40	1.87	19.06
45	1.98	22.89

The observed increase in MDD can be attributed to the improved particle-size distribution and enhanced packing efficiency resulting from the incorporation of fine fly ash particles into the soil matrix. The fly ash particles occupy the void spaces between soil grains, leading to a denser arrangement and reduced void ratio. Simultaneously, the increase in OMC with increasing fly ash content may be attributed to the larger specific surface area and porous nature of fly ash particles, which require additional water for lubrication and effective compaction. Furthermore, the increased fines content in the soil–fly ash mixtures enhance water absorption and retention, thereby increasing the moisture requirement for achieving maximum dry density. These findings indicate that fly ash significantly modifies the compaction behaviour of the silty soil and contributes to improved densification characteristics.

3.3 Shear strength results

The influence of fly ash addition on the angle of internal friction (φ) of the silty soil was evaluated through shear strength testing, and the results are presented in Table 4. The untreated soil exhibited an angle of internal friction of 21.9°, indicating relatively low resistance to shear deformation. Upon the incorporation of fly ash, a gradual increase in the friction angle was observed. The angle of internal friction increased to 24.8°, 27.3°, and 29.8° for fly ash contents of 20%, 30%, and 40%, respectively. However, a slight reduction to 28.6° was recorded at 45% fly ash content.

Table 4. Shear strength results

Fly ash content (%)	Angle of internal friction(φ)
0, (virgin soil)	21.9°
20	24.8°
30	27.3°
40	29.8°
45	28.6°

The improvement in the angle of internal friction with increasing fly ash content up to 40% can be attributed to enhanced particle interlocking, improved gradation, and better packing of soil particles resulting from the inclusion of fine fly ash particles. The fly ash particles filled the voids between soil grains, leading to a denser soil matrix and increased resistance to particle movement during shearing. The maximum friction angle obtained at 40% fly ash content indicates the optimum level of stabilization, where the beneficial effects of improved particle arrangement and interparticle interaction were most pronounced. The slight decrease observed at 45% fly ash content may be attributed to the excessive presence of fly ash particles, which could disrupt the natural soil skeleton and reduce effective particle-to-particle contact, thereby lowering the shear resistance.

3.4 Microstructural Analysis results

Scanning Electron Microscopy (SEM) was used to examine the microstructural features of virgin soil and soil stabilised with 40% fly ash, which had the optimum engineering performance. SEM micrograph of the untreated soil (Figure 3) shows a relatively loose and dispersed structure with irregularly shaped particles and larger interparticle voids with weak particle contacts. Presence of several pore spaces and discontinuous soil fabric are indicative of poor particle packing. This is in line with lower maximum dry density and shear strength for untreated condition.On the contrary, the SEM image of the soil with 40% fly ash as seen in Figure 4 showed a denser and compact microstructure. The fly ash particles are found to fill the voids between the soil particles thus resulting in a better particle arrangement and a reduction in the pore volume. The stabilised matrix exhibited better particle interlocking and stronger interparticle bonding, resulting in a more continuous and integrated soil fabric. The reduced void spaces and higher packing efficiency resulted in the higher maximum dry density and higher shear strength of the stabilised soil. Also, the spherical shape of fly ash particles helped in better particle distribution in the soil matrix and hence a dense microstructure was obtained. The SEM observations thus corroborate the geotechnical test results and confirm that the addition of 40% fly ash had a significant effect on the engineering behaviour of the silty soil through microstructural densification and improved soil-particle interaction.

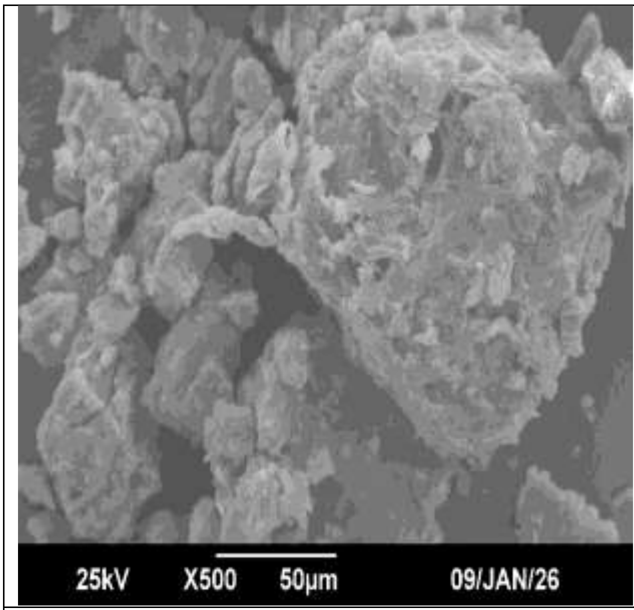	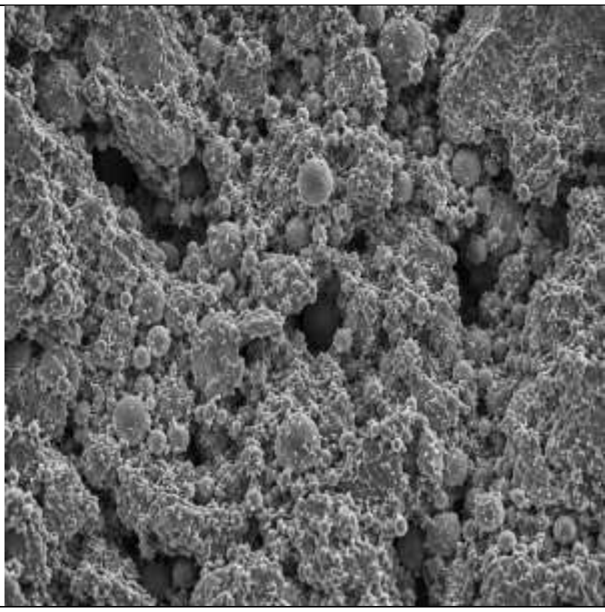
Figure 3. SEM image of virgin soil	Figure 4. SEM image of virgin soil +40% Fly ash

4. Discussions and limitations

The addition of fly ash improved the engineering characteristics of the silty soil by modifying its gradation and enhancing particle packing. An increase in the fines fraction resulted in improved compaction behaviour, reflected by higher MDD and OMC values. The angle of internal friction increased from 21.9° for the virgin soil to a maximum of 29.8° at 40% fly ash content, indicating enhanced shear strength. However, a slight reduction at 45% fly ash suggests that excessive fly ash may adversely affect the soil skeleton. Major limitations were incorporated in previous studies like Nawaj et al. [14] that controlled free lime content in fly ash can enhance strength and setting behaviour, although excessive amounts may adversely affect durability performance.

Jambhulkar et al. [15] focussed on beneficial reuse of fly ash must be balanced against potential risks arising from the presence of heavy metals. Swain et al. [16] stressed the limited use of fly ash in agriculture due to present of toxic metals. Warren [17] emphasized the alkaline nature of fly ash enabled its use as a liming material for acidic soils. Xuan et al.[18] studied on integrated pre-treatment techniques can significantly enhance the engineering performance of ash while reducing its environmental impacts. Shih et al.[19] emphasized the importance of evaluating the health and environmental implications of bottom ash reuse in transportation infrastructure projects.

5. Conclusion

This study evaluated the effectiveness of fly ash as a stabilizing agent for silty soil through geotechnical and microstructural characterization. The results demonstrated that the incorporation of fly ash significantly modified the soil gradation, improved compaction characteristics, and enhanced shear strength. Among the investigated dosages, 40% fly ash exhibited the optimum performance, producing the highest angle of internal friction (29.8°) along with favourable compaction behaviour. SEM analysis confirmed that the improved engineering properties were associated with a denser soil fabric, reduced pore spaces, and enhanced particle interlocking. The findings indicate that fly ash can serve as an effective and sustainable material for silty soil stabilization, while 40% fly ash represents the optimum dosage under the conditions investigated in this study. These results support the beneficial utilization of industrial by-products in ground improvement applications.

Reference

[1] Noaman, M.F. et al. (2022) 'A review on the effect of fly ash on the geotechnical properties and stability of soil,' *Cleaner Materials*, 6, p. 100151. https://doi.org/10.1016/j.clema.2022.100151.

[2] Athanasopoulou, A. (2013) 'Addition of lime and fly ash to improve highway subgrade soils,' *Journal of Materials in Civil Engineering*, 26(4), pp. 773–775. https://doi.org/10.1061/(asce)mt.1943-5533.0000856.

[3] Behera, S.K. et al. (2021) 'Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective,' *Construction and Building Materials*, 309, p. 125120. https://doi.org/10.1016/j.conbuildmat.2021.125120.

[4] Deepak et al. (2020) 'Influence of fly-ash on the engineering characteristics of stabilised clay soil,' *Materials Today Proceedings*, 37, pp. 2014–2018. https://doi.org/10.1016/j.matpr.2020.07.497.

[5] Tuncer, E. et. al. (2026) 'Stabilizing Soft Fine-Grained Soils with Fly Ash,' *Journal of Materials in Civil Engineering* - J MATER CIVIL ENG. 18. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(283).

[6] Ghazali, N., Muthusamy, K. and Ahmad, S.W. (2019) 'Utilization of Fly Ash in Construction,' *IOP Conference Series Materials Science and Engineering*, 601(1), p. 012023. https://doi.org/10.1088/1757-899x/601/1/012023.

[7] Inkham, R. et al. (2019) 'Low-cost alkaline substances for the chemical stabilization of cadmium-contaminated soils,' *Journal of Environmental Management*, 250, p. 109395. https://doi.org/10.1016/j.jenvman.2019.109395.

[8] Romero, E. and Simms, P.H. (2008) 'Microstructure Investigation in Unsaturated Soils: A Review with Special Attention to Contribution of Mercury Intrusion Porosimetry and Environmental Scanning Electron Microscopy,' *Geotechnical and Geological Engineering,* 26(6), pp. 705–727. https://doi.org/10.1007/s10706-008-9204-5.

[9] Ringrose-Voase, A. (1991) 'Micromorphology of soil structure - Description, quantification, application,' *Australian Journal of Soil Research*, 29(6), pp. 777–813. https://doi.org/10.1071/sr9910777.

[10] Chen, H., Zhang, J. and Yan, H. (2013) 'Quantitative evaluation of microstructure characteristics of cement consolidated soil,' *Bulletin of Engineering Geology and the Environment*, 72(2), pp. 233–236. https://doi.org/10.1007/s10064-013-0469-4.

[11] Ma, R. *et al.* (2015) 'Evaluation of soil aggregate microstructure and stability under wetting and drying cycles in two Ultisols using synchrotron-based X-ray micro-computed tomography,' *Soil and Tillage Research*, 149, pp. 1–11. https://doi.org/10.1016/j.still.2014.12.016.

[12] Pires, L.F. *et al.* (2007) 'Micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles,' *CATENA*, 72(2), pp. 297–304.
https://doi.org/10.1016/j.catena.2007.06.003.

[13] Murphy, C.P., Bullock, P. and Biswell, K.J. (1977) 'THE MEASUREMENT AND CHARACTERISATION OF VOIDS IN SOIL THIN SECTIONS BY IMAGE ANALYSIS. PART II. APPLICATIONS,' *Journal of Soil Science*, 28(3), pp. 509–518. https://doi.org/10.1111/j.1365-2389.1977.tb02259.x.

[14] Nawaz, A., Julnipitawong, P., Krammart, P., & Tangtermsirikul, S. (2015). Effect and limitation of free lime content in cement-fly ash mixtures. *Construction and Building Materials*, *102*, 515–530.
https://doi.org/10.1016/j.conbuildmat.2015.10.174

[15] Jambhulkar, H.P., Shaikh, S.M.S. and Kumar, M.S. (2018) 'Fly ash toxicity, emerging issues and possible implications for its exploitation in agriculture; Indian scenario: A review,' *Chemosphere*, 213, pp. 333–344. https://doi.org/10.1016/j.chemosphere.2018.09.045.

[16] Swain, C.K. *et al.* (2026) 'Fly ash in agriculture: A global perspective on utilization, benefits, and challenges,' *Environmental Geochemistry and Health*, 48(5). https://doi.org/10.1007/s10653-026-03104-z.

[17] Warren, C.J. (1992) 'Some limitations of sluiced fly ash as a liming material for acidic soils,' *Waste Management & Research the Journal for a Sustainable Circular Economy*, 10(4), pp. 317–327.
https://doi.org/10.1177/0734242x9201000403.

[18] Xuan, D., Tang, P. and Poon, C.S. (2018) 'Limitations and quality upgrading techniques for utilization of MSW incineration bottom ash in engineering applications – A review,' *Construction and Building Materials*, 190, pp. 1091–1102. https://doi.org/10.1016/j.conbuildmat.2018.09.174.

[19] Shih, H.-C. and Ma, H.-W. (2010) 'Assessing the health risk of reuse of bottom ash in road paving,' *Chemosphere*, 82(11), pp. 1556–1562. https://doi.org/10.1016/j.chemosphere.2010.11.061.