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GEOTECHNICAL CHARACTERISTICS OF CEMENT KILN BYPASS DUST AND ITS SUITABILITY FOR APPLICATION IN SOIL STABILIZATION AND PAVEMENT ENGINEERING

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Abstract

Cement kiln bypass dust (CKBD), a CaO-rich by-product of the cement industry, exhibits significant potential for soil stabilization and the construction of pavement sublayers. This study investigated three material groups: pure CKBD, fly ash with CKBD additions (10–50%), and clayey soil with CKBD (5–20%). The geomechanical properties of the mixtures were evaluated through Proctor compaction tests, unconfined compressive strength, swelling, and California Bearing Ratio (CBR) tests. Results indicate that pure CKBD provides high compressive strength and CBR values with minimal swelling. The addition of CKBD to fly ash activates pozzolanic reactions, significantly enhancing compressive strength and CKBD, with an optimal content of 20%. Stabilization of clayey soil with CKBD led to a compressive strength increase of up to 75% and a reduction in swelling by over 80%, while maintaining stable CBR values under wet conditions. Water durability tests confirmed the structural stability of CKBD-containing mixtures, whereas untreated fly ash exhibited partial degradation. The findings suggest that CKBD, either alone or in combination with fly ash and clayey soil, is an effective material for improving geotechnical properties and is suitable for application in pavement subbase layers.

Keywords: CKBD, soil stabilization, fly ash, pavement subbase layers, CBR, compressive strength, clayey soil, pozzolanic reactions

1 Introduction

The cement industry consumes large quantities of raw materials and energy, with thermal energy accounting for 20–25% of total production costs. A key challenge is the conservation of non-renewable resources. One response is the use of alternative fuels, such as RDF (Refuse Derived Fuel) and SRF (Solid Recovered Fuel), derived from high-calorific waste from households, industry, and other sectors. These fuels must meet strict quality requirements. Chlorine in alternative fuels affects cement clinker formation, leading to acidic gas emissions. To limit chlorine in clinker, a kiln bypass system extracts part of the kiln gases. Gas extraction and dedusting are performed with bag filters, and the collected cement kiln bypass dust (bypass dust) is stored in a dedicated silo and dosed to the cement mills. Significant quantities of bypass dust cannot be fully reintroduced and require disposal. Although aged bypass dust is often stockpiled and altered by environmental exposure, it can still be processed and reused. Due to the large quantities generated, high disposal costs, and demand for cost-effective construction materials, interest in bypass dust valorization has been steadily increasing.

2 Review of previous research and objectives of the study

Over the past five decades, extensive research has been conducted on the potential applications of bypass dust. These studies have addressed a wide range of directions and engineering fields. Ramzi Taha et al. [2] studied the stabilization of clayey–sandy soils using bypass dust additions of 3%, 6%, and 9% by mass of soil. The results demonstrated improvements in the evaluated properties with increasing bypass dust content: the swelling potential decreased, while pH values and California Bearing Ratio (CBR) showed an increasing trend. The authors concluded that bypass dust exhibits behavior similar to lime or cement when used for the improvement of clayey soils. Essam F. Badrawi and Mahmoud S. El-Kady [3] concluded that bypass dust can be successfully utilized as an embankment material or mineral filler. Bypass dust was added in amounts ranging from 3.88% to 18.63%, and increasing bypass dust content resulted in improved geotechnical soil parameters during placement and compaction. Comprehensive investigations carried out by Valley Forge Laboratories (Robert J. Collins and John J. Emery), commissioned by the Federal Highway Administration (FHWA), Washington, D.C. [4], demonstrated that bypass dust reacts favorably with fly ash and aggregates in the construction of pavement base and subbase layers. The achieved strength, durability, dimensional stability, and other engineering characteristics were found to be comparable to those obtained using conventional materials. The obtained results are in agreement with studies highlighting that the successful use of CKD in highway and geotechnical applications requires systematic characterization and evaluation of its physical, chemical, and mechanical properties due to its inherent variability (Sreekrishnavilasam and Santagata [5]). The main objectives of this study were:

- to evaluate the basic physico-chemical and geomechanical properties of pure CKBD, including compaction characteristics, compressive strength, swelling behavior, and CBR values, in order to assess its suitability as a geotechnical material
- to investigate the effect of CKBD addition to fly ash on pozzolanic reactions, strength development, and CBR performance, and to determine the optimal CKBD content for maximum improvement
- to examine the stabilization potential of clayey soil using CKBD focusing on strength enhancement, reduction of swelling, and behavior under wet conditions
- to assess the water stability of the mixtures, comparing CKBD-stabilized materials with untreated fly ash, and evaluating structural integrity after direct water exposure
- to propose the application of CKBD-based mixtures for road subbase layers, based on the achieved improvements in strength and durability.

3 Physico-chemical and geomechanical properties of bypass dust

The investigation of the physico-chemical and geomechanical properties of the bypass dust was conducted on a representative sample, obtained through meticulous homogenization of multiple samples collected from different locations within a local cement plant. Due to restricted access to the production facility, sampling was entrusted to the manufacturer, accompanied by detailed instructions regarding sampling procedures as well as measures to prevent subsequent contamination and moisture changes. All tests were carried out in accordance with the EN and JUS standards applicable at the time of testing.

Table 1 Physical properties of bypass dust [1]

Particle size distribution Cumulative passing through the sieve	1.0 mm	%	100
	0.71 mm	%	95.12
	0.25 mm	%	93.15
	0.09 mm	%	84.20
	0.063 mm	%	81.11
Bulk density (loose state)		kg/m^3	409
Particle density		kg/m^3	2395
Fineness		cm^2/g	8995
Rigden voids		%	58.1

Table 2 Chemical properties of bypass dust [1]

Loss on ignition (LOI)	%	18.48
SiO_2	%	13.50
CaO	%	52.64
MgO	%	1.91
Fe_2O_3	%	2.22
Al_2O_3	%	3.21
SO_3	%	1.94
NO	%	6.68
Cl	%	3.02
Na_2O	%	0.47
K_2O	%	2.58

The CKBD used in this study contains a relatively high chloride content (3.02%). However, the investigated material is primarily intended for use in pavement subbase layers, where it is not in direct contact with reinforced concrete elements. In typical road structures, separation layers and sufficient cover thickness significantly reduce the potential interaction between chloride-containing materials and reinforced concrete components such as culverts or drainage structures. Potential application in pavement base layers would require additional limitations regarding CKBD content, particularly in environments classified as aggressive according to BAS EN 206+A2:2022. The sulfate content of CKBD (SO_3 = 1.94%) should also be considered when evaluating its potential application. Sulfates present in cementitious systems may theoretically contribute to delayed ettringite formation and secondary swelling. However, during the curing and testing period conducted in this study, no indication of such behaviour was observed. On the contrary, the results demonstrated a significant reduction in swelling, indicating effective stabilization of the clayey soil structure. Nevertheless, the potential long-term influence of sulfate-related reactions should be further investigated in future studies.

4 Suitability for application in soil stabilization and pavement engineering

For the purpose of assessing the suitability for application in soil stabilization and pavement engineering, all investigations were divided into three main groups, within which mixtures were prepared according to different formulations:

- bypass dust as a standalone material for the construction of pavement subbase layers
- bypass dust as an additive to fly ash in proportions of 5%, 10%, 20% and 50% by total mass for the production of pavement subbase layers
- bypass dust as an additive to clayey soil in proportions of 5%, 10% and 20% by total mass, with the aim of stabilizing the soil and improving its geotechnical parameters.

4.1 Bypass dust as a standalone material in the construction of pavement subbase layers

The relatively high optimum moisture content of CKBD (27.3%) can be explained by the extremely fine particle size and large specific surface area of the material. Fine particles require additional water to achieve proper lubrication during compaction. Practical solutions include pre-wetting of the material or mixing within controlled systems to reduce dust emissions.

Table 3 Geomechanical proprerties of bypass dust [1]

Optimum moisture content		%	27.3
Dry bulk density		kg/m³	1385
Bulk density of compacted wet sample		kg/m³	1760
Compressive strength	7 d 28 d	MPa	1.51 3.52
Frost resistance (strength reduction compared to reference sample)		%	12.5
Swelling before CBR testing		mm	0.02
CBR	Wet mass > 7 d	%	16.5 59.5

4.2 Bypass dust as an additive to fly ash in the construction of pavement subbase layers

The test results indicate improved properties of fly ash when bypass dust is added, manifested by an increase in both compressive strength and the California Bearing Ratio (CBR). These findings can be associated with the well-known fact that the addition of bypass dust activates the pozzolanic behavior of fly ash. A higher dosage does not necessarily lead to better performance, as demonstrated in the study, where mixtures containing 20% bypass dust achieved superior results compared to those with 50%. It can therefore be concluded that, in this case, the optimal bypass dust content is 20% by total mass of the mixture. The fly ash material did not exhibit significant swelling prior to CBR testing, and the addition of bypass dust further contributed to its stability.

Table 4 Test results of fly ash mixtures with bypass dust addition [1]

			R-1 (CS)	R-2 (10%)	R-3 (20%)	R-4 (50%)
Optimum moisture content		%	28.2	28.1	28.0	27.7
Bulk density of compacted wet sample		kg/m³	1545	1586	1626	1645
Compressive strength	7 d 28 d	MPa	0.35 1.42	2.26 9.42	2.92 10.65	3.55 9.25
Swelling before CBR testing		mm	0.14	0.08	0.07	0.05
CBR	Wet mass › 7 d	%	12.2 27.5	16.4 75.4	19.0 92.9	24.5 88.6

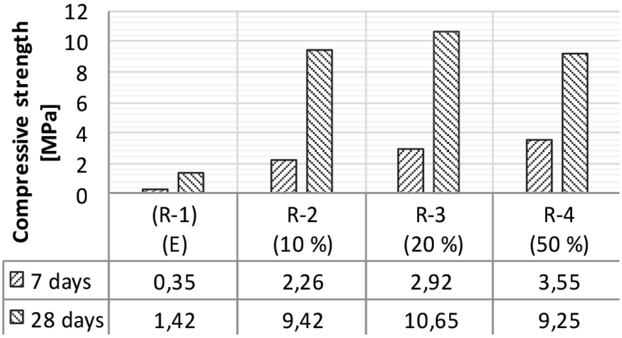

Figure 1 Comparative analysis of compressive strength of fly ash samples with bypass dust addition [1]

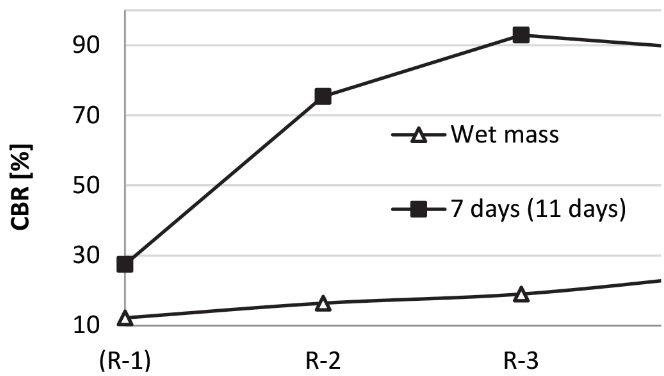

Figure 2 CBR values of Wet mass and 11-day specimens of fly ash mixtures with bypass dust addition [1]

4.3 Bypass dust as an additive to clayey soil for stabilization and improvement of geotechnical parameters

Analysis of the compressive strength test results revealed an increase in strength of the soil specimens with increasing bypass dust content. This increase was more pronounced at 28 days, where the mixture containing 20% bypass dust exhibited a strength gain of 75.3%, whereas a 28% increase was recorded at 7 days. This difference can be attributed to the ongoing hardening of bypass dust within the soil specimens, which, unlike the reference sample that does not gain strength over time, leads to a progressively larger strength differential. For clayey soil, however, the more relevant parameters are swelling and CBR values.

The swelling reduction trend line shows that the addition of bypass dust leads to a decrease in the swelling potential of the mixture. In particular, a 20% bypass dust dosage resulted in an 84.8% reduction in swelling. The tests also demonstrated that the addition of bypass dust improves the CBR values of specimens exposed to water. After water exposure, the CBR value of the plain soil sample decreased from 11.3% to 2.55%, whereas the mixtures containing bypass dust exhibited an increase in CBR and a simultaneous stabilization of the material.

Table 5 Test results of soil mixtures with bypass dust addition [1]

			R-1 (CS)	R-2 (5%)	R-3 (10%)	R-4 (20%)
Optimum moisture content		%	26.1	26.4	26.6	27.2
Bulk density of compacted wet sample		kg/m³	1896	1864	1850	1820
Compressive strength	7 d	MPa	0.75	0.81	0.87	0.96
	28 d		0.81	0.96	1.25	1.50
Swelling before CBR testing		mm	4.92	1.42	0.70	0.44
CBR	Wet mass	%	11.3	11.5	12.1	12.4
	› 7 d		2.55	10.1	16.2	22.7

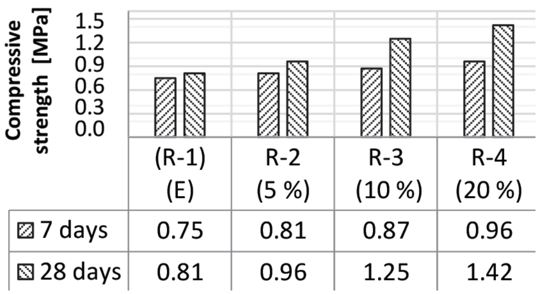

Figure 3 Compressive strength of soil specimens with bypass dust addition at 7 and 28 days of age [1]

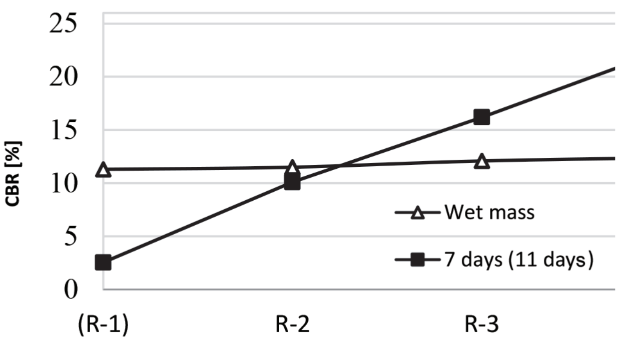

Figure 4 CBR values of soil specimens with bypass dust addition: Wet mass and after 7 days (11 days) curing [1]

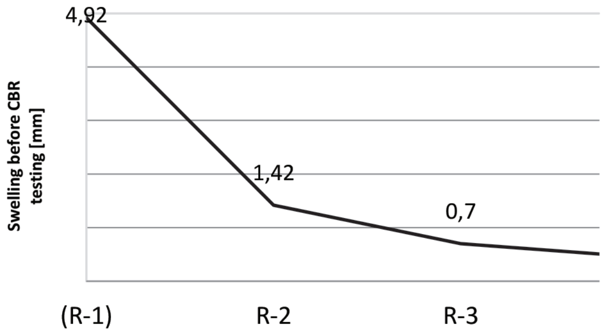

Figure 5 Swelling decline curve of clayey soil stabilized with bypass dust [1]

4.4 Direct water exposure test (24 h) on cured specimens

To evaluate the direct effect of water on the prepared specimens, they were immersed in water to a depth of 1–3 cm and observed over a 24-hour period. The test was conducted for specimens from all three investigation groups. Specimens composed entirely of bypass dust, fly ash mixtures containing 10%, 20%, and 50% bypass dust, as well as soil specimens with bypass dust addition, demonstrated stability under direct water exposure. While minor surface damage was observed, these specimens retained their original shape throughout the test duration. In contrast, specimens composed solely of fly ash exhibited partial disintegration upon immersion. The submerged lower portions of these specimens showed degradation, indicating insufficient resistance to direct water exposure, although some initial shape was partially preserved. Although visual inspection suggested stability in certain specimens, caution is warranted when interpreting these results. The satisfactory performance of a material under water exposure reflects a positive interaction among all constituent components, and it is not appropriate to generalize the effect of bypass dust on the water resistance of fly ash or soil when the base materials exhibit poor intrinsic properties. Furthermore, the long-term behavior of bypass dust mixtures under prolonged water exposure, particularly under mechanical load or repeated freeze–thaw cycles, remains uncharacterized.
Overall, it can be concluded that bypass dust does not adversely affect the water resistance of materials that already exhibit satisfactory stability. Environmental aspects such as leaching behaviour were not within the primary scope of this research, which focused mainly on the geotechnical and mechanical properties of CKBD-based mixtures. However, previous studies indicate that the strongly alkaline environment and cementitious reactions typical for cement kiln dust systems can significantly reduce the mobility of heavy metals by immobilization within hydration products. Consequently, the risk of heavy metal migration from stabilized mixtures is generally considered limited.

5 Conclusion

The following conclusions may be drawn:
- The tested bypass dust exhibits significant chemical potential for soil stabilization and application in pavement subbase layers, although chloride and alkali contents must be controlled depending on the intended use.
- Its high CaO content, together with silicate and aluminate components, promotes cementitious and pozzolanic reactions, substantially enhancing the bearing capacity and durability of stabilized soil layers.

- Treatment of fly ash and soil with bypass dust modifies their properties, rendering them suitable for standard-compliant performance and significantly improving their quality, making them applicable for the construction of pavement subbase layers.
- The addition of bypass dust improves the behavior of clayey soils, reducing swelling, increasing compressive strength, and stabilizing CBR values, particularly under water exposure conditions.
- Under controlled CKBD proportions, certain mixtures may also show potential for application in pavement base layers, although additional mechanical and durability testing would be required.

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References

[1] Institut za građevinarstvo, građevinske materijale i nemetale d.o.o. Tuzla (Institute for Civil Engineering, Building Materials and Non-Metallic Minerals, Tuzla, Study on the Possibility of Using Bypass Dust Generated in the Clinker Production Process at the Lukavac Cement Plant, document No. E-1024, June 2020.

[2] Taha, R., Al-Rawas, A., Al-Harthy, A., Al-Siyabi, H.: Use of cement by-pass dust in soil stabilization Department of Civil Engineering, Sultan Qaboos University Engineering Journal of the University of Qatar, 14 (2001), pp 61-76

[3] Badrawi, E.F., El-kady, S.M.: Stabilizing soft clay using geo-foam beads and cement bypass dust Structural Engineering Department, Faculty of Engineering, Zagazig University, Egypt Civil Engineering Department, Jouf University, Saudi Arabia

[4] Collins, R.J., Emery, J.J.: Kiln Dust-Fly Ash Systems for Highway Bases and Subbases Valley Forge Laboratories, Pennsylvania, USA September 1983., Report No. FHWA/RD-82/167

[5] Sreekrishnavilasam, A., Santagata, M.C.: Development of criteria for the utilization of cement kiln dust (ckd) in highway infrastructures, Joint Transportation Research Program, Project No. C-36-50Y, File No. 6-19-24 SPR-2784, School of Civil Engineering Purdue University, December 2006.