CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (3): 0362-0371
DOI: 10.59440/ceer/207706
Original Research Article

SHEAR STRENGTH OF WASTE LIMESTONE AGGREGATE FOR EMBANKMENT REINFORCEMENTS

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Abstract

The increasing demand for construction materials and the depletion of natural aggregates highlights the need for sustainable alternatives. This study investigates the feasibility of using lime waste, a byproduct of the Solvay process, as a material for embankment construction. The tested material was sourced from the JANIKSODA Production Plant landfill (CIECH Soda Polska S.A.) in Janikowo, Poland. A series of laboratory tests, including granulometric analysis, moisture content determination, and direct shear strength tests, were conducted using a Large-Scale Direct Shear Apparatus (WABS). The results indicate that the tested material has an internal friction angle of approximately 47° and a relative density index (I_d) between 0.65 and 0.85, confirming its suitability for use in embankment construction. These findings contribute to the development of sustainable geotechnical solutions by promoting the use of industrial waste as an alternative to natural aggregates. The study encourages further research and practical implementation of waste-based materials in construction, supporting environmentally friendly and durable earth structures.

Keywords: industrial waste material, lime waste, geotechnical engineering, direct shear test, embankment construction, sustainable materials, soil strength, alternative waste aggregates

1. INTRODUCTION

As the construction industry develops, the demand for aggregates continues to grow. Combined with limited natural resources and increasing environmental protection requirements, this may lead to aggregate shortages in the near future.

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According to analyses [1], the demand for construction aggregates in 2019 reached 51.7 billion tons and is projected to grow at an average annual rate of 5.2%. Currently, there are no indications that this trend will reverse.

The increasing environmental awareness and pursuit of sustainable development are driving the search for alternative solutions to natural aggregates. Growing attention is being given to recycling, reuse, and the application of industrial waste-derived materials as substitutes for traditional aggregates.

Unlike traditional industrial wastes such as slag or fly ash, waste limestone aggregate is an inert and nonhazardous by-product, which makes it a promising candidate for reuse in construction applications, including embankment fills, without posing significant environmental risks.

The most commonly used waste-derived mineral materials in geotechnics include fly ash from coal-fired power plants [2][3][4], blast furnace slag [5][6][7], stone dust [8][9][10], glass granules [11][12][13], and fly ash from biomass-fired boilers [14][15][16].

Limestone waste is one of the by-products of the Solvay process [17]. In simplified terms, this process involves the reaction of limestone ($CaCO_3$) with brine (NaCl) and ammonia (NH_3) to produce soda ash (Na_2CO_3) and ammonium chloride. During this reaction, carbon dioxide (CO_2) is also released as a gas. This process is widely used in the chemical industry for soda production. Although limestone waste is considered a by-product, it can often be successfully utilized in the construction industry.

The objective of this article is to analyze the feasibility of using limestone waste as a material for constructing embankment bodies of landfill containment structures (settling ponds). The study presents shear strength test results of the embankment fill material, allowing for an assessment of the technical and mechanical properties of limestone waste in comparison to traditional aggregates. The samples were subjected to direct shear tests following standardized procedures [18][19][20][21] using a large-scale Direct Shear Apparatus (WABS) as part of research [22] conducted for landfill monitoring purposes [23].

2. CASE STUDY

For the strength parameter tests, the material used for constructing the embankment body of the landfill containment structure (settling ponds) for non-hazardous waste was sourced from the JANIKSODA Production Plant in Janikowo, operated by CIECH Soda Polska S.A.

The site consists of a complex of several dozen settling ponds where lime sediments and industrial waste from the plant’s production process are stored, including post-soda sludges and ash pulp. The entire complex covers approximately 2.5 km² and is an embanked reservoir with internal dikes dividing it into individual ponds. The height of the external embankments ranges from 16 to 19 meters. The filling level of the reservoirs varies during their operational period, with a designated height reserve of 0.5 meters (the crest of the dike is 0.5 meters above the sediment level).

The slopes of individual pond dikes also vary in inclination, with the slope angles for the entire complex ranging between approximately 33° and 45° [23].

Fig. 1. View of the Waste Landfill at the JANIKSODA Production Plant in Janikowo, CIECH Soda Polska S.A.

Fig. 2. View of the Waste Landfill Embankment Structure: a – view from the crest, b – view from the external side

3. MATERIALS

The tested material was classified as an anthropogenic soil, formed as a by-product of the Solvay process [17]. It is a lime sediment that results from certain side reactions when, for example, not all the limestone is fully consumed in soda production. Limestone waste contains various calcium compounds, such as calcium oxide (CaO) and some insoluble calcium hydroxides. It may also contain residual undissolved brine and ammonia.

The material was collected from the dam's crest. Manual excavations were performed at three locations to a depth of approximately 1.0 m, after which the aggregate was packed into ~25 kg bags, facilitating its transport to the laboratory. In total, approximately 0.5 tons of aggregate was delivered for testing in several dozen bags.

Macroscopic analysis in the laboratory revealed heterogeneity of the aggregate across the individual bags submitted for testing. Slight differences in aggregate moisture content were also observed. Additionally, variations in the shape of coarse fraction grains were noted. The most distinct grain shapes are presented in Fig. 3a (more rounded) and Fig. 3b (more angular).

A site inspection during sample collection indicated that the material in the excavations appeared macroscopically homogeneous. However, some fractionation of the material occurred due to the sampling method. During production, the by-product may exhibit variations in grain size between different batches. It is deposited in stockpiles, from which it is partially mixed before being used for embankment construction. This could also explain the slight differences in grain shape observed in samples taken from different locations.

Before shear strength testing, the entire batch of aggregate was mixed and homogenized. The appearance of the homogenized aggregate is shown in Fig. 3c.

Fig. 3. a, b – characteristic samples differing in aggregate grain shape, c – homogenized aggregate sample for testing in a shear box apparatus

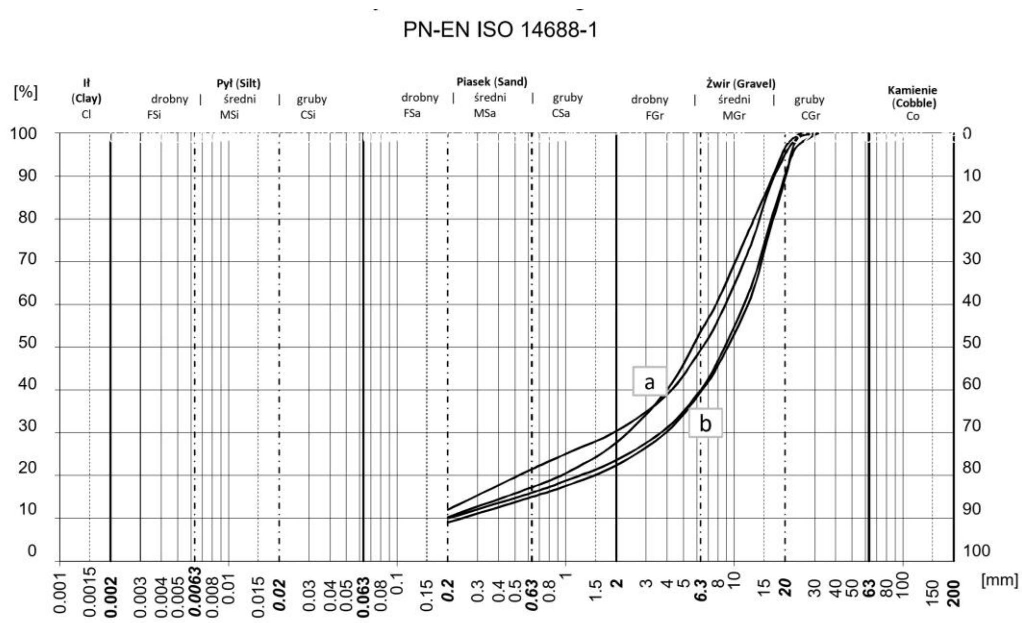

Fig. 4. Grain Size Distribution Curves of the Tested Material: a – aggregate from different batches of the supplied material, b – homogenized aggregate

Sieve analyses were also performed for a randomly selected bag, for the homogenized material, and for two samples taken after two shear tests. The grain size distribution curves are shown in Fig. 4.

Based on the analysis of the grain size distribution graphs, it can be concluded that the aggregate is highly well-graded and easily compactable.

Additionally, tests of basic physical properties were conducted, including soil moisture content (w), bulk density (ρ), and dry density of the soil skeleton (ρ_d). The results are summarized in Table 1.

Table 1. Summary of the measured physical properties of the tested aggregate

Soil moisture	Bulk density of soil	Bulk density of the soil skeleton
w	ρ	ρ_d
[%]	[g/cm^3]	[g/cm^3]
3,5 ÷ 4,0	1,64 ÷ 1,69	1,57 ÷ 1,63

4. METHODS

4.1 Laboratory test stand

The tests were conducted using a Large-Scale Direct Shear Apparatus (WABS), a proprietary design, which is part of the Soil Mechanics Laboratory at the Department of Geotechnics and Engineering Geology, Poznań University of Technology. This test stand is designed for shear strength testing of coarse-grained soils. A view of the test stand is shown in Figure 5.

Test Stand Specifications:

- shear box dimensions: 100 (120) × 100 × 48 cm,
- loadable volume: approximately 0.45 (0.54) m^3,
- constant shear rate continuously adjustable from 0.2 to 2 mm/min,
- maximum horizontal force (H): 250 kN,,
- maximum vertical force (N): up to 300 kN (practically limited by the resultant horizontal force H),
- measurement instrumentation includes a GEODATALOG module with peripheral transducers: strain gauge force transducers (class 0.5) and potentiometric displacement transducers with ± 0.002 mm accuracy.

Fig. 5. View of the WABS Test Stand, Testing Position: 1 – Testing chamber, 2 – Test stand drive system, 3 – Schenck press actuator for applying vertical loads, 4 – Test process control station, 4a – GEODATALOG for processing sensor signals, 4b – Schenck press controller, 4c – Test stand drive controller (lead screw) [22]

4.2 Test program

As part of the study, six shear tests were conducted in two experiments for three different normal stress values: σ_n = 28, 53, and 103 kPa. These stress levels were determined as the sum of the pressure from the self-weight of the upper loading plate of the apparatus and additional pressure, which was controlled and maintained at a constant level throughout the test by the programmed hydraulic system of the Schenck press.

The Large-Scale Direct Shear Apparatus (WABS) is the largest laboratory device of its kind in Poland and requires specialized procedures. A single shear test involved the following steps:

- Filling the shear box. The apparatus box was filled by layering pre-weighed portions of aggregate (approximately 20–30 kg per layer) from a small drop height. To maintain consistent moisture content across all shear tests, each layer (about 10 cm thick) was lightly sprayed with ~0.5 L of water and mixed. In total, ~2.5 L of water was used per test, which also helped reduce dust emissions. The box was filled to the upper edges, and the aggregate surface was leveled before being covered with the loading plate.
- Compaction. The test chamber was vibrated using electrovibrators to compact the aggregate. This was performed in 5–6 cycles, with settlement of the loading plate measured after each cycle. The compaction process continued until the required density was achieved.

- Application of vertical loads and shear testing. Once the box was positioned for testing, the designated vertical loads were applied for each shear cycle. After the sample stabilized and settled under the applied load, the shear test was initiated.
- Post-test procedures. After the shear process was completed, the box was moved back to the loading/unloading position. The sample was unloaded, and in most cases, a moisture content sample was taken from the shear zone in the center of the specimen.

5. RESULTS AND DISCUSSION

The shear test results for the analyzed mixtures are summarized in Fig. 6. All designations were made in accordance with the applicable procedures [18][19][20][24], modified to accommodate the large-scale apparatus (section 4.2) based on previous research experience [24].

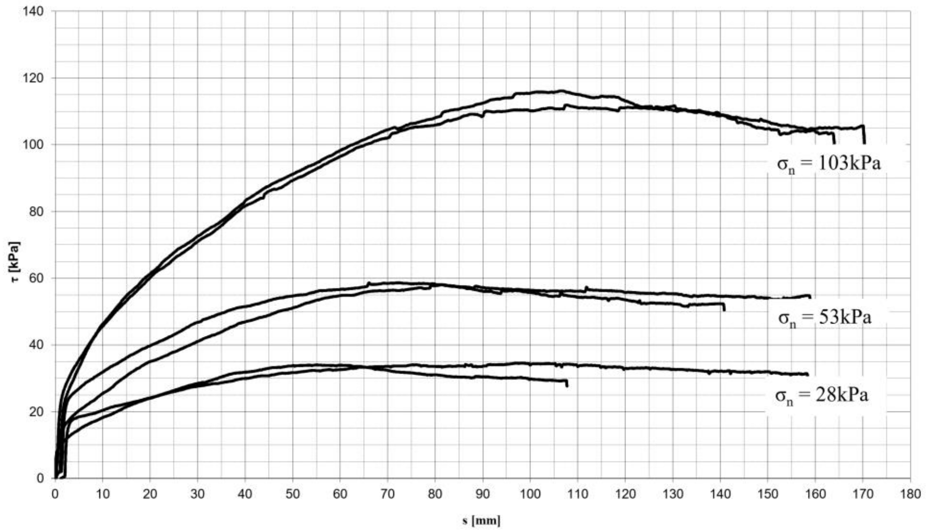

Fig. 6. Compilation of soil shear test graphs for different normal stress levels

To determine the shear strength parameters ϕ and c, Coulomb failure envelopes were derived using linear regression, both with and without the constraint of passing through the origin (0,0) in the (τ_f-σ_n) coordinate system. The obtained shear strength of the soil is presented in Figure 7.

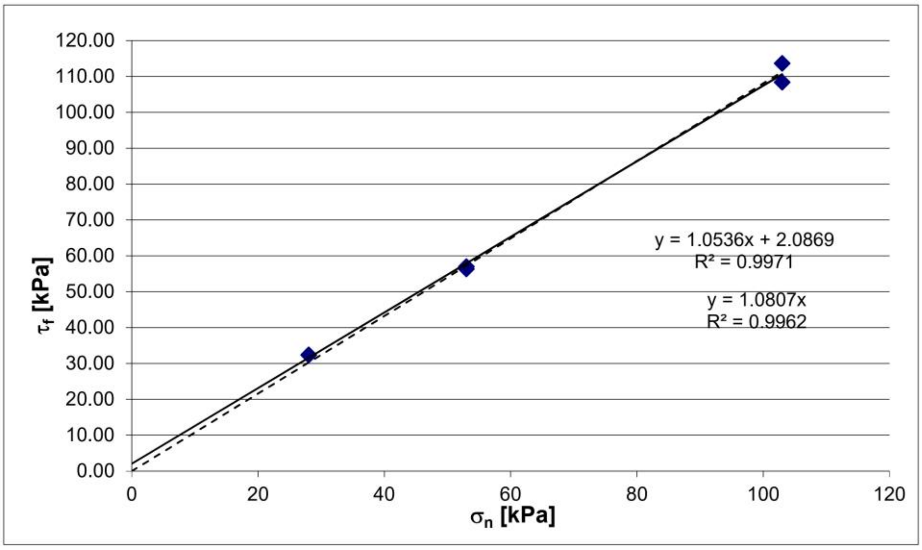

Fig. 7. Shear strength graph of the soil.

The values of the internal friction angle (ϕ) and cohesion (c) are ϕ = 46.51° and c = 2.09 kPa, respectively. However, when the shear strength envelope is forced to pass through the origin of the coordinate system, the internal friction angle is ϕ = 47.23°

Considering the intended use of the test results in the design (stability analysis) of embankments for a waste disposal site, the derived geotechnical parameters must be conservatively estimated in accordance with Eurocode 7. Therefore, the characteristic value of the internal friction angle is taken as ϕ = 46.51°, and the cohesion is assumed to be c = 0.0 kPa.

6. CONCLUSIONS

The obtained strength parameters of the tested lime waste material - an internal friction angle of approximately 47° and a relative density (I_d) ranging from 0.65 to 0.85 - confirm its suitability for embankment construction.

The results and conclusions from this study contribute valuable insights into the development of sustainable solutions in geotechnical engineering, promoting the reduction of natural aggregate consumption and encouraging the use of eco-friendly, yet durable, earth structures.

An additional objective of this article is to encourage further research and the practical implementation of waste aggregate materials in geotechnical applications. However, the study also acknowledges certain limitations, such as the need to assess the long-term chemical stability of the material and its potential sensitivity to water. In the longer term, after conducting additional tests such as chemical analyses (e.g. the effect of CaO and potential reactions with water), durability over time, determination of Cu and Cc coefficients, and Proctor tests (optimum moisture content and dry density), it will be possible to assess the potential use of this aggregate in road and railway embankment construction.

ADDITIONAL INFORMATION

Any additional information about e.g. the source of finance, acknowledgements of help with the figures, etc. should be included here.

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