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Characterization and management of waste stone dust – a case study

Biljana Kovačević Zelić
Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia, bkzelic@rgn.hr

Mirela Burečić Šafran
Zagreb University of Applied Sciences, Zagreb, Croatia

Petar Hrženjak
Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia

Luka Tomac
Kamen d.d., Pazin, Croatia

ABSTRACT: A thick-bedded biomicritic limestone, known commercially as *Giallo d'Istria*, is exploited on several locations on the Istrian peninsula. The long-established production of dimension stone in this area generates considerable amounts of stone waste. One stream of stone dust is produced during the extraction of dimension stone in quarries or underground mines. The other stream is the product of stone processing plants. Both streams are accumulated within the active mine as deposits on the surface and represent an environmental and financial burden for the company, especially due to the fact that the mine operates in one of the most famous tourist regions of the Republic of Croatia. The average annual production of commercially valuable natural stone is 38000 cubic meters of blocks per year. Due to the specific natural geological setting and exploitation method, the losses in the production and processing phase are also inevitable, giving an average amount of 9000 cubic meters of stone waste per year. This research involved determination of physical, index and design properties of waste stone dust. Waste stone dust is classified according to the unified soil classification system and also according to the tailings classification system, as the natural mineral raw material is exposed to the changes of its properties during exploitation and afterwards processing. Design parameters are also determined for the safety analyses of waste spoil heaps and for the evaluation of the waste stone dust potential use as the backfill material.

KEYWORDS: mining waste, stone dust, characterization, classification, compaction, shear strength.

1 INTRODUCTION

Soil stabilization is an important technique in geotechnical engineering to improve the physical and mechanical behaviour of natural soils. While conventional approaches rely on chemical binders such as lime or cement, the increasing generation of industrial and mineral waste encourages search for alternative, sustainable materials. Among these by-products, waste stone dust, produced during exploitation and processing of limestone aggregates, has become more interesting due to its availability, mineralogical stability, and environmental footprint.

In regions with dominant carbonate lithology, such as the Istrian peninsula in Croatia, large volumes of limestone powder are produced as a by-product of quarrying operations. This material, commonly referred to as stone dust, is typically deposited untreated within the quarry area, without systematic waste management. However, its fine granulometry, high calcite content (Coletti et al. 2005) makes it a suitable and environmentally friendly material for improving soil properties, as well as a potential replacement for natural aggregates in concrete and for producing building materials such as bricks, tiles, and paving blocks.

Recent studies have shown that the inclusion of stone dust in clayey soils can substantially increase their geotechnical performance. Laboratory studies indicate reductions in the plasticity index and swelling potential, increases in unconfined compressive strength (UCS), dry unit weight, and California Bearing Ratio (CBR), a reduction in the optimum moisture content and an increase in dry density (compaction test).

According to Pastor et al. (2019), the addition of 15–25% limestone powder to expansive clay enhanced strength and stability parameters. Similarly, Dekpoghole et al. (2019) reported that adding stone dust improved compaction behaviour, Atterberg limits, and bearing capacity, which suggests that the material is suitable for use in pavement subgrade construction.

Sivrikaya et al. (2014) tested bentonite and kaolinite-based clays mixed with stone powder from calcitic marble, dolomitic marble and granite powder, and showed that the treated soils had reduced plasticity, decreased optimum moisture content (OMC) and increased maximum dry density (MDD).

Besides its use in soil stabilization, waste stone powder has been considered as a functional additive in various construction materials. Due to its mineralogical consistency and fineness, it has been incorporated into asphalt concrete mixes and grouting formulations, demonstrating improvements in mechanical performance and durability (Hasita et al. 2020; Liu et al. 2022). The general availability of this by-product, particularly in countries with active natural stone industries, justifies its application in wider construction contexts beyond geotechnical engineering.

The applicability of the material has also been extended to concrete technology where stone dust is used as a partial replacement for natural sand. Silva et al. (2023) showed that substitution rates of 30–50% can improve compressive and flexural strength as well as resistance to surface abrasion, although with some reduction in workability due to particle fineness and angularity.

Likewise, field-scale applications, such as the test embankment constructed by Pastor et al. (2025), confirmed that sections built with limestone powder resulted in increased stiffness and reduced deformability compared to those made with natural untreated clay. These findings indicate that stone dust may serve not only as a soil stabilizer, but also as a structural fill material in infrastructure projects.

The overall body of research from past studies points to the conclusion that stone dust not only provide engineering advantages when blended with clayey soils, but also represents a promising solution for reducing the environmental footprint of quarry operations. Improvements in geotechnical parameters have been consistently reported, supporting its role as a sustainable material for infrastructure development, particularly in earthen road construction.

In this context, this study has two main objectives. First, it focuses on the characterization of stone dust from one underground quarry on the Istrian peninsula in Croatia, in order to determine its physical, index and engineering properties relevant to geotechnical applications. Second, the study aims to investigate the effects of adding terra rossa, a clay-rich residual soil commonly developed over limestone or dolomite bedrock in Mediterranean regions, to stone dust in varying percentages, on the compactability and shear strength of their mixtures.

So far, research has been done on the utilization of calcitic stone dust for agricultural purposes. It has been shown that waste stone dust from that specific quarry could be used as inorganic fertilizer, i.e. for the increase of pH of naturally acidic soil types.

This study was initiated because certain problems regarding stability, wind and water erosion were observed at waste stone dust deposits, alongside landscape disturbances and visual impacts. This is particularly important for the Istrian peninsula as it represents one of the most significant tourist regions in Croatia. Therefore, it would be beneficial for the company to find practical solutions for the reuse and better management of waste stone dust.

2 MATERIALS AND TESTS

2.1 *Origin of materials*

On the Croatian peninsula of Istria, the natural stone known under the commercial name *Giallo d'Istria* (*Istrain yellow*) is extracted at several deposits. The stone is a Lower Cretaceous thick-bedded biomicritic limestone, and the deposit in the Kanfanar quarry is characterized by a large overburden (up to 25 m).

Due to weathering processes the surface parts of the deposit are characterized by open cracks (pockets) filled with the clayey soil materials, i.e. terra rossa (Fig. 1).

Figure 1. Terra rossa pockets.

Substantial quantities of waste have been generated by the long history of dimension stone production on the Istrian peninsula. One stream of stone dust is generated during dimension stone exploration, either in quarries or underground mines. The other stream is the product of the stone processing plant. Both streams are accumulated within the active mine as surface deposits (Fig. 2) causing environmental and financial issues for the company.

Figure 2. Stone dust deposit.

Stone dust and natural soil samples (terra rossa) were collected from the Kanfanar quarry owned by the company Kamen d.d. Pazin, and used for the preparation of laboratory specimens of mixed samples with various ratios of components.

2.2 *Testing program*

It was already mentioned in the introduction that mineral waste deposits can have negative impacts on the environment. In case of inert rock waste materials such as stone dust, these impacts are mainly related to the land disturbance, geotechnical instabilities of waste stockpiles (settlements and slope failures), and wind or water erosion. In the Kanfanar quarry, 9000 cubic meters of stone dust is produced each year, which is currently deposited near the processing plant waiting for the final solution, i.e. reuse or safe disposal. The purpose of this research was therefore twofold:

- characterization and classification of waste stone dust,
- investigation of the effects of addition of the locally available clayey soil (terra rossa) to stone dust in varying proportions, on the compactability and shear strength of mixtures.

Table 1. Laboratory specimen specification.

Symbol	Stone dust (%)	Natural soil (%)
A	0	100
B	25	75
C	50	50
D	75	25
E	100	0

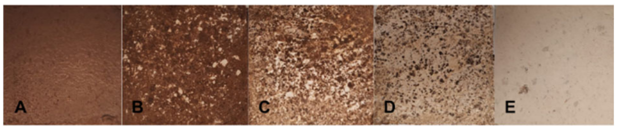

Figure 3. Testing specimens.

Testing was performed on the specimens of the natural soil material (terra rossa), waste stone dust and their mixtures as represented in Table 1 and Figure 3, and consisted of testing physical and index properties, compaction, and shear strength.

3 TEST RESULTS

3.1 *Physical and index properties*

Sieve analysis and hydrometer tests were performed in accordance with ASTM D422-63 (2007). Atterberg limits were determined in accordance with ASTM D 4318-00 (2000). Classification was performed by the standard practice for classification of soils ASTM D 2487-00 (2013) and by the classification practice for tailings (International Commission on Large Dams, 2023.).

Tailings can sometimes have similar properties to natural soil. However, due to various beneficiation processes, tailings properties may also substantially differ to natural soil properties. Figure 4 shows the relationship between the USCS classification of soils and the tailings classification based on grain-size distribution. Natural soil (terra rossa) contained more than 98%, while stone dust contained approximately 96% of particles smaller than 0.075 mm. Experimental curves obtained for the specimens of stone dust, natural clay and their mixtures (Table 1) belong to the fines (ASTM) and to the slimes (ICOLD). Figure 5 shows the relationship between soil and tailings classification based on plasticity. Again, experimental results are shown for five specimens (Table 1). It can be seen from the figure that stone dust belongs to the group of silts of low plasticity (ML), natural clay belongs to the group of clays of high plasticity (CH), and their mixtures belong to the group of clays mainly of low plasticity (CL). Plasticity of mixtures decreases as the stone dust content increases.

Looking at the tailings classification, stone dust and mixtures with natural clay overlap with both altered rock tailings (ART) and fine tailings (FT) groups based on grain size distribution (Fig. 4). Classification of samples based on plasticity shows that stone dust belongs to the group of altered rock tailings (ART), while the mixtures with natural clay belong to the groups ART or FT as the natural clay content increases (Table 1).

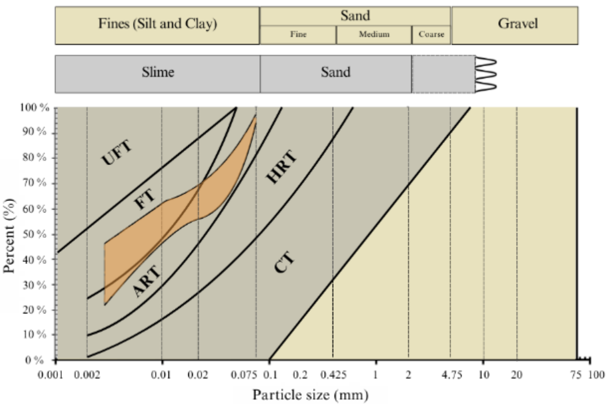

Figure 4. Classification by grain-size distribution.

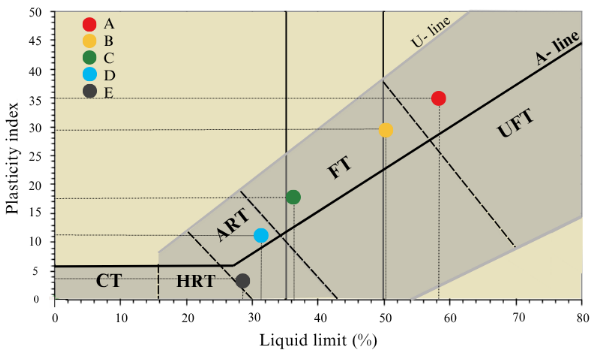

Figure 5. Classification by plasticity.

ICOLD (2023) also contains the comparison between tailings and natural soils. Altered rock tailings (ART) are described to be similar to sandy silt, with traces of clay, possessing low plasticity. Fine tailings (FT) are described as silt with traces of clay, exhibiting low to moderate plasticity.

3.2 *Compaction*

The compaction characteristics of specimens were assessed by ASTM D 698-12 (2021) testing procedure using standard compactive effort. Dry density is plotted against moisture content for stone dust, terra rossa and mixed specimens in Figure 6.

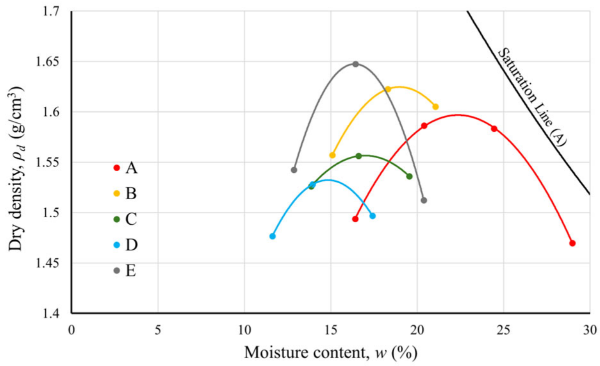

Figure 6. Compaction curves.

As expected, the stone dust specimen (mark E) resembles silt-like behaviour, while the terra rossa specimen (mark A) shows clay-like behaviour, which means that stone dust exhibits higher MDD and lower OMC than terra rossa. Dry density-moisture content curves for mixed samples (marks B, C and D) are positioned between the curves for pure stone dust and terra rossa specimens. Moreover, as the clay content increases in mixed samples, the OMC and MDD increase as well.

3.3 *Shear strength*

Direct shear testing was performed according to ASTM D3080 (2023). Testing specimens were prepared by compaction using standard effort, i.e. to the OMC and MDD. Testing was performed for the normal stress range from 50 to 200 kPa, consolidation of two days and a shearing rate of 0.05 mm/min.

Test results are interpreted by Mohr-Coulomb's failure criteria (Fig. 7). Pure stone dust (mark E) exhibits cohesionless behaviour and the largest friction angle. On the other hand, pure terra rossa specimen (mark A) shows the largest cohesion (typical for compacted clays of high plasticity) and the smallest friction angle. For the mixed samples (marks B, C and D), a continuous decrease of friction angle and an increase of cohesion are observed for the increased clay content.

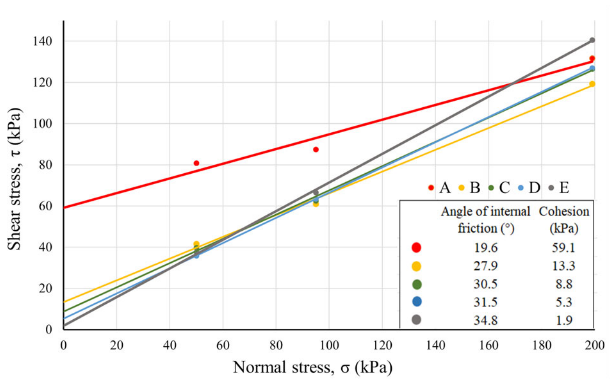

Figure 7. Direct shear test results.

4 CONCLUSIONS

In this study, waste stone dust, terra rossa and mixed samples were tested and classified according to the USCS classification system and the tailings classification system. Waste stone dust is classified as silt of low plasticity (ML), terra rossa as clay of high plasticity (CH) and their mixtures as clays of low plasticity (CL) by the USCS classification system. Using the tailings classification, waste stone dust is classified as altered rock tailings (ART). By adding 25 to 75% (by mass) of natural clay materials to waste stone dust, the resulting mixtures are classified as altered rock tailings (ART) or fine tailings (FT). Both systems recognize that by adding natural clay into the waste stone dust the plasticity of their mixtures gradually increases. However, the tailings classification describes these mixtures (both ART and FT groups) as silt-like, while the USCS classification groups all mixtures to clayey types of materials. It should be noted that, although the same testing methods are used for the determination of properties relevant for classification, a different logic is followed for the classification of various tailings materials into groups, e.g. A-line does not divide plastic from non-plastic or cohesive from non-cohesive materials. This can be justified by the fact that, although coming from the same parent rock materials, natural soils and tailings are products of disintegration processes that differ considerably. Natural soils are products of very slow geological processes, while tailings represent the final product of industrial processing procedures performed rapidly, causing changes to physical, chemical and mineralogical properties compared to the parent natural rock materials (Kovačević Zelić et al. 2025).

Compaction test and direct shear test results are compatible with the results of physical and index properties. The obtained compaction curves show that mixtures of stone dust with natural clay materials can be optimized and that compaction can successfully be performed on waste rock deposit sites. When natural clay material (CH) is added into mixtures with stone dust, it causes change from silt-like to clay-like engineering behaviour, and a gradual increase of plasticity by an increase of clay content. The original stone dust was almost non-plastic, although the content of clay-sized particles was more than 50%. For the mixed samples, a continuous decrease of friction angle and an increase of cohesion are observed for the increased clay content.

The next step of the research will be directed at the proposal and design of the waste stone dust deposit layout (maximum height, slope angle, stone dust/clay mixture ratio) at the Kanfanar quarry in order to obtain stable, erosion free and vegetation suitable geometry of the deposit by the use of locally available materials. Laboratory test results obtained thus far are promising. Further research on the erodibility of the waste rock dust mixtures in the laboratory and in-situ has yet to be conducted. The final desirable outcome for the company would be to minimize negative impacts on the landscape, to improve the reputation of the company in the local community and to reconcile the interests of the mining industry with the region's leading tourism sector, alongside which it coexists.

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