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Posted Date: 20 October 2023

doi: 10.20944/preprints202310.1219.v1

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Recycling of Industrial Waste as Soil Binding Additives—Effects on Soil Mechanical and Hydraulic Properties during Its Stabilisation Prior to Road Construction

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Abstract: In road construction, before applying an asphalt or concrete surface, the ground must be compacted and stabilized. There are two basic methods of soil stabilization: in situ and in a stationary node (ex-situ). The method of performing stabilization in place (in-situ) is the most frequently used method due to its convenience and lower price. The most popular type of binder for stabilization is a hydraulic binder (most often cement and various ashes). Such stabilization is performed at a depth of 10-50 cm, achieving the desired load-bearing parameters. In order to improve them, various chemical additives for stabilization are often used, such as ion exchange compounds, additives based on sulfuric acid, additives based on vinyl polymers or even organic additives using lignosulfonates. However, the use of such additives is associated with much greater costs and environmental burden, resulting in seeking for cheaper and equally effective alternatives. The win-win situation would be for instance recycling the problematic waste-based materials that on one hand are landfilled or impossible to recycle and on the other hand cause problems for the waste producers. Therefore, an interesting issue is the production of stabilization additives from various types of waste materials. As a result of the extensive testing of various waste-based materials blends with soil, the mechanical (compressive strength after 7 and 28 days) and hydraulic (capillary rise, water absorption, frost resistance) soil properties were measured. The optimization process led to obtaining additives compositions ensuring the best strengthening and sealing properties. These were for sandy soil: Pure foil (wax emulsion), Pure foil (wax emulsion) + waste sulphuric acid, RDF from waste tires (wax emulsion), Pure foil (wax emulsion) + "by-pass" waste ash + NaOHx2 and for clayey soil: Pure foil (wax emulsion) + NaOH, Pure foil (wax emulsion) + waste sulphuric acid, Tequant, Pure foil (wax emulsion).

Keywords: road construction; soil stabilization; soil binders; soil compressive strength; soil capillary forces; frost resistance; waste additives; industrial waste; pyrolytic wax; emulsions

1. Introduction

Soil stabilization is a very common process for almost all road projects. All types of soil stabilization can be divided into two basic groups of groups, i.e., mechanical stabilization and chemical stabilization. In mechanical stabilization, the classification of the soil is changed by mixing it with other types of soils of different classes. This way, a compacted soil mass can be obtained. Chemical stabilization, on the other hand, involves modifying soil properties by adding chemically active materials [1]. in the following article, we will focus on chemical stabilization using waste

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materials. The use of waste as a building material or soil stabilization is a new area in the construction industry [2].

Modification of native soils during road construction (if the soil does not meet the requirements of frost resistance, bearing capacity, etc.) with waste that does not have a negative impact on the ecosystem provides positive benefits for the environment. On the one hand, the extraction of natural resources is limited, which reduces the environmental degradation of the place where these aggregates are obtained. On the other hand, the use of waste materials allows them to give them functional properties and obtain the desired effects and soil properties, while reducing the amount of landfilling [3].

Classic stabilizers that chemically affect the mother soil and strengthen it are lime, cement, bitumen, fly ash and other such admixtures [4,5]. Of all the soil stabilization techniques, improvement by adding cement and lime is one of the most widespread and widely studied in recent decades. Research on the stabilization of calcareous and cement soils has resulted in comprehensive theoretical knowledge on the mechanisms of stabilization for many years. In addition, the effectiveness of stabilization of calcareous and cement soils has been investigated and confirmed by many authors [6–12].

Another way to improve soil cohesiveness parameters can be the addition of a hydrophobic agent. Hydrophilizing anionic chemical solutions that are currently available on the market give unsatisfactory results because they do not change the hydrophilic character of the soil. This is because the anionic components of these substances are not attracted to the negatively charged minerals contained in the soil [13].

Many studies also show that plastic waste serves to improve the parameters of the native soil. Combining them with the soil showed some improvement in terms of soil strength, but even so, the potential of this waste has not been fully assessed for the different types and forms of plastic waste with natural soil substrate in the road industry [14–17].

The geotechnical and mechanical properties of soils stabilized with waste, such as biomass ash from electricity generation, along with small amounts of silica-based nanotechnology stabilizers, are being studied. The results obtained suggest a potential reduction in the use of traditional binders by incorporating by-products, while maintaining soil properties, and even improving properties through the use of nanosized additives. [18], Mohamed E. Sultan et al. have shown that the use of cement bypass flue gas with alkali activation results in a cementitious material with good mechanical properties [19]. Recently, various polysaccharide-based biopolymers have been used to improve the hydromechanical properties of soils. Xanthan gum, starch, chitosan, cottage cheese, glucan, agar gum, gellan gum, guar gum, and sodium alginate are conventional biopolymers in geotechnical engineering [19–21].

The research of Zezhuo Song et al. shows that polyol prepolymer can effectively improve the mechanical properties of clay soil. The existence of lattice membrane structures induced by polyol prepolymer/water reactions linked soil particles together, which significantly improved the cohesion of clay soil, and the angle of internal friction was maintained at a relatively stable level. [21], Waciński et al. in their patent application no. P.438697 also described a dust-based hydraulic binder with sodium hydroxide activated bypass [22]. The use of alkaline materials allows geopolymers to be formed by creating a three-dimensional network of interconnected molecules resembling conventional mineral binders [23].

Bauxite is a typical alkaline waste used in the stabilization process. Many authors have explored the possibility of its application in this process [24–27]. Alzanova et al. showed that the alkaline properties of bauxite residues decrease with increasing duration after use: cation convertibility and sodium exchange capacity decrease with increasing time after removal. [26]. In addition to stabilising the soil, bauxite also has properties that stabilise heavy metal and fluorine pollution [28].

Another stabilization approach is soil hydrophobic (so-called artificial hydrophobic soils), which are new geomaterials with great potential for engineering applications due to their low affinity for water. For saline soils, hydrophilization of such soils can mitigate soil salinization and subsequent

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engineering disasters such as salt expansion and chloride corrosion. Hydrophobic agents such as organosilanes, fatty acids, and waxes are commonly used to induce soil hydrophobicity [29–32].

Compared to natural sands, wax-coated sands are hydrophobic and exhibit excellent, although not yet fully understood, mechanical and hydraulic properties. Baret et al. showed that laboratory test results show that a wax content of up to 6% can triple the permeability and double the compressibility. These models show that the increase in permeability is related to the aggregation of smaller sand particles due to the stickiness of the wax, which generates larger gaps. Smaller particles attach to other particles and make the sand thicker. The wax coating also softens the contact between the sand particles and makes the wax-coated sand more compressible [32].

Through current study the authors investigated more than 600 test scenarios of using waste-derived materials for improving soil mechanical (compressive strength) and hydraulic (capillary rise, water absorption, frost resistance) properties in clay and sand. The novelty here is focused on seeking for an optimal scenario for:

1. Best strengthening soil stabilizing additives
2. Best sealing soil stabilizing additives
3. Best strengthening and sealing soil stabilizing additives
4. Utilization of waste materials in a safe manner without a pollution risk to the environment

2. Materials and Methods

The aim of the research was to develop the most optimal recipe supporting the stabilization of both cohesive and non-cohesive soils, which is an addition to the traditional hydraulic binder (BV cement). The main idea was to use waste materials to create recipes, especially those for which no alternative use has yet been found.

In accordance with the assumptions adopted above, the tests were carried out for 5% cement content in relation to the soil mass. Each time 8 kg of soil has been used. To obtain greater reliability, each type of soil was sampled from the same source before each test.

2.1. Materials—Commercial soil stabilizing additives

The benchmark for examining alternative stabilization additives was to compare them with those available on the market. Before starting the first tests, several weeks of extensive market research was carried out on all available soil stabilization additives. Starting from studying all available materials (scientific publications, industry texts, advertising campaigns or a thorough search of websites), through contacting in order to receive a quote, ending with obtaining samples, an extensive database of such additives was created. Due to the low availability of such agents on the Polish market, most contacts were established with foreign producers and distributors (USA, Russia, China, India, Ukraine, Lithuania, Norway, Germany, Switzerland, Great Britain, the Netherlands, South Africa).

Below is a list of all stabilization additives found. Additionally, all received samples of additives were tested.

- Tested additives: Geosta K-1, PAS 500-01, Dustex, ETONIS 1400, UPD acid, ProRoad NE, ProRoad Waterproof, Synexil, Terrasolid, Chinese additives from SHANDONG WELLDONE ENVIRONMENTAL NEW MATERIALS, resin additives from Russia and example emulgators Tequat, ROKAmin
- Untested additives: StabilGrunt, NICOFLOK, BASE-SEAL BS-100, Perma-Zyme 11x, GRT9000, MidWest, Soilworks, CONSOLID, Envirotac AW, TerraSil, Statut-3, Sealcoat, ANT, RRP-235-Spezial, Dorzin (Roadzyme), Perenium, Rovene (4045, 6126), Soil Stabilization Plus (MC Polymers), ECOroads, System SOIL, RBI Grade 81.

 doi:10.20944/preprints202310.1219.v1

2.2. Materials—waste derived additives

As a result of the project, the team accessed various types of waste to be tested as potential substitutes of commercial soil stabilization additives. Many of the wastes turned out to have a positive impact not only on the strength but also on the sealing of the stabilized soil. The waste was obtained from various industries, e.g. the food industry, ceramics industry, chemical industry, cosmetics industry, energy sector, municipal waste processing plants, etc.

2.3. Mixtures preparation

Before starting the research, a detailed scenario was developed regarding the tested additive and its amount. For each scenario, a separate amount of soil (cohesive or non-cohesive) was measured using a scale, depending on the required number of samples. Measured amounts of soil, cement and additive were taken to the mixer where they were placed in the following order: soil, cement, water, additive. Mixing took no less than 5 minutes to obtain a homogeneous consistency. The mixture was then removed from the mixer and delivered to the compactor.

2.4. Samples preparation for mechanical tests

After preparing the mixture, it was transferred to the next station and placed in molds where it was then compacted in an automatic compactor in three cycles of 25 blows in accordance with the PN-EN 13286-50 standard. The completed samples were placed in foil to retain moisture, and after 24 hours they were removed from the mold and weighed. Then, all samples were placed in containers with moist sand for further care.

2.5. Compressive strength test

The compressive strength test was carried out on an automatic hydraulic press in accordance with the PN-EN 13286-50 standard. In accordance with the adopted assumptions, samples were tested for durability after 7 or 28 days of care. At least 3 samples were used to conduct the strength test. The press results were given in kN. This result was written down and then converted into MPa. The area of the base of the sample is 25π cm2 ≈ 78.5 cm2 = 0.00785 m2. To convert kN/m2 to MPa, the formula 1 kN/m2 = 0.001 MPa was used, i.e., for example, 1 kN of pressure on the sample corresponds to approximately 0.127 MPa. The final result for each additive was always the average obtained from each sample.

2.6. Capillary rise test

Soil hydraulic properties denote the potential of the additive-amended soil to prevent water penetration (1) from the bottom upwards by means of capillary forces and (2) from the surroundings inwards during total immersion. The sealing properties of the mixtures was tested using proprietary tests developed by the company. This test consisted of two stages: a capillary rise test and a water absorption test. The result of the test was the measurement of the capillary rise/ water absorption coefficient (%). This coefficient was calculated from the formula:

$$WN = \left(1 - \frac{m_w}{m_s}\right) x\ 100\%$$

Where:

- WN – Capillary rise/ Absorption coefficient (%)
- m_w – mass of the soaked sample (via capillary rise or immersion) (g)
- m_s – mass of dried sample (g)

The test was carried out on 7-day-old samples. A minimum of 2 samples were used for each scenario. After removing the samples from the sand, they were placed in a dryer and dried overnight at a temperature of 50°C. After this time, the dried samples were marked and weighed on a scale.

After weighing, the samples were tested for capillary rise. This test involved placing the dried samples in a container flooded with water to a height of 2 cm. After 4 hours, the samples were removed, photographed and weighed. Then, the mass of the dry sample was subtracted from the result of the weighed sample and the mass of absorbed water was obtained. The obtained results were substituted into the formula and the water absorption via capillary rie coefficient was determined.

2.7. Water absorption test

After receiving the results of the capillary rise test, the water absorption test was started. The samples were then placed back in the container and poured with water until the samples were completely covered. After 20 hours, the samples were taken out and weighed again. The mass of the dry sample was subtracted from the obtained result and the mass of water absorbed by the entire sample was obtained. All the results were substituted into the formula to determine the water absorption coefficient. After weighing, the samples were additionally subjected to strength tests.

2.8. Frost resistance test

The frost resistance test was carried out on 28-day-old samples in accordance with the PN EN 13286 41 standard in accordance with WT 5. Falling involves examining the durability of samples after 14 cycles of freezing and thawing. The study was carried out together with a durability test for 28-day samples, the results of which were the reference point. A minimum of 3 samples (usually 4) were used to conduct the test. The test began by placing the samples in water for approximately 7 hours to soak them. Then, the soaked samples were weighed and subjected to 14 alternating freezing and thawing cycles.

Freezing was carried out by placing the samples in a freezer at a temperature of approximately -20°C for at least 4 hours. Then the samples were placed in containers with water at a temperature of approximately +20 oC to thaw them. After a minimum of 2 hours, the samples were removed from the water, ending one cycle, and placed back in the freezer, starting the next cycle. After the 14th cycle, the thawed samples were weighed again to check for weight loss and subjected to strength tests. According to the standard, samples should not lose more than 5% of their weight and should retain 60% of their strength.

CAUTION: Frost resistance test results were obtained only for non-cohesive soils. None of the scenarios carried out on cohesive soils survived the full 14 freezing and thawing cycles (the samples were completely destroyed).

3. Results

3.1. First round of tests (2020-2021). Compressive strength.

The tests were carried out separately for clay (229 research scenarios + 17 control scenarios with only cement in the amount of 5% by weight) and for sand (227 research scenarios + 19 control scenarios with only cement in the amount of 5% by weight). The following groups of additives were tested, which were the basis for developing original recipes for hydraulic binders, and their discussion is presented in the following order:

1. Group I SUBSTITUTES OF COMMERCIAL STABILIZERS:

- "By-pass" waste ash from the ceramic industry (Nr 2 from Table 1), the so-called ash from the brickworks bypass, which is an alternative to the popularly used commercial binder GEOSTA (constituting a mixture of salts, i.e. chlorides of magnesium, sodium, potassium, calcium, iron; potassium carbonate and iron, aluminum, sodium sulfates)
- Sulfuric acid of waste origin (Nr 6 from Table 1), which is an alternative to the popularly used Roadbond EN-1

Table 1. The list of waste-based materials chosen for the tests.

Waste-based material tested	Dosages used/ 8 kg soil and 5% cement	National potential [t/ year]
1. Pyrolytic wax from the plastic waste (RDF), emulsion	<700 g	4-5 mln[1]
2. "By-pass" waste ash from ceramic industry (Geosta substitute)	10-200 g	30 000
3. Emulsion from the chewing gum production	100-400 g	1 200
4. Pyrolytic oil from waste tires, emulsion	20-140 g	Not in production
5. Pyrolytic wax from the HDPE, emulsion	20-100 g	Not in production
6. Waste sulphuric acid with limonene (EN-1 substitute)	<420 g	No data
7. Waste sodium hydroxide	46-93 g	No data
8. Waste from Nivea cream production	10-60 g	120
9. Waste from washing powder production	60-140 g	120
10. Waste polyols from chewing gum production	100-400 g	No data
11. Pyrolytic oil from RDF sulfonated, emulsion	40-60 g	4-5 mln[1]
12. "Water Glass"	20-70 g	No data
13. Sodium stearate	10-20 g	No data
14. Pyrolytic wax from pure foil (waste), emulsion	70-350 g	No data

[1] Assuming 40-50% of the mineral fraction in the global municipal solid waste in Poland.

2. Group II EMULSIONS from PYROLYTIC WAXES from the pyrolysis of polyolefins, including:

- Made of pure HDPE (High Density PolyEthylene) (Nr 5 from Table 1)
- From RDF waste (Nr 1 from Table 1)
- From waste tires (Nr 4 from Table 1)
- Made from waste pure foil

3. Group III EMULSIONS from CHEWING GUM WASTE, i.e. from waste from the food industry, namely from the production of chewing gum (Nr 3 from Table 1)

4. Group IV HYBRIDS above additives.

After analyzing the above-mentioned compressive strength results, 15 most promising scenarios with additives on sand, 7 on a mixture of sand and clay and 2 on clay were selected for further tests of water absorption and frost resistance. As a result, several soil parameters were compared and a multi-criteria analysis was performed based on:

- Compressive strength after 7 days and 28 days,
- Capillary rise after 4 hours and water absorption after 24 hours, expressed as the amount of water absorbed by the soil and expressed in % (g H_2O/g dry soil mass)
- Frost resistance as compressive strength after 14 frost-thaw cycles, related to the initial compressive strength after 28 days, expressed as a % of the initial strength,
- Several parameters recalculated on the basis of the above-measured ones,

Group I SUBSTITUTES OF COMMERCIAL STABILIZERS

The results of the average values of compressive strength for binders based on the addition of substitutes from GROUP I are presented below. The addition was from 10 to 200 g of the "by-pass" waste ash (Geosta substitute) and from 0.6 to 1.2 ml of the waste sulphuric acid (EN-1 substitute) with 5% cement and 8 kg of soil.

Due to the fact that the addition of the "by-pass" waste ash alone gives a slight improvement in compressive strength (5.7% and 11.1% for clay and sand, respectively) and the use of the waste sulphuric acid (EN-1 substitute) does not affect the strength (Table 1), it was decided to enrich the binders not only with substitutes from GROUP I, but with the addition of an emulsion of pyrolytic waxes from GROUP II, expecting a hybrid effect of additives from both previously defined groups.

The results of average compressive strength values for binders based on hybrids, i.e. the addition of substitutes from GROUP I and the addition of emulsions from pyrolytic waxes from GROUP II, are summarized below. The addition of substitutes was from 10 to 200 g of "by-pass" waste ash and from 0.6 to 1.2 ml of waste sulphuric acid, and the emulsion was from 10 to 40 g with 5% cement and 8 kg of soil.

+ *Emulsions from pyrolytic waxes of plastic waste*

As shown on Table 3 and Figure 1 the addition of wax emulsion (data averaged for waxes from HDPE, RDF, Foil) significantly improved the compressive strength of soils where only substitutes were used (Table 2). Thus, the strength on clay increased by almost 30% and 22% (for the Geosta and EN-1 substitutes, respectively), and on sand by as much as 57% and 44% (for the Geosta and EN-1 substitutes, respectively). Standard deviations were greater for sand results (up to 30%) and smaller for clay results (up to 15%), which would mean that sand showed greater heterogeneity than clay and, in practice, that the influence of the above-mentioned additives and their hybrids will be more visible in this soil.

Table 2. The average soil compressive strength values for substitutes of commercial stabilizers.

Additive	"By-pass" Waste Ash		Waste H_2SO_4	
Soil	**CLAY**	**SAND**	**CLAY**	**SAND**
Samples	**63**	**63**	**24**	**23**
MPa	0,99	1,17	0,95	0,99
SD/2	0,14	0,29	0,16	0,32
Change (%)[1]	5,67%	11,08%	1,36%	-5,63%

[1] Refers to the average control treatment where only 5% cement was used (for clay average from 17 samples and for sand average from 19 samples).

Table 3. The average soil compressive strength values for substitutes of commercial stabilizers with the addition of pyrolytic wax from various polyolefines (HDPE, RDF, pure foil)

Additive	"By-pass" Waste Ash + pyrolytic wax		Waste H_2SO_4 + pyrolytic wax	
Soil	**CLAY**	**SAND**	**CLAY**	**SAND**
Samples	**14**	**14**	**8**	**9**
MPa	1,21	1,66	1,14	1,52
SD/2	0,16	0,15	0,13	0,27
Change (%)[1]	29,67%	57,12%	21,87%	44,14%

[1] Refers to the average control treatment where only 5% cement was used (for clay average from 17 samples and for sand average from 19 samples).

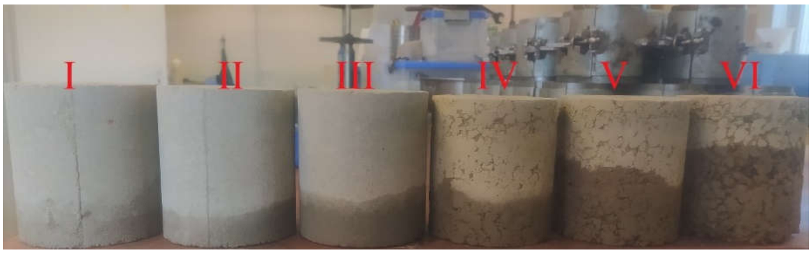

Figure 1. View of the samples during capillary rise test.

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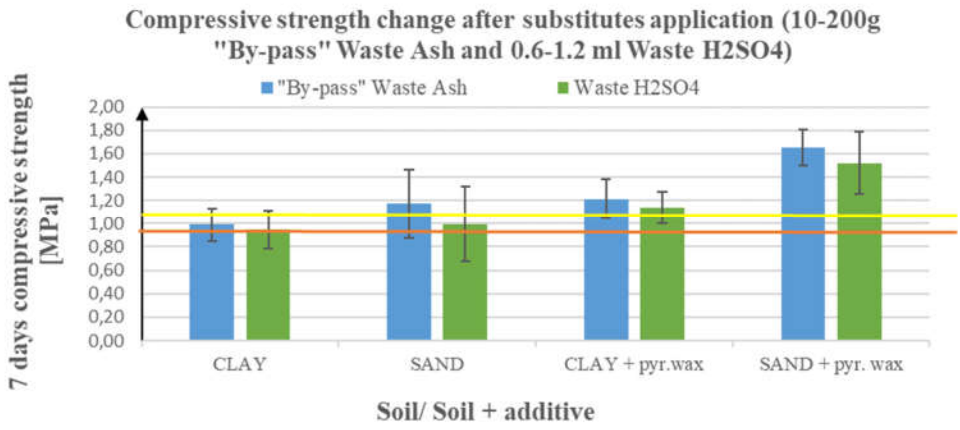

Figure 2. Average effect of the addition of substitutes on compressive strength (first 4 bars) and average effect of the addition of substitutes enriched with pyrolytic wax emulsions (next 4 bars). The yellow line represents the control value (average compressive strength using only cement without additives) for sand and the brown line for clay.

Group II EMULSIONS from PYROLYTIC WAXES

The results of average compressive strength values for binders based on the addition of emulsions from GROUP II are summarized below. The addition was from 10 to 40 g with 5% cement and 8 kg of soil.

Table 4. The average soil compressive strength values with the addition of emulsions from pyrolytic waxes from particular polyolefines (HDPE, RDF, pure foil).

Additive	**HDPE wax emulsion**		**RDF wax emulsion**		**Pure foil wax emulsion**	
Soil	**CLAY**	**SAND**	**CLAY**	**SAND**	**CLAY**	**SAND**
Samples	**7**	**8**	**13**	**14**	**17**	**20**
MPa (7d)	1,23	1,22	1,24	1,49	1,28	1,63
SD/2	0,10	0,15	0,16	0,23	0,49	0,20
Change (%)[1]	30,77%	15,67%	32,75%	41,75%	36,77%	54,84%

[1] Refers to the average control treatment where only 5% cement was used (for clay average from 17 samples and for sand average from 19 samples).

The results indicate a positive effect of the use of wax emulsions, with the best results observed for foil emulsions (37% increase for clay and 55% increase for sand), but RDF emulsions were slightly worse (33% for clay and 42% for sand). In contrast, the effect of using HDPE emulsion turned out to be two times better on clay than on sand. Any differences are probably due to inevitable impurities contained in thermally processed waste polyolefins. The good news is that RDF, much more polluted than foil, does not pose a threat to a significant reduction in the bearing capacity of the soil compared to a cleaner material such as foil. Standard deviations reached approximately 15-20%.

+ Substitutes of the commercial stabilizer ("by-pass" waste ash and waste sulphuric acid)

Despite the good results of the increase in compressive strength after using an emulsion made of post-pyrolytic waxes of waste polyolefins, the results for binders, where the addition of wax emulsion was also enriched with a substitute (Geosta or EN-1), are presented separately below on Table 5. The effect of this addition compared to the use of the emulsion itself turned out to be small for the HDPE emulsion (from 31 to 33% for clay), slightly more significant for the RDF emulsion (from

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42 to 54% for sand) and decreased for the emulsion with pure foil (from 37% to 22% for clay and from 55% to 44% for sand). Therefore, taking into account the results from Tables 1 and 2, it is suggested to use pyrolytic wax emulsions as an additive as a priority, and temporarily, depending on the soil and situation, to use emulsion hybrids with substitutes which gave the highest results for the combination of emulsions with Geosta substitute (up to 30% on clay and 57% on sand). Standard deviations reached approximately 15-20%.

Table 5. The average soil compressive strength values with the addition of emulsions from pyrolytic waxes from particular polyolefines (HDPE, RDF, pure foil) enriched with substitutes of commercial stabilizers.

Additive	**HDPE wax emulsion + "by-pass" Waste Aash**		**RDF wax emulsion + "by-pass" Waste Ash**		**Pure foil wax emulsion + Waste H_2SO_4**	
Soil	**CLAY**	**SAND**	**CLAY**	**SAND**	**CLAY**	**SAND**
Samples	**3**	**4**	**8**	**10**	**9**	**9**
MPa (7d)	1,25	1,13	1,27	1,62	1,14	1,52
SD/2	0,13	0,20	0,20	0,22	0,14	0,27
Change (%)[1]	33,25%	6,96%	35,74%	53,76%	21,69%	44,14%

[1] Refers to the average control treatment where only 5% cement was used (for clay average from 17 samples and for sand average from 19 samples).

+ Emulsion from chewing gum waste and NaOH

The compressive strength results for hybrids in the form of pyrolysis wax emulsions (HDPE and RDF) + chewing gum emulsion and pyrolysis wax emulsions (pure foil) + NaOH are listed below in Table 6. The best results using chewing gum waste were achieved for HDPE emulsion, i.e. up to 43% growth on clay and up to 24% on sand and up to 35% on clay when using RDF emulsion. The addition of NaOH to the foil emulsion had no effect on the results on clay, and on sand it increased the compressive strength by up to almost 70%.

Table 6. The average soil compressive strength values with the addition of emulsions from pyrolytic waxes from particular polyolefins (HDPE, RDF, pure foil) enriched with the emulsion from chewing gum waste and NaOH.

Additive	**HDPE wax emulsion + chewing gum waste**		**RDF wax emulsion + chewing gum waste**		**Pure foil wax emulsion + NaOH**	
Soil	**CLAY**	**SAND**	**CLAY**	**SAND**	**CLAY**	**SAND**
Samples	**4**	**4**	**8**	**4**	**3**	**7**
MPa (7d)	1,34	1,31	1,26	0,84	0,88	1,79
SD/2	0,09	0,05	0,20	0,21	0,06	0,10
Change (%)[1]	42,70%	24,20%	34,91%	-20,65%	-6,15%	69,35%

Group III EMULSIONS from CHEWING GUM WASTE

+ Emulsions from pyrolytic waxes of plastic waste

+ "By-pass" waste ash from ceramic industry

As shown in Table 7 and its graphical interpretation on Figure 3, the effect of using chewing gum emulsion on sand is negative, while on clay only in hybrids with RDF emulsion (37% increase) and with the Geosta substitute (24% increase) is observed significant improvement in the compressive strength of the soil. Standard deviations for increases reached 15-20% and even up to 50% for decreases.

Table 7. Average effect of the addition of an emulsion from chewing gum waste and additionally with (1) an emulsion from pyrolytic waxes and (2) a Geosta substitute, on the soil compressive strength.

Additive	Chewing gum		Chewing gum + RDF		Chewing gum + "by-pass" Waste Ash	
Soil	**CLAY**	**SAND**	**CLAY**	**SAND**	**CLAY**	**SAND**
Samples	**48**	**32**	**13**	**8**	**22**	**12**
MPa (7d)	1,01	0,43	1,28	1,07	1,16	0,43
SD/2	0,18	0,26	0,16	0,19	0,16	0,28
Change (%)	7,92%	-58,99%	36,67%	1,77%	23,97%	-59,60%

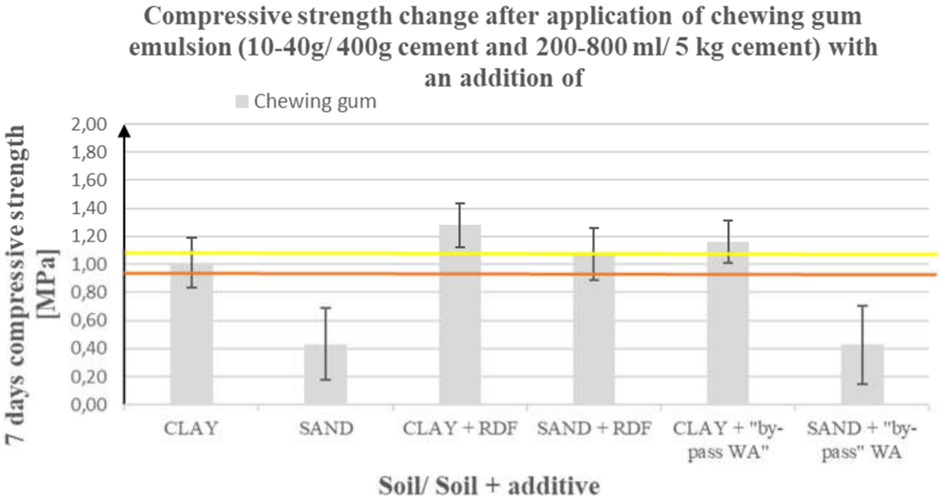

Figure 3. Average effect of the addition of emulsion from chewing gum waste (first 2 bars) and additionally with (1) emulsion from pyrolytic waxes (next 2 bars) and (2) Geosta substitute (last 2 bars) on soil compressive strength. The yellow line represents the base value (average compressive strength using only cement without additives) for sand and the brown line for clay.

3.2. First round of tests (2020-2021). Soil water absorption and frost resistance.

As the Table A1 (Appendix A) shows, for sand, the addition of 10-50% (by weight in relation to cement) of a 1:1 water emulsion with post-pyrolytic wax from RDF from pure foil ensures maximum frost resistance of 70-93% (at 46% for the control sample), which is closely related to the low water absorption of 0.35-8.00% for these mixtures. However, the addition of only emulsion with wax only slightly improved the compressive strength, i.e. from 8.6% to 33% (after 7 days) and to 24% (after 28 days). Therefore, further optimization was carried out and it turned out that only the addition of NaOH to the wax-based emulsion after pyrolysis (RDF from Foil was replaced with RDF from waste polyolefins) causes a significant increase in compressive strength (up to 70% after 7 days, i.e. 2.07 MPa and up to 25 % after 28 days, i.e. 2.53 MPa) with relatively low water absorption (3.5% after 4 hours and 6.3% after 24 hours) and still high frost resistance (57%).

3.3. Second round of tests (2021-2022). Soil compressive strength, water absorption and frost resistance.

SAND

Best sealing materials – sorted by the frost resistance

All results from studied materials were sorted by frost resistance value. Only results higher than 35.6% are presented, which is the average value for the control scenario with cement only.

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Advantages: + The highest frost resistance values, i.e. above 80% (excluding the result above 100%), were achieved for the following additives: Pure foil, RDF Pure foil + NaOH, ProRoad Waterproof + Water Glass. + For these scenarios, capillary rise and water absorption values were mainly below 3% and below 8%, respectively. Disadvantages: - The disadvantage of using these additives is only a slight increase in compressive strength after 7 days (15-40%) and after 28 days (26-36%).

Subjective assessment of additives: + + -

Best sealing materials – sorted by the capillary rise

All results from studied materials were sorted by the capillary rise value (water absorption over 4 hours). Only results better (lower) than 2% are presented (the control value is 6% for the binder only with cement). Advantages: + The lowest capillary rise values i.e. less than 1% were achieved for the following additives: Pure foil, RDF, Sodium Stearate, waste from Nivea cream production and RDF Mixture, ProRoad Waterproof, Nivea Soap, RDF Sulfonated, waste from Nivea cream production, waste from washing powder production, + For these scenarios frost resistance values (if measured) ranged from 22% to 74%. Disadvantages: +- The uncertainty of using these additives is the unstable change in compressive strength after 7 days (-80 +231%) and - rather, the decrease in compressive strength after 28 days to -25% (if measured).

Subjective assessment of additives: + + + - -

Best sealing materials – sorted by the water absorption

All results from studied materials were sorted by the water absorption value (during 24 hours). Only results better (lower) than 5.1% were presented, which is twice as low as for the control scenario with cement only (9.9%). Advantages: + The lowest absorption values, i.e. below 3%, were achieved for the following additives: Tequant, ProRoad Waterproof, RDF, Pure foil, Sodium Stearate, waste from Nivea cream production, waste from washing powder production, vaseline. Disadvantages: +- Frost resistance values were not measured for these scenarios. - The disadvantage of using these additives is a very unstable change in compressive strength after 7 days (from -79% to +231.6%) and, here and there, a decrease in compressive strength after 28 days.

Subjective assessment of additives: + + - - -

Best strengthening materials – sorted by 7 days compressive strength

All results from studied materials were sorted by the compressive strength value after 7 days. Only results that are better (higher) by 50% or more compared to the control scenario with cement only (1.15 MPa) are presented. Advantages: + The highest compressive strength values above 2 MPa (change of 75% and more) were achieved for the following additives: waste from Nivea cream production and RDF mixture, waste from washing powder production, waste from Nivea cream production + RDF + waste from washing powder production, Concrete additive, Water glass + NaOH, RDF sulfonated, waste from Nivea cream production + RDF. For these scenarios, frost resistance and compressive strength values after 28 days were not measured (apart from two visible ones from 9/02/21 and 9/03/21). + Capillary rise values for these scenarios were mostly below 3% (with 6% for the control scenario).

Subjective assessment of additives: + + +

Best strengthening materials – sorted by 28 days compressive strength

All results from studied materials were sorted by the compressive strength value after 28 days. Only results that are better (higher) by 14% or more compared to the control scenario with cement only (1.98 MPa) are presented. Advantages: + The highest compressive strength values above 2.2 MPa were achieved for the following additives: waste from washing powder production, Proroad Waterproof, Prorad Waterproof + Water Glass, Sodium stearate, "by-pass" waste ash + RDF + NaOH x2 and x1, Pure foil + NaOH, Pure foil + waste sulphuric acid, RDF from waste tires. + For these scenarios, frost resistance values ranged from 34 to 88% and + compressive strength after 7 days was increased by 56-80% for waste additives (RDF-based) and unfortunately - decreased by 27-65% for

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commercial additives. ++ The capillary rise and water absorption values for these scenarios were mainly below 4% and 10%, respectively.

Subjective assessment of additives: + + + - + +

CLAY

Best sealing materials – sorted by the frost resistance

The tests failed due to samples disintegrating during freezing-thawing cycles.

Best sealing materials – sorted by the capillary rise

All results from studied materials were sorted by the capillary rise value (water absorption over 4 hours). Only results better (lower) than 4.2% are presented (the control value is 4.24% for the binder with cement only). Advantages: + The lowest capillary rise values, i.e. below 3%, were achieved for the following additives: Tequant, ROKAmin, Pure foil + NaOH, Pure foil + EN-1 Substitute, Concrete Additive, ProRoad Waterproof, Disadvantages: - The uncertainty of using these additives is the unstable change in compressive strength after 7 days (-42 +81%) where a significant (>40%) increase in compressive strength after their use occurred only for 3 scenarios: Pure foil + NaOH, Pure foil + EN-1 Substitute, Concrete Additive, + Compressive Strength after 28 days, measured for 3 scenarios, it varied from -38% to 119%.

Subjective assessment of additives: + - +

Best sealing materials – sorted by the water absorption

All results from studied materials were sorted by the water absorption value (water absorption during 24 hours). Only results better (lower) than 11% are presented (the control value is 11.14% for the binder only with cement). Advantages: + The lowest water absorption values, i.e. below 10%, were achieved for the following additives: Tequant, ROKAmin, Pure foil + NaOH, Pure foil + EN-1 substitute, Pure foil + ROKAmin + NaOH, ProRoad Waterproof, Concrete additive (these are also the same additives that ensured the lowest capillary rise), - The uncertainty of using these additives is the unstable change in compressive strength after 7 days (-41 +81%) where a significant (>40%) increase in compressive strength after their use occurred only for 3 scenarios: Pure foil + NaOH, RDF ure foil + EN-1 Substitute, Concrete Additive, + Compressive strength after 28 days measured for 3 scenarios varied from -38% to 119%.

Subjective assessment of additives: + - + (the same additives had a relatively even effect on both capillary rise and water absorption).

Best strengthening materials – sorted by 7 days compressive strength

All results from studied materials were sorted by the compressive strength value after 7 days. Only results better (higher) than 10% and more compared to the control scenario with cement only (0.7 MPa) are presented. Advantages: + The highest compressive strength values above 0.9 MPa (change of 30% and more) were achieved for the following additives: Pure foil + EN-1 Substitute, Pure foil, Concrete Additive, chewing gum waste + Pure fil + NaOH, Pure foil + NaOH, Glass Water + NaOH, RDF with pyrolytic oil. + For these scenarios, the compressive strength values after 28 days were not measured (apart from the two from 28/04/21 where these values improved significantly, i.e. by 64 and 119%). Disadvantages: +- the capillary rise values for these scenarios were mostly in the range of 2.3%-10% for the best scenarios, 10%-12% for the moderate scenarios with two exceptions of 12% and 14.8%. (at 4.2% for the control scenario).

Subjective assessment of additives: + + + -

Best strengthening materials – sorted by 28 days compressive strength

All results from studied materials were sorted by the compressive strength value after 28 days. All results are presented relative to the control scenario with cement only (0.84 MPa). Disadvantages: - The highest compressive strength values above 1 MPa were achieved only for the following additives: RDF Foil + NaOH, Pure foil + EN-1 Substitute. Disadvantages: - For the first scenario, frost resistance was only 7.53% and + Compressive strength after 7 days was increased by 41-81%. The +

capillary rise and + water absorption values for these scenarios were mainly below 3% and 10%, respectively (with reference values of 4.2% and 11.1%, respectively).

Subjective assessment of additives: - - + + +

4. Discussion

4.1. First round of tests (2020-2021). Compressive strength.

As the Figures 4 and 5 show, for clay, the use of post-pyrolysis waxes from the pyrolysis of various polyolefins (RDF, Foil, HDPE), including hybrids with a "by-pass" waste ash (a Geosta substitute) or with an emulsion from waste from the production of chewing gum, increases the compressive strength from approx. 10 to approx. 40% regardless of the type of polyolefins or additional material used.

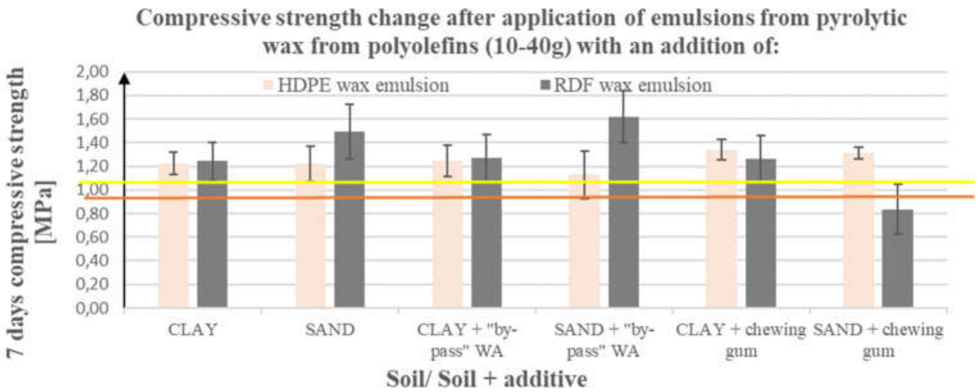

Figure 4. Average effect of the addition of emulsion from pyrolytic waxes (HDPE and RDF - first four bars), additionally with the Geosta substitute (next four bars) and with emulsion from chewing gum waste (last four bars), on soil compressive strength. The yellow line represents the base value (average compressive strength using only cement without additives) for sand and the brown line for clay.

For sand, the increases are more varied (5-80%), with the highest values for foil emulsion and hybrids, i.e.: RDF emulsion and Geosta substitute, pure foil wax emulsion and EN-1 substitute, and foil emulsion and NaOH, while the use of made of chewing gum in a hybrid with an RDF emulsion remains irrelevant to the compressive strength on this soil. Standard deviations for both soils were generally insignificant, except for the chewing gum scenarios where they reached 15-25%.

In general, the use of RDF emulsion has a greater impact on the strength of the soil than that of HDPE emulsion for both clay and sand (the exception are the recent scenarios with hybrids with rubber emulsion, where the tendency is the opposite).

By using a pure foil wax emulsion and the addition of NaOH, clay achieves a reduced load-bearing capacity, while sand achieves up to 70% higher load-bearing capacity.

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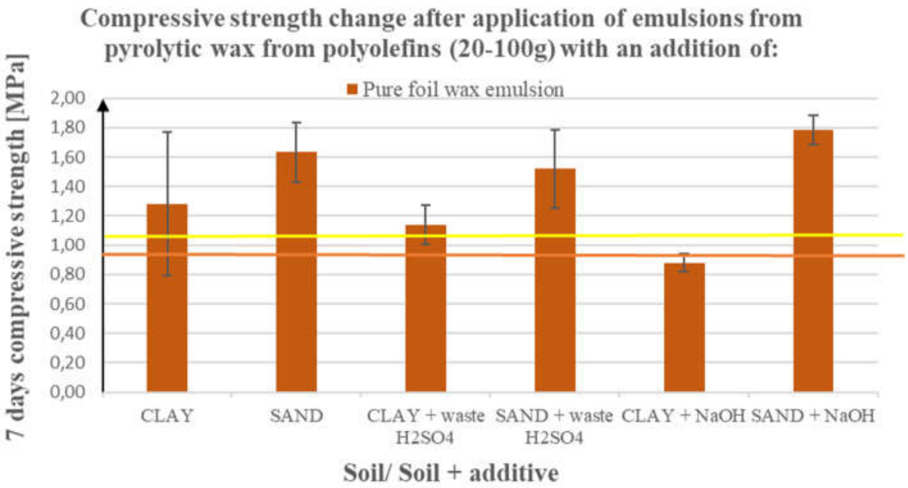

Figure 5. The average effect of the addition of an emulsion from pyrolytic waxes from pure foil (the first two bars) additionally with the EN-1 substitute (the next two bars) and NaOH (the last two bars) on the soil compressive strength. The yellow line represents the base value (average compressive strength using only cement without additives) for sand and the brown line for clay.

4.2. Second round of tests (2021-2022). Soil compressive strength, water absorption and frost resistance.

Seeking correlations between soil mechanical and hydraulic parameters

The soil stabilized prior to road construction should have optimal mechanical and hydraulic properties. Since we tested vast amounts of different waste materials, the relation between frost resistance and compressive strength was searched. The hypothesis was that the more empty spaces, cracks and thin pores, the highest capillary force, hence lowest frost resistance. In the same time, compression strength in such perforated soil should be lower. So the relation should be somehow inversely proportional.

1. *Frost resistance vs. compressive strength*

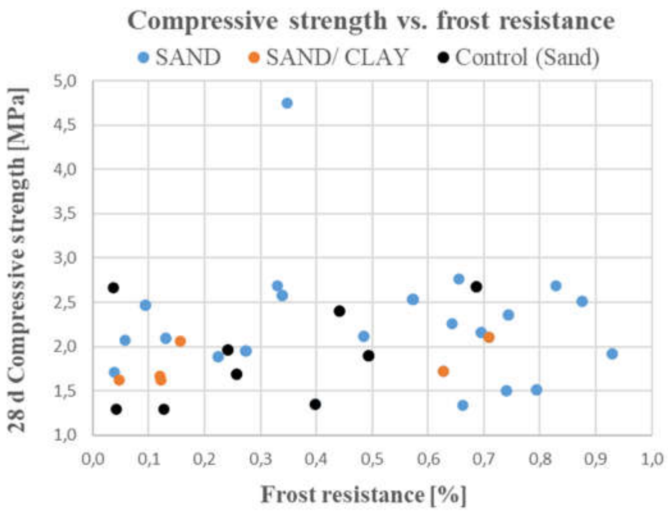

Figure 6. 28d soil compressive strength as a function of frost resistance. The data show now clear tendency. 39 data rows for Sand, 6 for Sand/ Clay and 15 for Controls.

Conclusion: Lack of correlation

2. *Absolute frost resistance vs. capillary rise and water absorption*

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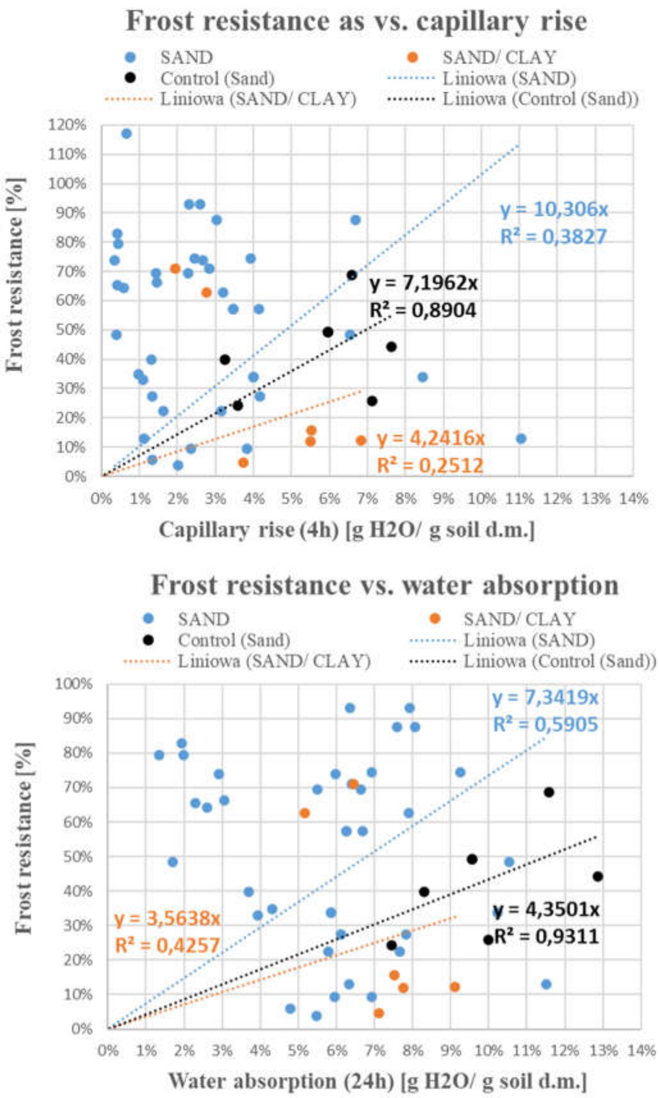

Figure 7. Frost resistance as a function of capillary rise (up) and as a function of water absorption (down). 39 data rows for Sand, 6 for Sand/ Clay and 7 for Controls.

Capillary rise: Linear correlation only for control scenarios with a high correlation coefficient (0.8904). Frost resistance is easy to calculate (without the need to conduct 14-frost frost tests) by multiplying the capillary rise value (in % of the mass of water sucked into the soil in relation to the initial dry mass of the soil) by the factor 7.1962. There is no clear relationship for mixtures with sealing additives or too few points to demonstrate this relationship (correlation coefficients 0.3827 for sand and 0.2512 for sand and clay). Therefore, it is impossible to say how much frost resistance depends on wicking in this case. This is due to the heterogeneity of the samples, various additives and their different recipes.

Water absorption: Linear correlation only for control scenarios with a high correlation coefficient (0.9311). Frost resistance is easily calculated by multiplying the water absorption value (in % of the mass of water absorbed in relation to the initial dry mass of the soil) by the factor 4.3501. There is no clear relationship for mixtures with sealing additives or too few points to demonstrate this relationship (correlation coefficients 0.3827 for sand and 0.4257 for sand and clay). Therefore, it is impossible to say exactly how much frost resistance depends on water absorption in this case. This is due to the heterogeneity of the samples, various additives and their different recipes.

Optimized strengthening and sealing materials – sorted by optimization parameter

SAND

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In order to select the best materials for use in soil stabilization both in terms of strengthening the bearing capacity (increasing compressive strength) and in terms of tightness/ sealing and preventing soil damage by frost-thaw cycles (capillary rise/ water absorption affecting frost resistance) presented in Results section, an artificial parameter was created for optimization purposes. First, the compressive strength was standardized after 28 days, relating it to 1 kg of soil, because different additives with different compositions affect the bulk density of the sample, which translates into strength. Hence, a new set of data was generated, the so-called relative strength related to soil mass [MPa/ 1 kg of soil]. Then, the capillary rise parameter was standardized, which was created by dividing the capillary rise after 4 hours in % of absorbed water by the previously generated relative strength in MPa/kg of soil. As a result, an artificial OPTIMIZATION PARAMETER was obtained, which combines both sealing properties (water absorption by the capillary rise after 4h) and strengthening properties (compressive strength after 28d).

All results from studied materials were sorted by the OPTIMIZATION PARAMETER. All results for which optimization was possible are presented. The lower the parameter, the better the additive in its strengthening and sealing properties. The lowest values of the optimization parameter (below 30) were achieved for the following additives: Pure foil, Pure foil + waste sulphuric acid, RDF from waste tires, Pure foil + "by-pass" waste ash + NaOHx2.

Optimized strengthening and sealing materials – sorted by optimization parameter

CLAY

All results from studied materials were sorted by the OPTIMIZATION PARAMETER. All results for which optimization was possible are presented. The lower the parameter, the better the additive in its strengthening and sealing properties. The lowest values of the optimization parameter (below 300) were achieved for the following additives: Pure foil + NaOH, Pure foil + EN-1 Substitute, Tequant, Pure foil.

5. Conclusions

From among the groups of additives selected for this extensive, the best scenarios of additives in terms of compressive strength were selected for hydraulic binders, for which tests on a real scale are recommended:

CLAY

Table 8. Selected best waste ingredients compositions in terms of compressive strength for clayey soil.

	Ingredient 1	Ingredient 2	7d compressive strength change (%)
1	Pure foil, wax emulsion		37
2	RDF, wax emulsion	"by-pass" waste ash	36
3	HDPE, wax emulsion	Chewing gum waste emulsion	43
4	Chewing gum waste emulsion	RDF, wax emulsion	37

SAND

Table 9. Selected best waste ingredients compositions in terms of compressive strength for sandy soil.

	Ingredient 1	Ingredient 2	7d compressive strength change (%)

1	RDF, wax emulsion		42
2	Pure foil, wax emulsion		55
3	RDF, wax emulsion	“by-pass” waste ash	54
4	Pure foil, wax emulsion	Waste sulphuric acid	44
	Pure foil, wax emulsion	NaOH	70

From the groups of additives selected above, the best additive scenarios were selected in terms of frost resistance and compressive strength for hydraulic binders, for which real-scale testing is recommended:

As a result of the optimization process presented above, individual additives ensuring the best strengthening and sealing properties are proposed for the following priorities:
SAND: Pure foil (wax emulsion), Pure foil (wax emulsion) + waste sulphuric acid, RDF from waste tires (wax emulsion), Pure foil (wax emulsion) + “by-pass” waste ash + NaOHx2. CLAY: Pure foil (wax emulsion) + NaOH, Pure foil (wax emulsion) + waste sulphuric acid, Tequant, Pure foil (wax emulsion).

6. Patents

1. "Hydraulic sealing binder for cohesive soils and the method of its production and connection with the native cohesive soil", No. P.438697, on behalf of Construction Company WACIŃSKI Witold Waciński
2. “Sealing additive for hydraulic binder for non-cohesive soils and grained native soils, method of its production and connection with native soil", No. P.444266, on behalf of Construction Company WACIŃSKI Witold Waciński

Author Contributions: Conceptualization, Ksawery Kuligowski, Witold Waciński; methodology Marek Zając, Robert Tylingo, Szymon Mania, Paweł Kazimierski, Małgorzata Olejarczyk, validation Adam Cenian, Robert Tylingo, Szymon Mania, Paweł Kazimierski, Włodzimierz Urbaniak, formal analysis Witold Waciński, investigation Marek Zając, Robert Tylingo, Szymon Mania, Paweł Kazimierski, Włodzimierz Urbaniak, Małgorzata Olejarczyk, resources Witold Waciński, data curation Marek Zając, Ksawery Kuligowski, writing—original draft preparation Ksawery Kuligowski, writing—review and editing Adam Cenian, Marek Zając, Robert Tylingo, Szymon Mania, Paweł Kazimierski, Włodzimierz Urbaniak, Małgorzata Olejarczyk, visualization Ksawery Kuligowski, supervision Witold Waciński, project administration Marek Zając, funding acquisition Ksawery Kuligowski. All authors have read and agreed to the published version of the manuscript.”.

Funding: The research has been carried out by the Construction Company "WACIŃSKI" via the project: “Development and implementation of effective stabilizing mixtures for the foundation of road surfaces using fly ashes from the coal-based energy sector in Gdansk” (Regional Development Programme of Pomorskie Voivodeship/ Action 1.1.1 Expansion via innovations), https://www.wacinski.pl/projekty-ue/.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request.

Acknowledgments: Authors would like to express the thanksgiving foe the staff of the WACIŃSKI Construction Company for providing access to the mechanical laboratory and extensive testing.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Chosen set of data from Year 1 study (2020-2021) covering compressive strengths, frost resistance and correlations between them for both sandy and clayey soils.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Nr	Date	Ingredients	Amounts	**7 days compressive strength [MPa]**	**28 days compressive strength [MPa]**	7d compressive strength change [%]	28d compressive strength change [%]	Sample mass (g)	Capillary rise (g H2O/ g soil d.m.) **4h**	Water absorption (g H2O/ g soil d.m.) **24h**	Water absorption/ Capillary rise ratio (24h/4h)	28d compressive strength/ 24h Water absorption (MPa/ % H2O)	Frost resistance [% 28d soil compressive strength after 14 freeze-thaw cycles]	Frost resistance/ 24h Water absorption (MPa/ % H2O)
SAND															
P	1	16.03.2021	*Cement, RDF Pure foil*	*1400 g, 140 g*	1,324	1,920	8,64%	-5,35%	1867,1	2,31%	7,93%	3,43	24,23	93,03%	22,54
P	2	27.04.2021	*Cement 5%, RDF Pure foil, NaOH*	*1400 g, 70 g, 70 g*	1,621	2,510	33,03%	23,70%	1863,2	6,69%	8,07%	1,21	31,10	87,58%	27,24
P	3	16.03.2021	*Cement, RDF Tires*	*1400 g, 140 g*	1,351	2,357	10,87%	16,19%	1874,5	2,45%	9,25%	3,77	25,49	74,31%	18,94
P	4	16.06.2021	*Cement 5%, RDF Pure foil*	*1400 g, 700 g*	1,426	1,502	17,04%	-25,97%	1988,6	0,35%	2,92%	8,31	51,50	73,93%	38,08
P	5	16.06.2021	*Cement 5%, RDF Pure Foil, Waste H2SO4*	*1400 g, 210 g, 420 g*	1,675	2,156	37,46%	6,29%	1943,3	1,43%	6,63%	4,63	32,51	69,45%	22,57
P	6	09.02.2021	*II Cement, "by-pass" Waste Ash, RDF, NaOH*	*1400 g, 46.6 g, 46.6 g, 46.6 g*	2,066	2,530	69,51%	24,71%	1925,9	3,46%	6,26%	1,81	40,44	57,25%	23,15
P	7	09.03.2021	*II Cement, "by-pass" Waste Ash, RDF, NaOH*	*1400 g, 46.6 g, 46.6 g, 46.6 g*	2,066	2,530	69.51%	24,71%	1925,9	3,46%	6,26%	1,81	40,44	57,25%	23,15
P	8	01.04.2021	*II Cement 5%, "by-pass" Waste Ash, MgO*	*1400 g, 112 g, 28 g*	1,793	2,112	47,14%	4,11%	1869,2	6,55%	10,55%	1,61	20,03	48,47%	9,71
P	10	09.02.2021	*III Cement, "by-pass" Waste Ash, RDF, NaOH x2*	*1400 g, 46.6 g, 46.6 g, 93.2 g*	1,791	2,575	46,97%	26,91%	1939,7	4,01%	5,86%	1,46	43,92	33,87%	14,88
P	11	09.03.2021	*III Cement, "by-pass" Waste Ash, RDF, NaOH x2*	*1400 g, 46.6 g, 46.6 g, 93.2 g*	1,791	2,575	46,97%	26,91%	1939,7	4,01%	5,86%	1,46	43,92	33,87%	14,88
P	12	14.06.2021	*Cement 5%, RDF Pure foil*	*1400 g, 350 g*	1,300	1,955	6,69%	-3,65%	1970,4	1,34%	6,11%	4,57	31,97	27,37%	8,75
P	13	14.06.2021	*Cement 5%, RDF Pure Foil, Waste H2SO4*	*1400 g, 350 g, 420 g*	1,338	1,892	9,76%	-6,75%	1976,9	1,64%	5,78%	3,53	32,72	22,42%	7,34
P	14	01.04.2021	*III Cement 5%, "by-pass" Waste Ash, NaOH, MgO, Bio-ash*	*1400 g, 36 g, 46.6 g, 46.6 g, 5 g, 5 g*	1,686	2,090	38,36%	3,00%	1852,9	11,03%	11,50%	1,04	18,17	13,03%	2,37
P	15	27.04.2021	*Cement 5%, RDF Pure Foil, Waste H2SO4*	*1400 g, 350 g, 420 g*	1,916	2,465	57,21%	21,53%	1919,6	3,84%	6,92%	1,80	35,63	9,34%	3,33
SAND and CLAY															
PG	1	14.04.2021	*II Sand, Cement 5%, RDF Pure Foil*	*1400 g, 140 g*	1,699	2,103	51,62%	17,31%	1951,8	1,94%	6,46%	3,34	32,57	70,94%	23,11
PG	2	11.03.2021	*III Cement, "by-pass" Waste Ash x2, RDF x2, NaOH x2*	*1400 g, 93.2 g, 93.2 g, 93.2 g*	0,975	1,724	-12,98%	-3,84%	1970,7	2,77%	5,17%	1,87	33,34	62,68%	20,89
PG	3	07.04.2021	*III Cement 5%, "by-pass" Waste Ash, RDF, NaOH, MgO, Bio-ash*	*1400 g, 36 g, 46.6 g, 46.6 g, 5 g, 5 g*	1,685	2,061	50,29%	14,95%	1887,7	5,52%	7,53%	1,36	27,38	15,72%	4,30
PG	4	07.04.2021	*II Cement 5%, "by-pass" Waste Ash, MgO*	*1400 g, 112 g, 28 g*	1,391	1,620	24,11%	-9,62%	1838	6,84%	9,12%	1,33	17,77	12,13%	2,15
PG	5	14.04.2021	*III Sand/ Clay, Cement 5%, RDF Pure Foil*	*1400 g, 140 g*	1,503	1,668	34,12%	-6,99%	1881,1	5,51%	7,76%	1,41	21,50	11,99%	2,58
PG	6	11.03.2021	*II Cement, "by-pass" Waste Ash, RDF, NaOH*	*1400 g, 46.6 g, 46.6 g, 46.6 g*	1,405	1,628	25,36%	-9,19%	1908,2	3,73%	7,12%	1,91	22,85	4,68%	1,07
PG	7	14.04.2021	*I Glina, Cement 5%, RDF Pure Foil*	*1400 g, 140 g*	0,737	0,962	-34,27%	-46,33%	1778,4	7,29%	12,28%	1,68	7,83		
CLAY															
G	1	29.04.2021	*Cement 5%, RDF Pure Foil, Waste H2SO4*	*1400 g, 350 g, 420 g*	1,273	1,387	8,31%	24,84%	1850,8	2,82%	9,36%	3,32	14,81		
G	2	29.04.2021	*Cement 5%, RDF Pure Foil, NaOH*	*1400 g, 70 g, 70 g*	0,992	1,848	-15,57%	66,34%	1904,3	2,36%	8,38%	3,55	22,07	7,53%	1,66

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