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Investigations into stabilized structures with the use of waste foundry sand

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Abstract. In the light of carbon-neutral society and circular economy, attempts were made in this study to utilize the waste foundry sand (WFS) in high volume as a pavement construction material. A series of laboratory tests, including but not limited to particle size distribution, Proctor, pH values, shear box and compressive strength test were performed to investigate the technical soundness of the material. Insufficient strength of the stabilized WFS has promoted the utilization of a mixture containing not only WFS but also quarry fines. The compressive strength test results show high potentials of such stabilized mixtures for pavement constructions. Yet further research is still needed to consider the durability and environmental aspects in the future.

1. Introduction

In the Finnish construction business, the legislation has become more lenient on the utilization of secondary raw materials. While the legislators are most concerned about environmental risks and for example leaching, this study aims to prove the technical soundness of some typical secondary materials in Finland. The main focus of this study is in waste foundry sand (WFS) and quarry fines (QF), with investigations into secondary raw materials as stabilizers as well. Even though recycled materials such as WFS have found its applications in non-load bearing structures, e.g. embankments and noise barriers [1], it is of great importance in the circular economy business to reduce the natural resource depletion and promote the utilizations of recycled and secondary materials. It is also important to find substitutive solutions for higher quality materials and high requirement applications rather than consuming substantial amounts of non-renewable natural resources. For these reasons it is important to also research ways of getting higher strength from the secondary materials [2]. The usage of WFS in load-bearing pavement structures was studied with mixtures of stabilized samples.

For viable applications under higher loading conditions, the physical and mechanical properties of the WFS have been investigated in this research. A series of laboratory tests to characterize the virgin and bonded WFS were performed. Physical properties including specific gravity, optimal water content, gradation and pH values, as well as the mechanical indices of shear strength and unconfined compressive strength were among the investigated properties.

Virgin WFS was proven to have inadequate load bearing capacity as structural layer material and therefore refinement was necessary. Cement and three types of sustainable binders were adopted as stabilizers which adds to the merits of secondary material utilization. Secondary binders used were fly ashes from a coal and a biomass plant and a commercial eco-binder. Quarry fines of 0-4mm grain size were used to make admixtures with WFS to improve the gradation and mechanical properties.

2. Materials and methods

2.1. Materials

The main aggregates were waste foundry sand and quarry fines. For binders quick cement was used as a reference for three secondary raw material binders of fly ash, bio ash and eco-binder. All these materials and used test methods are detailed in the next chapters.

2.1.1. Waste foundry sand

The most common type of foundry sand in Finland, ester cured alkaline phenolic resin sand, was collected for the laboratory tests. In the binding process, the sand resolution phenol-formaldehyde resin is mixed with ester which acts as a hardener. The proportion of resin is from 1.0 to 1.5% by weight of the sand, and the ester is about 20-25% of the amount of resin. Hardening depends on the reaction between the alkali metal (potassium or sodium) in the resin and the acid component of the ester, forming alkali metal salts. [3]

One sample was also prepared using thermally reclaimed foundry sand (WFSR) to see how much of an effect the purity of the WFS aggregate has on the results. Thermal reclamation is a process in which the WFS is burned in high temperature to make it better suited for reuse inside the foundry process. Thermally reclaimed sand was obtained from a previously studied facility [4].

2.1.2. Quarry fines

Quarry fines are a by-product from aggregate production when the rocks are crushed and processed. The mineralogical composition of quarry fines is very dependent on that of the host rock, which influences the mechanical properties of quarry fines itself. The host rock where the quarry fines is extracted and used in this study is verified to be good-quality material according to the mineral compositions, indicating possible good properties of the quarry fines.

2.1.3. Binders

Cement, which is an inorganic fine-grained material commonly used as a binder, was selected as a reference to evaluate the effectiveness of other types of binders in stabilizing the WFS. A fast-setting Portland cement containing chemically calcium, silicon, aluminum, iron and magnesium, was used and termed as CEM in this study. [5]

The Ecolan recycled binder is a mixture of coal ash, bio ash, lime and cement produced by Ecolan Oy. It should be noted that the compositions of this mixture vary in batches due to the variations in raw resources adopted for the production. In this study it is abbreviated as ECO. [6]

Fly ash is a product of coal combustion that has found its applications for many engineering purposes, especially for concrete or as pozzolan, an alternative to Portland cement. The fly ash used in this study has a low content of CaO, and is non-self-cementitious. As a result, quick cement of a very low dosage (1%) has been added as an activator to the mixture, to ensure the setting of the material. The fly ash used in this study comes from the Helen Oy Hanasaari power plant and termed as FA hereafter. [7]

The biofuel fly ash has similar geotechnical properties to fly ash from coal combustion, but the properties vary with the incineration biomaterial, fuel and technology used for combustion and collection. Especially the combustion temperature and fly ash separation technology are two major factors that influence the compositions of the biofuel fly ash. Biofuel fly ash adopted in this study is from Fortum Oy Järvenpää combustion plant and termed as BA hereafter. [8]

2.2. Optimal water content and maximum dry density

Optimal water content and the maximum dry density of the WFS were determined by the improved Proctor Test according to the European standard EN 13286-2 *"Unbound and hydraulically bound mixtures. Part 2: Test methods for laboratory reference density and water content—Proctor compaction"*. [9] In this method, a range of water content from around 5% to 20% was selected according to previous experience. Dried WFS was mixed with varied amounts of water and compacted by the Proctor hammer in five layers inside a test cylinder. The water-density relationship of the WFS was then plotted to obtain the optimal water content at which the material can be compacted to the maximum dry density under the same compaction energy.

2.3. Specific gravity

The specific gravity of the foundry sand was determined by pycnometer from four samples following the Geotechnical Laboratory Guidelines GLO-85 [10]. The oven-dried foundry sand samples were weighed with pre-calibrated pycnometers. After weighing, distilled water was added to the pycnometers and left to soak the samples for one hour. Vacuum was applied to pycnometers to suck out excess air entrapped inside the samples. After vacuum, the pycnometers were filled with distilled water, sealed with caps and placed in a water bath to reach a temperature of 22.9°C. The weight of samples with pycnometers was measured again for specific gravity calculation.

2.4. Gradation

Grain size distribution of the WFS was determined using European Standards SFS-EN 933-1: 2012 *“Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving method”* [11] as work instructions. Only the wet sieving method was applied to obtain the full gradation for the WFS because a low fine fraction content (<0.063mm) of 1% was contained in the material. For the quarry fines with 0-4mm grain size, both the wet sieving method and hydrometer method were applied to obtain the full gradation curve, considering that the fines smaller than 0.063mm is higher than 10%.

2.5. Minimum and maximum porosity

Porosity refers to the percentage of pore volume including those filled with water and air, compared to the total volume of a material. Another indicator of the volumetric property, pore number, is a similar ratio but based on the volume of solid skeleton only. Porosity and pore number are interdependent and are two commonly used indicators for volumetric property.

The determination of the minimum and maximum pores was performed by the Kolbuszewsky method, for which guidance is given in Chapter 7.32 of GLO-85 [10]. The experiment determines the pore number of the WFS in two states, natural loose and densely compacted with water.

2.6. pH

The pH value of the WFS was determined using a calibrated electronic pH detector. Three oven-dried and three non-dried samples of WFS were examined. The samples were prepared by mixing 20ml of powdered foundry sand and 50 ml of distilled water in a beaker, allowing the distilled water to be absorbed into the sample for 24 hours. After soaking, the mixture was thoroughly agitated and the pH value of the mixture was determined with a calibrated detector.

2.7. Shear box test

The shear box test is performed to determine the shear strength of the stabilized WFS mixtures in this study. Following the European Standard SFS-EN ISO 17892-10: 2019 [12], identical samples were firstly pre-consolidated while vertical depression is monitored with a vertical displacement sensor installed above the samples. When the sample has reached consolidated state, shear loading was applied at a constant strain rate of 0.5 mm/min, monitored by horizontal stress and strain transducers. In the shear box test, two sets of the WFS in dry condition and of 14% water content were investigated.

2.8. Unconfined compressive test and sample mixtures

Compressive strength is a typical design parameter to evaluate the mechanical capability of a material. The compressive strength test is selected to investigate the foundry sand mixtures because the test is easily accessible and the results are comparable to other engineering materials. In this study, compressive strength was determined using the Aalto University Zwick & Roell uniaxial compression tester according to European Standard SFS-EN 13286-41: 2003 [13]. Constant strain rate at the speed of 1.2 mm/min, which is corresponding to 1% of the specimen's height, was applied on test pieces compressed to failure while the development of stress and strain was recorded.

For the unconfined compression tests, a variety of mixtures with different aggregate and binder compositions were studied. Details of all these mixtures are in table 1 below. In the results section of this paper only the abbreviations given in the first column of the table are used when presenting data for these samples.

Table 1. Names and compositions of compressive test mixtures

Mixture	Aggregate composition	Binder composition	Sample count	Water [%]	Degree of compaction based on proctor
WFS+CEM	100% WFS	4% CEM	3	14	96%
WFS+FA-1		9% FA, 1% CEM	3	12	
WFS+FA-2		11% FA, 1% CEM	3	12	
WFS+FA-3		13% FA, 1% CEM	3	12	
WFS+ECO-1		4% ECO	3	13	
WFS+ECO-2		6% ECO	3	13	
WFS+ECO-3		8% ECO	3	13	
WFS+BA-1		10% BA	3	13	
WFS+BA-2		12% BA	3	13	
WFS+BA-3		14% BA	4	13	
WFS+BA+A		11% BA, 1% CEM	4	13	
WFSR+CEM	100% WFSR	4% CEM	3	14	
WFS+QF+CEM-1	50% WFS, 50% QF		3	11.6	90%
WFS+QF+CEM-2	25% WFS, 75% QF		3	10.4	89%
WFS+QF+CEM-3	50% WFS, 50% QF		3	11.6	96%
WFS+QF+CEM-4	25% WFS, 75% QF		3	10.4	96%

3. Results

3.1. Optimal water content and specific gravity

The water-density relationship is plotted in figure 1 based on six varied water contents applied in the laboratory test. The optimal water content and the maximum dry density of the foundry sand were determined to be 15.5% and 1.69kN/m^3 respectively. Results for QF were specific gravity of 2.04 kN/m3 and optimal water content of 9.3% [14].

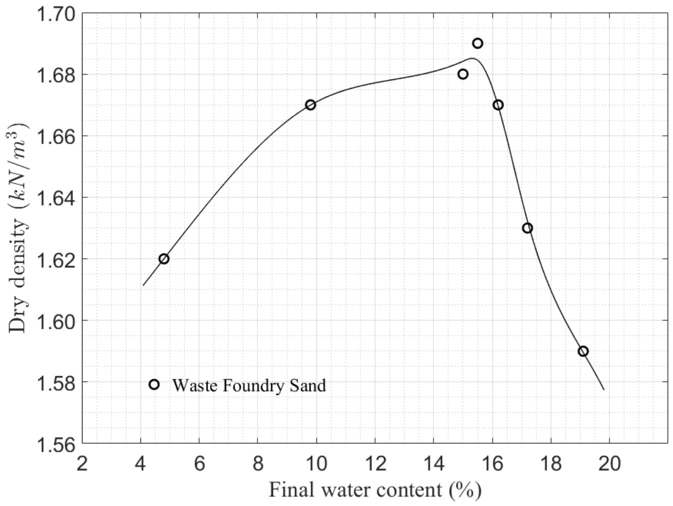

Figure 1. Optimal water content. Note: While the curve fit does not reach the highest point, that point is used in tests as the optimal values.

3.2. Gradation

The mean gradation curves for samples of WFS and QF are presented in figure 2 below.

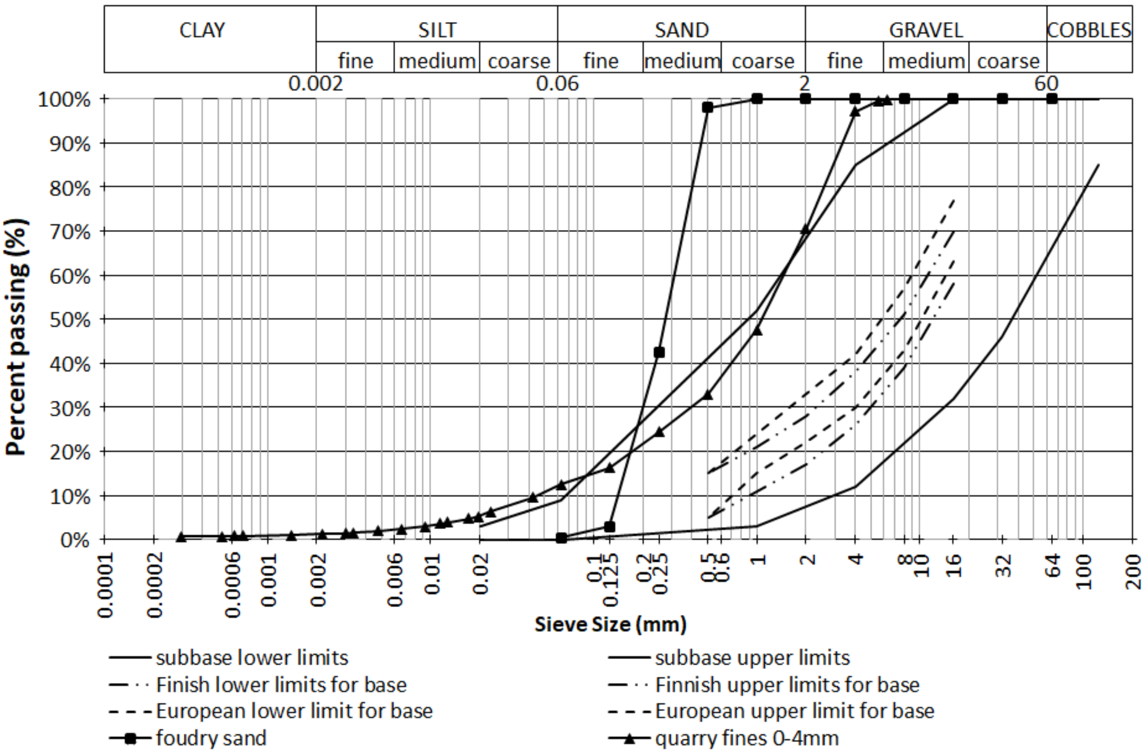

Figure 2. Gradation curves and typical limits for pavement layers

From figure 2, it is clear that the WFS is not qualified for direct applications in pavement base or subbase layers, since the gradation curve is exceeding the typical ranges. It is also found that it has a narrow grain size distribution, indicating uniform grain sizes. According to European Standard SFS-

EN ISO 14688-2: 2018 [15], the coefficient of curvature c_c and coefficient of uniformity c_u are determined to be 0.89 and 0.2, respectively. Based on the classifications WFS satisfies the requirements of $c_u < 3$ and $c_c < 1$ and therefore is by definition uniformly-graded. The gradation curve of quarry fines shows that the quarry fines can be classified as well-graded medium to coarse sand.

3.3. Minimum and maximum porosity

Based on porosity values in table 2 below, the WFS is a porous material in a dense space. This is explained by the low percentage of fine particles in its gradation. The gradation is of course fit to the casting process and dusts are separated at the foundry.

Table 2. Results for the porosities of WFS

Sample	Porosity value *e*		Porosity *n* [%]	
#	MIN	MAX	MIN	MAX
1	0.59	0.84	37.2	45.6
2	0.59	0.85	37.3	46.0
3	0.59	0.84	37.2	45.6
4	0.59	0.85	37.0	45.9
Mean value	**0.59**	**0.84**	**37.2**	**45.8**

3.4. pH

The averaged pH-values for oven-dried and non-oven-dried samples are 9.17 and 9.4 respectively, as listed in the table 3 below. The oven-dried WFS is found to be slightly more alkaline than non-oven-dried samples according to the test results, indicating possible evaporation of some acid components during heating. Compared to some pH values for the WFS in literature, the values for the alkaline WFS in this study are slightly lower [16]. However, it is normal that the pH values of WFS vary widely between foundries and process variations can affect them in any foundry.

Table 3. Results for the pH of WFS

Sample	Temperature [°C]	pH
Dried-1	22.9	9.4
Dried-2	22.9	9.39
Dried-3	22.9	9.4
Mean value		**9.4**
Non-dried-1	24.4	9.15
Non-dried-2	24.4	9.18
Non-dried-3	24.4	9.18
Mean value		**9.17**

3.5. Shear box test

Two sets of the WFS samples were investigated in the shear box test, with the first set in dry condition and the other set prepared with a target water content of 14% and all tested under a room-temperature. The results for the test series are tabulated below in table 4, where a degree of compaction is also listed for reference. The maximum deformation of the box shear tests were 0.02 in the first test series and in the second test series between 0.01 and 0.02. There is no significant difference in friction angle between the two series but cohesion is higher at the optimal water content.

Table 4. Results for the box shear test for WFS.

Sample number #	Final water content w_{FI} [%]	Friction angle ϕ [°]	Cohesion c [kPa]	Degree of compaction[a] [%]	Deformation maximum ε [%]
1	0.2–0.3	40.1	8.3	98.2–99.8	0.02
2	13.7–13.9	38.4	9.7	93.5–94.6	0.01–0.02

[a] The degree of compaction is calculated from the maximum dry density as obtained from the Proctor test.

3.6. Unconfined compressive test

As shown in figure 3, the compressive strength of stabilized WFS is highly dependent on the type of binders applied. Quick cement is the most effective type of binder to stabilize the WFS, resulting in the mixture of highest compressive strength. However, cement stabilized WFS is also the most brittle mixture among the others. The bio ash itself is not effective in stabilizing the WFS but a small amount of activator (e.g. cement) will contribute to the binding process and improve the compressive strength of the mixture significantly. The fly ash and Ecolan binder are shown to work better than the bio ash itself. In general, the compressive strength of the stabilized WFS is still not adequate for a structural layer in pavement, and further improvements are necessary.

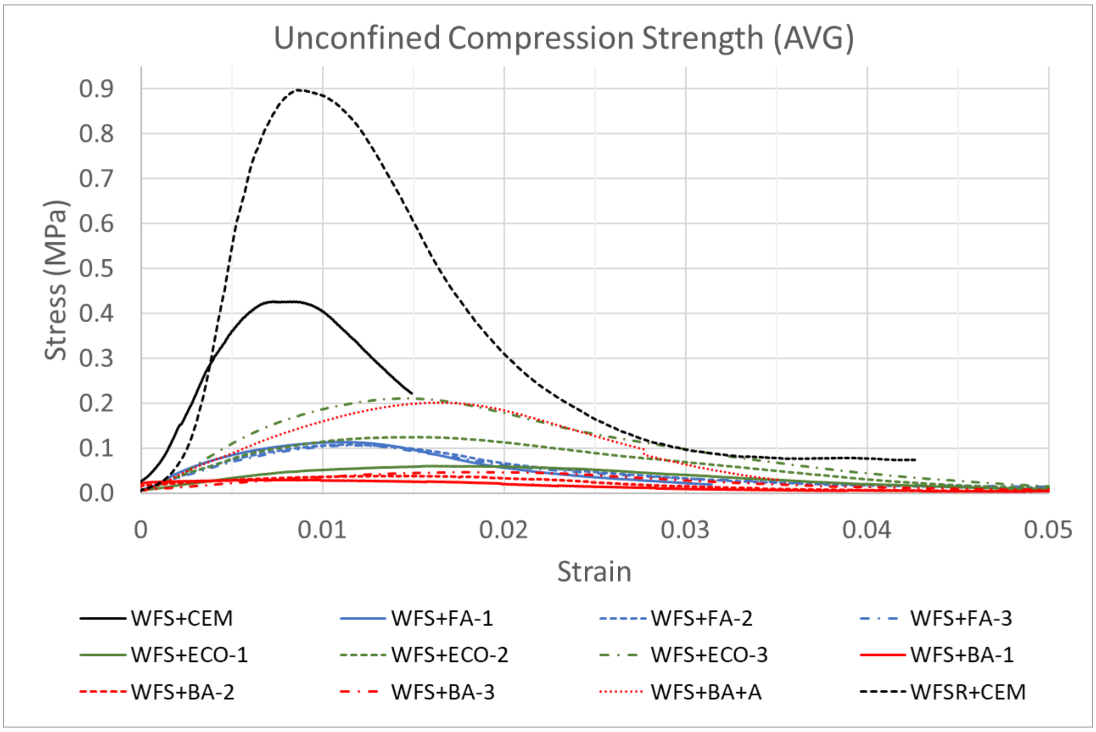

Figure 3. Results for compression strength of foundry sand mixtures

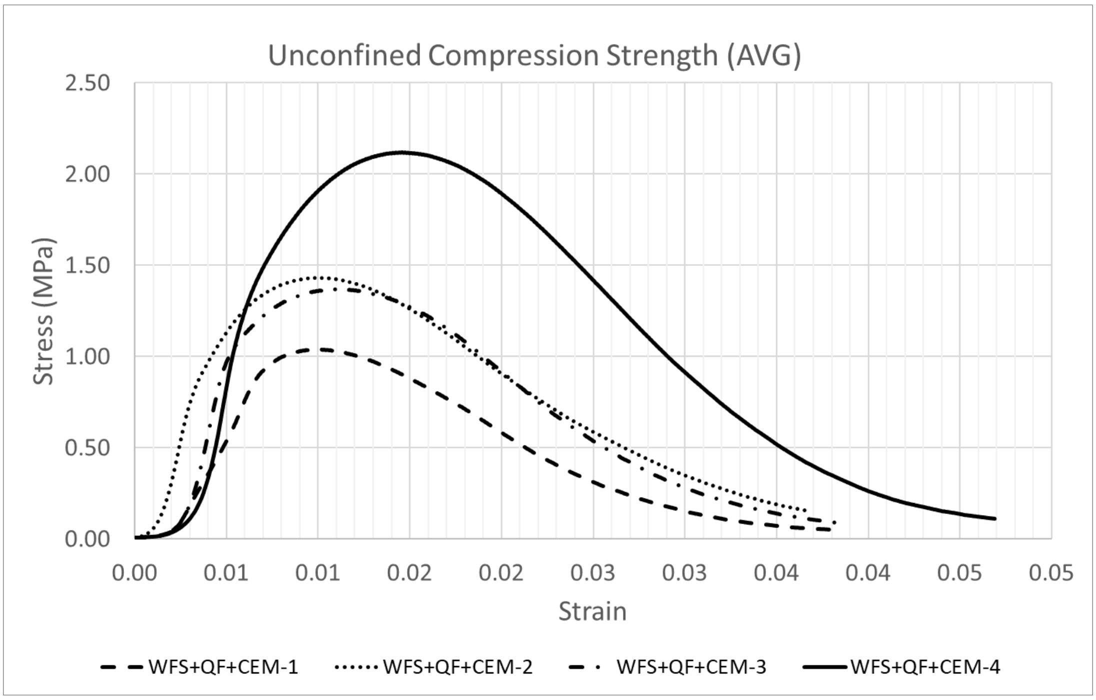

Figure 4. Results for compression strength of quarry fine and WFS mixtures

One of the methods to improve the strength of stabilized WFS, without increasing the binder content or sacrificing the merits of utilizing secondary materials, is to modify the gradation. In this study, such modification was done by adding quarry fines (0-4mm) to the WFS at different fractions to work as the aggregate skeleton. Figure 4 shows the compressive strength of stabilized WFS and quarry fine mixtures, indicating that the addition of quarry fines is effective in strength improvement. Compared with the stabilized WFS, the compressive strength of stabilized quarry fine and WFS mixture could satisfy the requirements for pavement base or subbase layers provided by some agencies [14]. The detailed information about compressive strength of stabilized WFS mixtures are listed in table 5.

Table 5. Results for compression strength of WFS mixtures

Mixture	Sample count	Compression strength [kPa]			Sample age (d)
		Minimum	Maximum	Mean value	
WFS+CEM	3	401	478	443	7
WFS+FA-1	3	111	116	114	
WFS+FA-2	3	103	117	110	
WFS+FA-3	3	99	117	107	
WFS+ECO-1	3	59	64	61	
WFS+ECO-2	3	118	133	126	
WFS+ECO-3	3	208	216	213	
WFS+BA-1	1	30	30	30	
WFS+BA-2	1	38	38	38	
WFS+BA-3	4	44	54	47	
WFS+BA+A	4	174	220	204	
WFSR+CEM	3	931	963	947	
WFS+QF+CEM-1	3	1040	1070	1060	
WFS+QF+CEM-2	3	1400	1470	1440	

WFS+QF+CEM-3	3	1360	1380	1370	6
WFS+QF+CEM-4	3	2100	2160	2120	

4. Conclusion

The virgin WFS showed capabilities for construction, but not for higher load conditions. For those applications, the results showed that with better gradations, the strength can be improved. With these initial results, it is expected that more technical applications and studies will arise. Further studies have already begun with mixtures of WFS and crushed rock of a maximum 20mm grain size.

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