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Investigations into stabilized waste foundry sand for applications in pavement structures

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ABSTRACT

The foundry industry needs effective, alternative methods to reuse the recycled waste foundry sand (WFS) other than landfills, under the new lenient legislations in Finland. In this study, the viability of stabilized WFS and crushed rock mixtures were evaluated for applications in structural layers in pavements through a series of laboratory tests and analysis. Mechanical properties including flexural and compression strength of the binders, unconfined compressive strength and resilient modulus of the mixtures were determined by standard laboratory testing methods, to provide baselines for the viability evaluations. To ensure proper durability of the mixtures as pavement construction materials, the long-term performance was investigated in terms of frost heave and resistance to freezing-thawing cycles. In general, stabilized WFS and crushed rock mixtures showed great potentials in strength and durability for pavement structural layers. Cost and emission assessment also showed that the use of foundry sand in a filter layer is beneficial in reducing cost and CO_2 emission by up to 50% and 46% compared with reference structures. This paper provides insight into the possibility and way of characterizing and improving recycled and secondary material properties for reuse in civil engineering projects. Recommendations are provided on how to further investigate and improve the properties of the stabilized WFS mixtures, and recycled materials in similar for reuse in pavement constructions.

1. Introduction

The final disposal of the waste from disposable sand molds including foundry sand and dusts has been a big challenge for the foundry industry for a long time. These wastes are traditionally treated by disposal in landfills until the strategy changed in Finland in 2013 to prohibit disposal of foundry sand in organic waste landfills, as stated in the Government Decree 331/2013 (Government, 2013). Foundry sand has also been used as structural component in landfills in the past, whereas the ceases of newly opened landfills have significantly reduced the applications of foundry sand thereof. It is then clear that new approaches of foundry sand management and utilization are highly demanded.

Targets and strategies were made in Europe during the years to promote environmental preservation, sustainability and circular economy. The Paris Climate Agreement of 2015 set the goal of limiting global warming to below two Celsius degree compared to the pre-industrial times. In the year of 2018, the European Commission set four waste directives with focuses on decreasing the amount of waste, increasing recycling, and diminishing the need for landfills, and the solid target to recycle and reuse the building and demolition waste is 70% in weight by the year of 2020. Carbon-neutral societies by the year of 2030 is targeted in the United Nations Agenda for Sustainable Development (Agenda 2030). Many big cities in Finland have committed themselves to taking action in regard to the related strategies and agenda, including the aim to promote carbon-neutrality and the wise use of resources. They defined their own targets for carbon neutrality and to support circular economy, among which the city of Helsinki is pursuing efforts to be carbon-neutral by the year 2035. The newly updated Finnish regulation, MARA Regulation (843/2017), has also entered into force in 2018. This MARA Regulation allows the use of foundry sand in fairway, field structures and industrial and warehouse infrastructure, provided that its chemical properties and application rates are within the limits specified in this regulation (Government, 2017). This makes foundry sand much easier to be utilized in construction due to the simplified government notification procedures. Achieving these aforementioned targets will require ambitious emission reduction measures from governments in all sectors, including construction (Honkonen and Kulovesi, 2019). These targets also require a much higher level of circular economy and

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promote the use of secondary materials. Such more lenient legislations, like the MARA Regulation, have provided advantages and alternative ways to reuse the by-products from the foundry industry in Finland, promoted circular economy that reduce the consumption of virgin natural resources and climate emissions from construction.

Foundry sand with improvements has showed great potentials for civil engineering purposes in some previous studies. The study by Vilenius has previously investigated the viability of foundry sand for road construction, and it is concluded that foundry sand is suitable for filter layers according to its technical properties. It is also found that with stabilization, foundry sand could be used for a load-bearing layer of a pavement structure with adequate unconfined compressive strength (Vilenius, 2019). Orkas et al. (2001) found that resin-bonded foundry sand is a good substitute for natural sands in various engineering applications, e.g. asphalt concrete and cement concrete, landfill mineral liners and so forth. The U.S. studies have also found that the resin-bonded foundry sands are suitable for road substructure, separation layer, or for a load-bearing layer with stabilization (American Foundry Society, 2019; Kleven et al., 2000). The basic geotechnical properties of WFS are known to work as low-grade fill in for example embankments. Yaghoubi et al. (2020) made a series of test with the same conclusion as from previous results by authors (Zhang et al., 2020) that WFS would need mixing with better graded aggregates to work in load-bearing structures. Yazoghli-Marzouk et al. (2014) demonstrated a successful field trial in using cement bound WFS in sub-base layer. The laboratory test for WFS containing bentonite and 6% cement were higher than in authors previous results, but that can be contributed to the use of green sand with bentonite, as that can strengthen the hydraulic bonding, unlike chemical binders used in the WFS of this research. The mixing of WFS with hydraulic binders is presented also by Gedik et al., 2008 and mixing of higher graded aggregates with addition of hydraulic binders is researched by Guney et al. (2006).

Challenges were also encountered with the attempts of WFS utilizations, and enhancement in the material properties is still necessary in the future research. Although the foundry sand has been widely applied to produce the controlled low strength material (CLSM), or as a replacement to fine aggregates/sands for the cement-based materials (Siddique and Noumow, 2008; Siddique, 2009; Venkatesan et al., 2019), its applications are still to some extend limited. The CLSM is primarily used and suitable in fill applications of a low compressive strength requirement of 2.0 MPa or less (Siddique, 2009), and an increase in the replacement level of fine aggregates/sands with foundry sand is reported in some cases harmful to the strength or freezing-thawing resistance of the mixture. In cold regions, the requirements in frost susceptibility have further restricted the replacement level. In our previous study, the viability of the utilization of the WFS in high volume as a pavement construction material has been investigated (Zhang et al., 2020). Based on a series of laboratory tests, properties of the virgin and stabilized WFS including particle size distribution, water-density relationship, pH values, box shear and compressive strength were evaluated and compared with typical values of traditional engineering materials. Stabilization is recommended due to the low frost susceptibility as observed for the virgin WFS, whereas insufficient strength of the stabilized WFS has promoted the utilization of a mixture containing not only WFS but also coarser aggregates. Quarry fines of 0–4 mm grain size were added with coarser aggregate in the first trial where improved compressive strength has been observed, indicating high potentials of such modified and stabilized WFS mixtures for pavement constructions. However, the strength is still at the lower boundary as required for pavement structural layers, thus further modification is needed. In addition, the durability of the mixtures is also a key factor to be checked to consider the environmental effects and long-term performance.

As part of the Business Finland funded research project 3204/31/2018, this study is based on previous research outcomes and aims at approaches for better mechanical properties of the stabilized waste foundry sand (WFS) mixtures, to enable its applications in high volume for pavement structural layers especially under the Nordic conditions. Further investigation on the dynamic responses and durability in term of frost susceptibility is another highlight of this study. This would be beneficial for improving the competitiveness of foundries through environmental awareness, circular economy-based approaches and the development of industrial symbiosis in response to changed legislation on foundry by-products and disposal (Sappinen et al., 2018).

2. Materials

2.1. Virgin foundry sand

The foundry sand consists of mostly pure quartz sand that has been bound to retain the shape of the mold and then broken down after pouring and solidifying of the metal. In the casting process, a fine grain with uniform grain sizes is preferred. Fine grains provide a smooth casting surface and uniform grain size distribution that provides permeability for gasses formed during interaction between molten metal and sand. It is an engineered fit for the process, but a challenging property for earth construction.

Different binder types exist in the molding process. The most common method globally is green sand bound with bentonite clay which has been proven to work also in pavement stabilization (Guney et al., 2006). For this research though, the foundry sand was bound with ester cured alkaline phenolic resin, a two-part chemical binder with alkalic properties. It was chosen because it is the most used type in Finland, and because foundry sand without bentonite is more challenging to be utilized in construction. No investigation is made into leachate characteristics of the sands, as that is well researched (Mroueh, 2002 and Siddique et al., 2010) and foundries already know if their waste is in legislative limits. Some field trials made in the industry have shown that the legislative limits that might hinder utilization are maximum concentrations of 0.2 mg/kg benzene in green sand, 10 mg/kg phenolic compounds in furan sands and 500 mg/kg dissolved organic carbon in ester-cured alkaline phenolic sands. Foundries also have the possibility to store their sands to promote evaporation of controlled compounds before utilization in a structure, if their sand is not in legislative limits straight from the casting process. These aspects are currently being researched too, so the focus of this paper was put on technical performance and not on the environmental compatibility of the sands.

WFS is produced around 65 000 tons annually in Finland, estimated with a thumb rule of 1 ton WFS per 1 ton of produced ferrous castings (CAEF, Production ferrous (2018)). While that amount is a burden for the Finnish foundry business to take care of, amounts like that are easily manageable from road construction's perspective. Therefore using WFS in less structurally demanding and more mass centric structures like embankments, which are also more researched (Arulrajah et al., 2017), was not perceived as important as trying to get the best out of it with fewer amounts and then combining with other materials that also need ways of efficiently reuse.

2.2. Stabilized mixture of waste foundry sand and coarser aggregates

Previous research has confirmed that the virgin WFS has capabilities for construction but not for pavements of higher load conditions. To improve the mechanical properties and broader the applications of virgin WFS, coarser aggregates were added to achieve better gradations. Crushed rock (0–20 mm) which was sieved from 0 to 32 mm to remove the particles above grain sizes of 20 mm, was selected as coarser aggregates to mix with the WFS. The crushed rock is produced from high-quality host rock with major mineral compositions of plagioclase, quartz, feldspar, and low percentages of soft minerals.

The mixture of the WFS and crushed rock is further stabilized with several sustainable ashes including fly ash, the Ecolan recycled binder composed of coal ash, wood biomass, lime and cement, and bio ash for tests. The quick cement is used as a reference binder with major

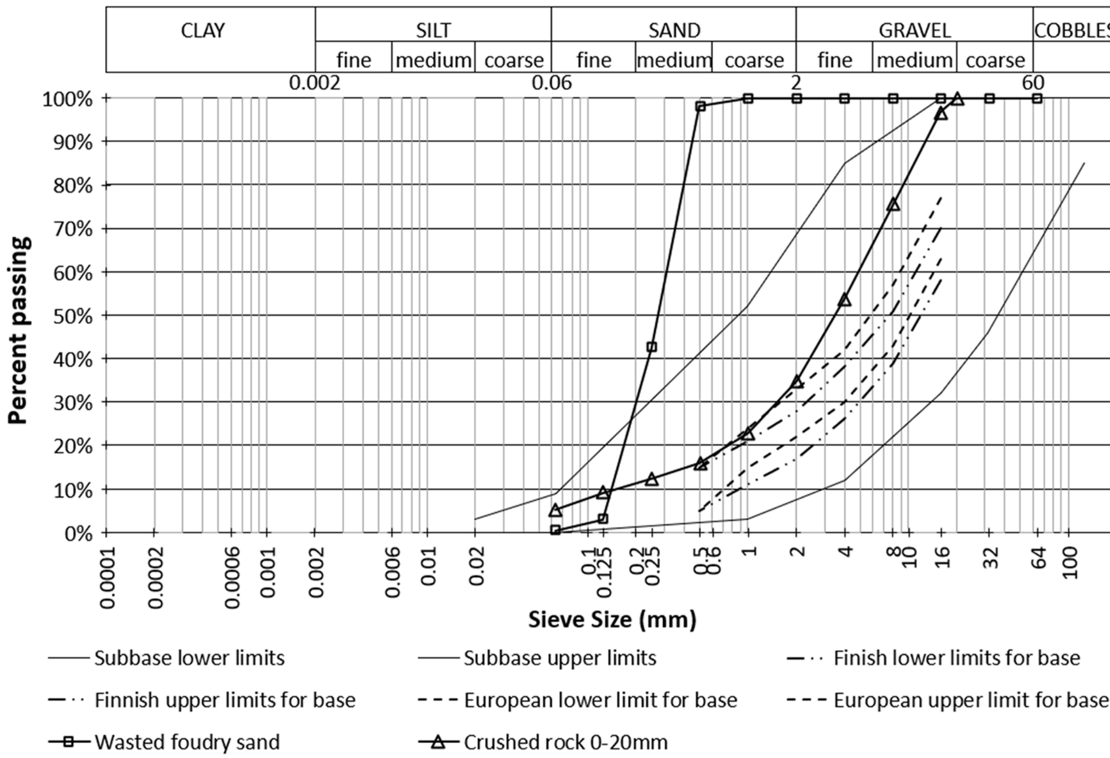

Fig. 1. Particle grain size distributions of the WFS, crushed rock.

chemical compositions of CaO and SiO_2 in mass percentages of 63 to 65 and 20 to 22 respectively. The binder content was selected based on the reference values provided by standard and literature, as well as by experience from the previous research by Aalto University on quarry fines (0–4 mm). According to the superstructure stabilization guide (FINNRA, 2007) the amount of cement for the cement stabilized mixture is recommended as 2.5–7.0% by weight, and for mixtures stabilized with blast furnace slag 10–15% by weight (no activator) or 4–10% by weight (with activator) is recommended. The amount of activator is typically 0.5–1.5% by weight of the added binder. Within these recommended reference ranges, 4% of quick cement was adopted for all the reference mixtures, while the suggestions for blast furnace slag were scaled for all the other mixtures with and without an activator.

The gradations of the selected materials were examined by dry sieving method according to the SFS standard EN-933–1 (Finnish Standards Association, 2012a, Finnish Standards Association, 2012b) and SFS-EN 993–2 (Finnish Standards Association 1996). The measured grain size distributions are shown in Fig. 1.

The water-density relationship of the WFS can be found from previous research published (Zhang et al., 2020). The crushed rock of maximum 20 mm particle size is a self-draining material so that the optimal water content would be difficult to identify. An alternative way was performed where 10% water by weight was added to the crushed rock and compaction was done by gyratory compactor ICT until the sample reached stable density. Typical operation parameters of 22 mrad (1.261°) angle of gyration, 26.2 rpm rotational speed, and 600 kPa pressure have been adopted. The maximum dry density was determined to be 1.97 g/cm^3 and the corresponding final water content was 5.78%. The optimal water content of the stabilized WFS and crushed rock mixtures were determined by the similar method to be 5.3%, 4.8%, 5.31% and 5.1% when cement, Ecolan, fly ash with activator and bio ash with activator were used as stabilizers. Based on these results, 6% of water content was selected for specimen preparation to assure adequate compaction but to avoid excessive water with fine particles draining out during compaction.

3. Investigation into stabilized foundry sand mixtures

3.1. Sample preparation

Typical mixing method for concrete fabrication was followed to prepare stabilized mixtures of the WFS and quarry fines in Aalto University's Concrete Laboratory. Stabilized mixtures of the WFS and crushed rock were manually prepared due to the limited capability of mixing machine in availability. However, all the mixtures were prepared in an identical way that dry materials were blended firstly, followed by adding water to the mixtures with stirring to form homogeneous mixtures. All stabilized specimens for mechanical property test were manufactured by an ICT gyratory compactor into cylinders to a 96% degree of compaction, which is recommended for Non-Cement Stabilization by the superstructure stabilization guide (FINNRA,2007). Cement-stabilized mixtures were also compacted to 96% degree of compaction (97% in the guide), for better comparison between mixtures. The stabilized specimens were prepared to cylinders of 100 mm in diameter while heights varied to follow the requirements for different types of test. All the stabilized specimens were stored in the conditioning room at an ambient temperature around 20 °C and 95% humidity, until they reached the ages of 7-day, 28-day or 91-day.

The binder-only specimens were also prepared at room temperature to investigate the compressive and flexural strength of different binder materials. The preparation was started by mixing and stirring binder and water in a ratio of 2:1, firstly at a low rotation speed for 90 s and then at a faster rotation speed for 60 s. The well-mixed binder was then cast into prismatic steel molds with length of 160 mm, height and width of 40 mm. After casting, surface of the specimen was smoothed out with a spreader and a plastic wrap was placed on the top of the mold to prevent evaporation of water. The test pieces were allowed to strengthen in molds for 24 h at ambient temperature of 23 °C, and cured in conditioning room at 95% humidity for 28 days. Three and six parallel samples were prepared for the bending and compression test respectively (Vilenius, 2019; Juuti, 2020).

Different types of mixtures and specimens as prepared in this study

Table 1
List of specimens for mechanical property tests.

Stabilized mixture	Aggregate mixture	Binder content%	Water content%	Degree of compaction	Age	Sample dimensions	Type of test
WFS-CR-CEM	WFS (25%) + CR 0/20 (75%)	Quick cement 4%	6.0	96%	7-day 28-day 91-day	Cylinder, diameter 100 mm, height 120mm	UCS
WFS-CR-FA	WFS (25%) + CR 0/20 (75%)	Fly ash + activator 10% + 2%	6.0	96%	7-day 28-day 91-day	Cylinder, diameter 100 mm, height 120mm	UCS
WFS-CR-BA	WFS (25%) + CR 0/20 (75%)	Bio ash + activator 8% + 2%	6.0	96%	7-day 28-day 91-day	Cylinder, diameter 100 mm, height 120mm	UCS
WFS-CR-ECO	WFS (25%) + CR 0/20 (75%)	Ecolan binder 8%	6.0	96%	7-day 28-day 91-day	Cylinder, diameter 100 mm, height 120mm	UCS
WFS-CR-CEM	WFS (25%) + CR 0/20 (75%)	Quick cement 4%	6.0	96%	41-day	Cylinder, diameter 100 mm, height 200mm	Resilient modulus
WFS-CR-FA	WFS (25%) + CR 0/20 (75%)	Fly ash + activator 10% + 2%	6.0	96%	41-day	Cylinder, diameter 100 mm, height 200mm	Resilient modulus
WFS-CR-ECO	WFS (25%) + CR 0/20 (75%)	Ecolan binder 8%	6.0	96%	41-day	Cylinder, diameter 100 mm, height 200mm	Resilient modulus

Note: 1. CR refers to crushed rock; 2. Triplicated specimens were prepared and tested for each mixture; 3. Quick cement is used as the activator.

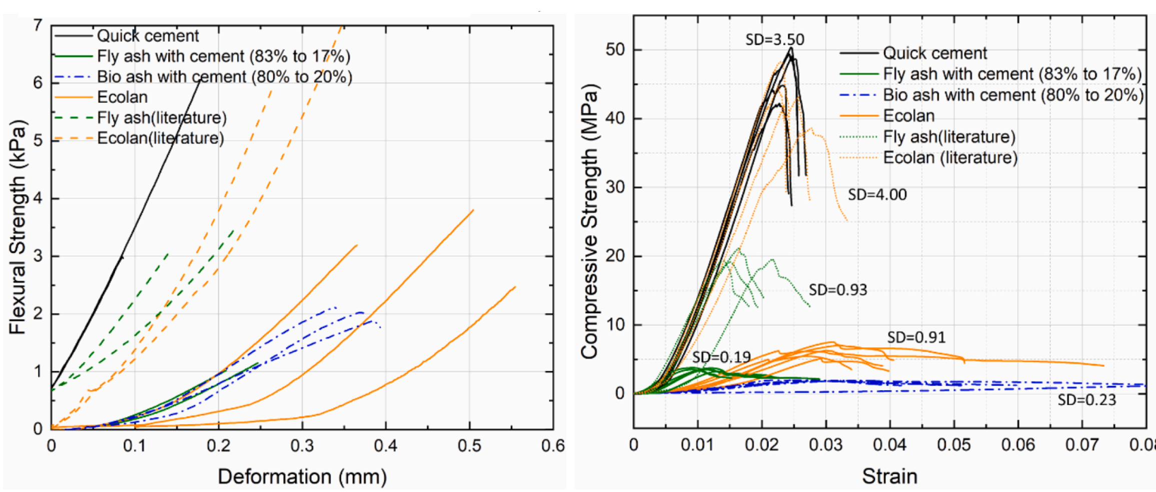

Fig. 2. Flexural strength and compressive strength of binder prisms.

are listed in Table 1. It should be noticed that some of the bio-ash-stabilized samples were observed expansion failures during curing stage, which could be a result of chemical incompatibility but requires confirmation by further research. Therefore, they are excluded in the resilient modulus test.

3.2. *Flexural and compression strength of binders*

Flexural and compression strength of the binders have been investigated according to the European Standard SFS-EN 196–1 (Finnish Standards Association, 2016). The standard is developed to determine the mechanical properties of cement mortar, whereas it has also been applied on other types of binder mixtures in this study. An activator of quick cement was added to fabricate fly ash and bio ash specimens to promote the formation of cementitious materials, and to imitate the composition of the stabilized WFS and crushed rock mixtures.

The flexural tensile strength and compressive strength with Standard Deviation (SD) of different binders are shown in Fig. 2. The results of the flexural tensile and uniaxial compressive strength tests are in line with the UCS of stabilized WFS mixtures. Quick cement is the strongest binder under three-point bending and compressive loadings, followed by the Ecolan's binder. The flexural tensile strength of fly ash with activator remains the lowest, whereas bio ash with activator shows slightly higher strength comparatively. This might be explained by a higher degree of activator concentration of the bio-ash mixture.

Different types of binders with varied components, for example, pozzolanic-material-based or cementitious-material based, determine the chemical reactions within the aggregate, binder and water, and consequently influence the development of strength. Nevertheless, discrepancies in strength of the same binder type are found in comparison with literature (Xiong, 2018), even though most of the test conditions were kept the same, including water to cement ratio, specimen

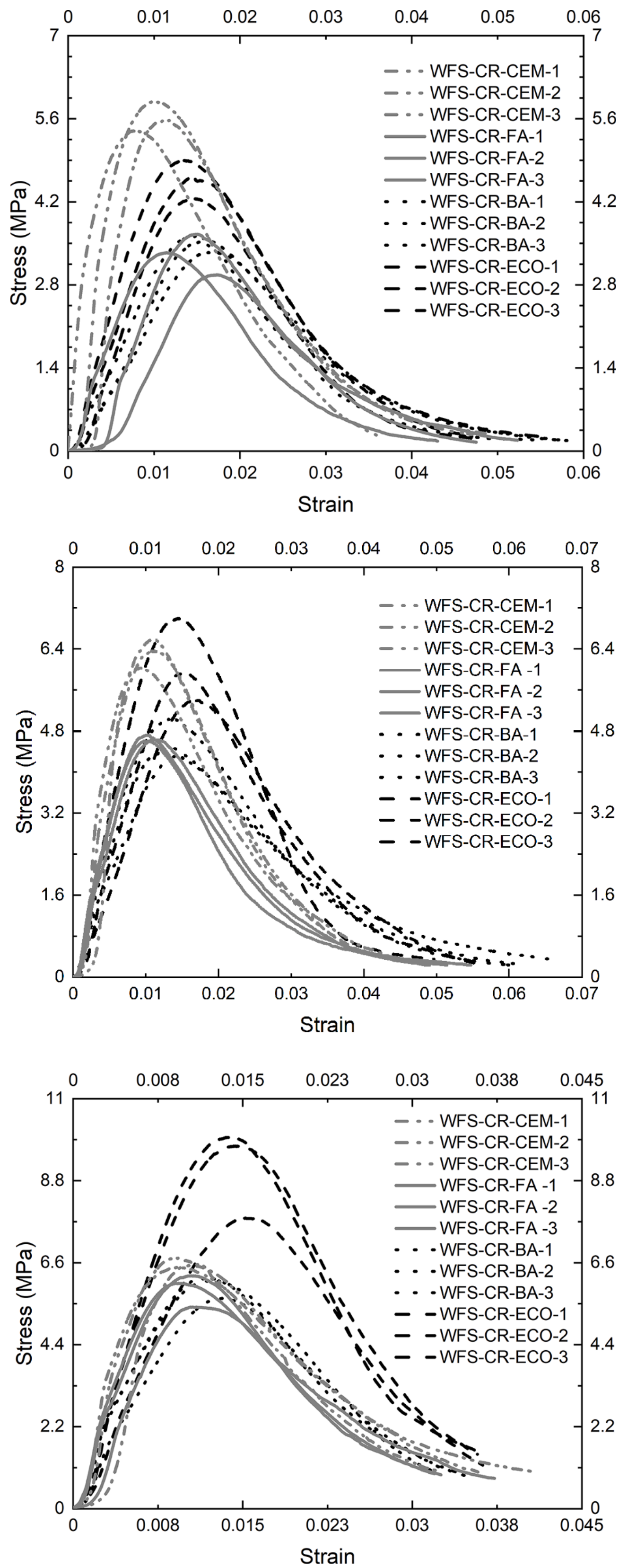

Fig. 3. Unconfined compressive strength of stabilized WFS at 7-day, 28-day and 91-day age.

preparation and curing conditions. This indicates that the variations in strength could result from the specific compositions of the tested binder materials. In fact, since the Ecolan and fly ash binders are from different batches where compositions are confirmed to have been changed compared with those adopted in literature, a decrease in strength is possible as shown in Fig. 2. Another possible source of the strength discrepancy could be the different test operators, but the main cause still remains uncertain.

3.3. Unconfined compressive strength of mixtures

The compressive strength of stabilized mixtures of foundry sand and crushed rock was determined according to the standard SFS-EN 13,286–41 (Finnish Standards Association, 2003). The obtained compressive strengths with standard deviations for 7-day, 28-day and 91-day-old test specimens are shown in Fig. 3.

The observed compressive strength of stabilized WFS and crushed rock mixtures show the development of compressive strength with increased curing time for all binder types. At 7-day age, it is clear that quick cement stabilized material has the highest compressive strength, followed by the Ecolan-stabilized test pieces. The binding effects of fly ash and bio ash with activator are comparable at 7-day age. However, the strength of specimens stabilized with Ecolan binder improved faster than the others from 7 days to 28 days. As a result, individual strength has exceeded that of specimens stabilized with quick cement, and the averaged strengths are comparable at 28-day age. There is, again, no significant difference between the compressive strength of specimens stabilized with fly ash and bio ash (with activator) at 28-day age. From 28 days to 91 days, the constantly fast growth of compressive strength of Ecolan stabilized mixture has made it of the highest compressive strength. It is also interesting to notice that during this period, there is only a slight increment of compressive strength in cement stabilized mixture, whereas the constantly development of strength was observed on mixtures stabilized with fly ash or bio ash. At the age of 91 days, there is almost no difference in strength among the mixtures with cement, fly ash or bio ash as binders. The slowdown in the development of strength was expected for quick cement because the binder type indicates that it should gain most strength during the first few days.

Compressive strength requirements for cement stabilization according to the superstructure stabilization guide are shown in red lines in Fig. 4. As can be seen from Fig. 4, the strength of all stabilized mixtures can satisfy the required strength for cement-stabilized materials (3–5 MPa) at 7-day age. Note that at 28-day age, the mixture stabilized with fly ash or bio ash hardly meets the requirement, but there is continuous pozzolanic reaction and strength development till 91-day age. Compared with the requirements for activated blast furnace slag (activator 0.5–1.3 wt.%), the mixtures stabilized with activated fly ash or bio ash have also shown higher strength at all ages. The results indicate that as long as the curing time of 3 months can be assured, the strength of mixtures stabilized with fly ash or bio ash can be as high as that of cement stabilized mixtures. However, since the strength of fly ash- or bio ash-stabilized WFS is slightly lower than the requirements at 28-day age, special measurements might be necessary for applications where early strength is important.

3.4. Cyclic load test

The cyclic triaxial test investigates the ability of a material to withstand repeated load in accordance with traffic loadings in the road structure. The resilient modulus as obtained from the test describes the relationship between stress and reversible deformation during the time of a single load impulse, which is often shown in relation to the sum of the principal stresses, i.e. the sum of deviatoric and triple of the hydrostatic stress. Resilient modulus is also used to predict modulus of elasticity or for fatigue analysis in the design of road structures.

Cyclic triaxial test was performed on the stabilized WFS specimens

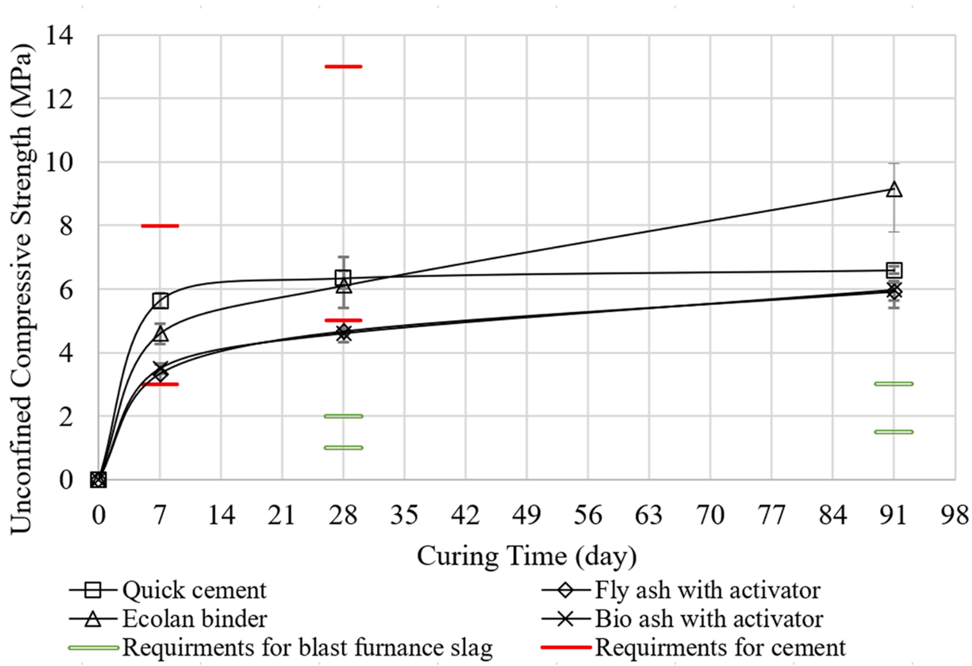

Fig. 4. Development of compressive strength over time.

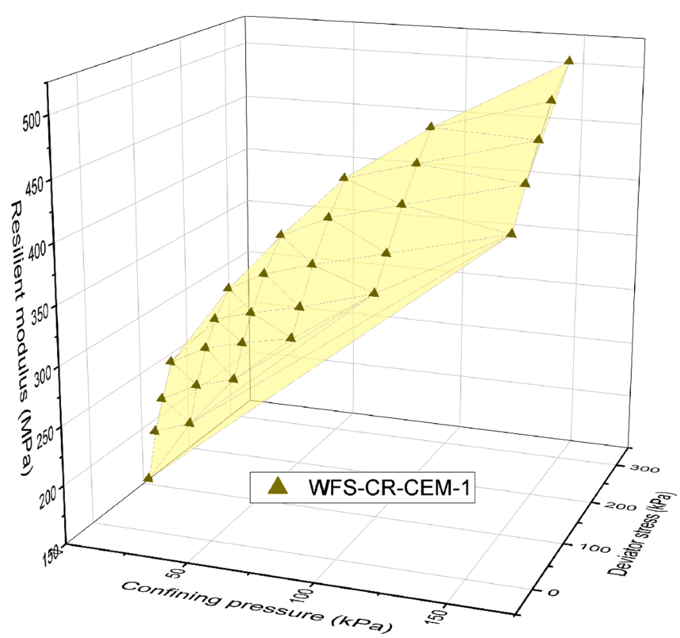

Fig. 5. Typical relationship between resilient modulus, confining pressure and deviator stress of the stabilized WFS mixtures.

according to the European standard SFS-EN 13,286–7 (Finnish Standards Association, 2004), applying a constant cell pressure from 20 to 150 kPa and low stress levels from 20 to 300 kPa. In this method, only deviatoric stress was changed while cell pressure remained stable for each step. The experiment was performed using an IPC UTM-25 device and a UTS data management program.

Triplicated cylindrical specimens of each binder were prepared for the experiment, with a diameter of 100 mm and a height of 200 mm. Two membranes were placed around the specimens for better assurance of air tightness and accurate confining pressure. Experiment was conducted when specimens were at age of 41 days due to unexpected technical problems which were then solved to avoid affecting the results. No preloading was performed considering the test specimens were stabilized. Vertical deformation was measured by two LDVTs attached to the loading plate outside the pressure cell, as well as the internal sensor of load cell. The loading system was placed in an environmental chamber where the temperature was controlled at 21 °C.

Similar to unbound granular materials, resilient moduli of stabilized WFS mixtures increase with the confining pressure or deviator stress when the other keeps constant. Such relationship can be interpreted as the surface plotting in Fig. 5. Compared with unbound granular materials, the resilient modulus of stabilized mixture is higher, but much less dependent on stress state. That is, the mixtures do not behave as differently under different stress conditions as the unbound materials do.

Ehrola (1996) reported that when the sum of principal stresses is at 200 kPa, the obtained resilient modulus is approximately corresponding to the modulus of bearing layer materials in the Finnish Odemark design method. This, however, does not apply to stabilized or bonded material well. According to the Finnish Agency's design guidelines, 1500 MPa should be used as the E-modulus for hydraulically bonded material with a cement strength of more than 3 MPa, or 3500 MPa for cement strength greater than 5 MPa. Nevertheless, it can be seen from the results that the resilient modulus of stabilized WFS mixtures hardly reach as high as the specified values, indicating that the selection of the modulus for this stabilized WFS mixtures in design procedures should be carefully considered, and probably corresponding to realistic stress status.

$$M_R = 216.92\left(\frac{\theta}{P_a}\right)^{0.18}\cdot\left(\frac{\tau_{oct}}{P_a}+1\right)^{0.68} \tag{1}$$

Where M_R is the resilient modulus; θ is the sum of principal stresses; τ_{oct} is the octahedral shear stress; P_a is the atmospheric pressure.

An empirical prediction model has been used to fit all the measured resilient modulus data of the stabilized WFS mixtures, and the resultant parameters are shown in Eq. (1). As can be seen from left side in Fig. 6, the data points are to some extend scattering around the equality line. Even though this prediction model is not perfectly describing the resilient modulus of the stabilized WFS mixtures of various binder types, it's still better than some other prediction models without octahedral stress considered, according to comparisons performed additionally. The results also indicate that the type of binder is a key factor to the behavior

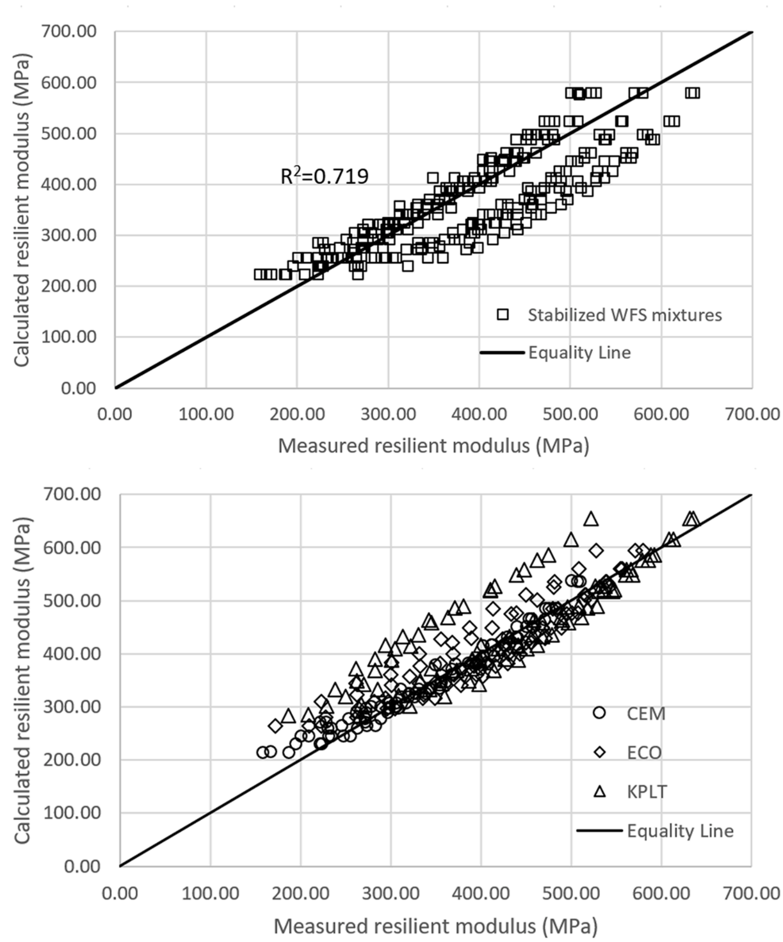

Fig. 6. Measured versus calculated resilient modulus of the stabilized WFS mixtures.

of the stabilized mixture, since better fitting could be achieved for some individual binder type than the others as shown on the right side. The coefficients of determination of individual fitting for cement and Ecolan are 0.96 and 0.85 respectively, compared to 0.72 for the fly ash and all-data fitting.

3.5. Frost heave test

Frost activity refers to the phenomenon where pore water freezes (at about 0 °C) and expands inside the voids, which is unfavorable because it causes a change in volume and as a result the ground level begins to rise. The amount of frost heave depends on the material properties especially grain size and its distribution, the amount of available water in the pores and supplies, and the temperature conditions. Due to the disadvantages of frost heave to pavement infrastructures, the level of frost activities must be controlled within the designed values. The frost heave test is a laboratory test method modeling the natural frost condition to quantitatively determine the intensity of frost potential for a certain material, given in the frost coefficient of segregation potential (SP). The SP is the ratio of the rate of frost heave to the temperature gradient of the frozen bed, in unit of mm^2/Kh.

Specimens were prepared at a target water content of 6.0% and compacted to reach 96% degree of compaction. One cylinder test piece with a diameter and height of 100 mm was prepared from each binder mixture for the frost heave test. They were cured for 28 days, frozen in the freezer and installed pre-frozen in the frost heave test equipment. The frost heave test was performed according to the method description TPPT 6 (Onninen, 2001), with a split frost cell built at Aalto University. The depth of frost boundary and the change in height of the sample were measured and recorded every five minutes during the frost heave test by transducers embedded in the split cell. Fig. 7 illustrates the setups of the frost heave test.

The quick cement stabilized sample have shown no frost heave at all during the entire test. Samples stabilized with other binders only had a slight frost heave at the end of the test possibly due to comparatively slow development of strength to resist the tensile force. According to the measured values of the frost coefficient SP for the stabilized WFS specimens as shown in Table 2, as well as the classification standards (ISSMFE-TC 8, 1989, Slunga et al., 2005), the stabilized WFS is classified as a non-frost-susceptible material since the segregation potential was all well below 0.5 mm^2/Kh.

The low frost-heave results are as expected because the bound mixtures can withstand tension force so that the expansion from freezing water could not break the bonds between the granules as long as the binding is strong enough. It is found that frost heave can hardly occur in a stabilized material if its compressive strength reaches at least 5 Mpa. In that case the tensile strength of the stabilized material is also sufficient (Thom, 2008). In this study, it is found that even though the 28-day compressive strength of fly ash-stabilized mixture was less than 5 MPa, still no significant frost heave was observed. This might be partly explained by the low water permeability of the stabilized materials as determined in previous research (Zhang et al., 2019). Low water permeability could prevent the formation of ice lens by preventing additional water flow required to supply the freezing front.

It should be noted that the frost heave test was also performed on virgin WFS specimens with no coarser aggregates added in a previous study. A higher segregation potential of 0.17mm^2/Kh was obtained as determined by the same test method. This is expected because the

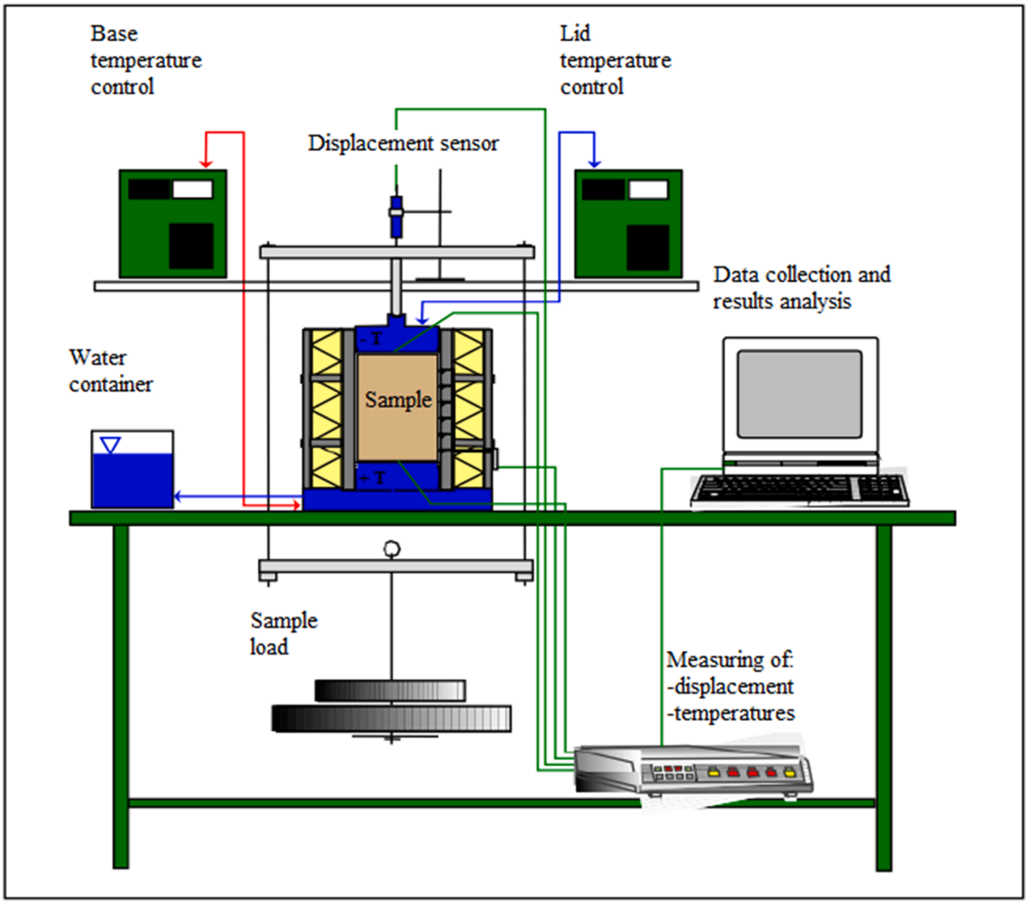

Fig. 7. Frost heave test setups (Onninen 2001).

Table 2
Frost heave properties of stabilized WFS specimens.

Frost heave test results	*Height before test (mm)*	*Height after test (mm)*	*Water content before test (%)*	*Water content after test (%)*	*Measured frost heave (mm)*	*Calculated frost depth (mm) **	*Segregation potential (mm^2/Kh)*
Quick cement	100.4	100.4	6.1	7.0	0.0	76.0	0.04
Fly ash	100.3	100.4	7.0	8.0	0.1	70.0	0.01
Ecolan	100.7	101.4	6.8	7.3	0.7	62.0	0.10
Frost Class	Negligible		Low		Medium		Strong
SP (mm^2/Kh)	<0.5		0.5–1.5		1.5–3.0		>3.0

* Calculated as the average of the last 10 observations.

stabilized mixtures with coarser aggregates would be less frost susceptible due to larger nominal maximum particle size, in addition to the binding effects provided by the stabilizers.

3.6. Freezing-thawing resistance

The freeze-thawing resistance of the stabilized WFS mixtures was determined by following the technical specification CEN / TS 13,286–54 (Finnish Standard Association (2014)) and European standard SFS-EN 13,286–41 (Finnish Standards Association,2003). During the test, half of the test pieces were exposed to 20 freezing-thawing cycles whereas the rest were regularly cured and worked as the control group. Comparison between the compressive strengths of test pieces subjected to different conditioning situations provides an indicator of the freezing-thawing resistance: strength ratio, as listed in Eq. (2) and Table 3. The Set A specimens were exposed to freeze-thaw cycles while the Set B specimens were a control group in regular conditioning room throughout the conditioning period.

$$R = \frac{R_A}{R_B} \cdot 100\% \tag{2}$$

Where R_A and R_B are the compressive strengths of test pieces in Set A and B subjected to different conditioning situations.

The results show that the strengths of the cement-stabilized specimens decreased slightly as a result of frost stress, while those stabilized with fly ash clearly lost more strength. The strengths of the Ecolan-stabilized specimens are not affected by frost stress and even slightly higher strength was measured from the specimens subjected to freezing-thawing cycles. Such increase in unconfined compressive strength should not be the consequence of freezing-thawing cycles but rather the variations between individual specimens, considering that only a few specimens were tested. This indicates, however, that the effects of freezing-thawing conditions on Ecolan-stabilized WFS mixtures were very limited, if not none.

According to the superstructure stabilization guide (FINNRA, 2007), the compressive strength of cement-stabilized material must be at least 67% of the strength obtained without a frost stress. However, the

Table 3
Freezing-thawing resistance of stabilized WFS mixtures.

Type of mixture		Unconfined compressive strength (MPa)	Strength ratio R_A / R_B (%)
Set A	CEM 1	6.72	94.44
	CEM 2	6.69	
	Average	6.71	
Set B	CEM 3	7.47	
	CEM 4	6.73	
	Average	7.10	
Set A	AFA 1	6.23	76.19
	AFA 2	5.21	
	Average	5.72	
Set B	AFA 3	7.26	
	AFA 4	7.76	
	Average	7.51	
Set A	ECO 1	8.31	101.19
	ECO 2	7.69	
	Average	8.00	
Set B	ECO 3	7.53	
	ECO 4	8.28	
	Average	7.91	

[1]Set A are duplicated specimens with 20 freezing-thawing cycles; Set B are duplicated specimens of regular curing conditions.
[2]CEM: quick cement; AFA: activated fly ash; ECO: Ecolan.

guideline specified another test method based on PANK-4305 (PANK, 2008), where the specimens should be immersed under water during the thawing cycle and the frequency of freeze-thaw cycles is doubled than adopted in this study. Since stricter conditioning requirements are specified in the guidelines, it is estimated that the results from this study is less conservative even though all the tested mixtures have met the requirements.

The result for cement-stabilized specimens is well in line with previous studies where a reduction in compressive strength of 3% (10 freeze-thaw cycles), 5%−7% (12 freeze-thaw cycles) for the cement-stabilized crushed rock, and 5%−9% for the cement-stabilized quarry fines (10 freeze-thaw cycles) were reported (Melander, 2018; Zhang et al., 2019;Kortelainen, 2019). Significant loss of strength after freezing thawing for activated fly ash stabilized mixtures was also observed on quarry fine specimens previously (Zhang et al., 2019). The lower freeze-thaw resistance of specimens stabilized by activated fly ash may be related to its slower development of compressive strength. The development of the strength is severely disturbed during freezing-thawing cycles, while the strength of the control pieces develops steadily in the curing room. As a result, the strength ratio is low for such specimens which rely on comparatively slow pozzolanic reactions to gain strength and to withstand the deteriorations during freeze-thaw cycles. For Ecolan-stabilized mixtures, complicated results were found in comparison with literature. Reductions in strength of 2.2% and 19.2% were reported due to the freeze-thaw cycles in literature (Melander, 2018; Zhang et al., 2019), which might be resulted from the different granular material as adopted, degree of compaction of the specimens, and changing compositions of the binder product.

As for the failure mode in compression, all test pieces failed in a similar way. The stress-strain behavior is almost linear before fracture which occurs with a small deformation, and after the initiation of fracture the stress decreases rapidly, indicating that the mixtures in this study are brittle. Therefore, when the stabilized WFS mixtures are subjected to failure conditions under compression, deficiency in resisting deformations and a quick reduction in strength should be expected.

4. Simplified estimation on cost and emission

With the increasing attentions and efforts towards a sustainable society, the sustainable use of natural resources and the reduction of emissions have become important considerations in project decision-making. The environmental impact of a project can be evaluated by Life Cycle Assessment (LCA) on the basis of emission calculations. The calculation can be limited to a certain phase in the life cycle of the structure (e.g. only in construction phase), where CO_2 alone or CO_2 equivalent emissions from conversion of all-climate-change emissions are calculated. (Teittinen,2019). In this section, comparisons based on a simplified cost and emission assessments of different pavement structures were performed. Structures containing a filter layer of foundry sand, natural sand or filter cloth with thicker separation layer were analyzed.

There are some assumptions made to simplify the calculation: (1) The calculation is limited to the phases from materials processing to the completion of the structure construction, including only emissions from the manufacture, transport, application and compaction of the material in pavement construction. (2) Only separation layer and filter layer are considered in the calculation. (3) The width of the structure is assumed to be 10 m, and the transport distance for all materials is assumed to be 20 km. Based on the emission parameters provided by Aulakoski et al. (2014) and Rapal's Fore system (Rapal Oy 2020), the estimated cost and

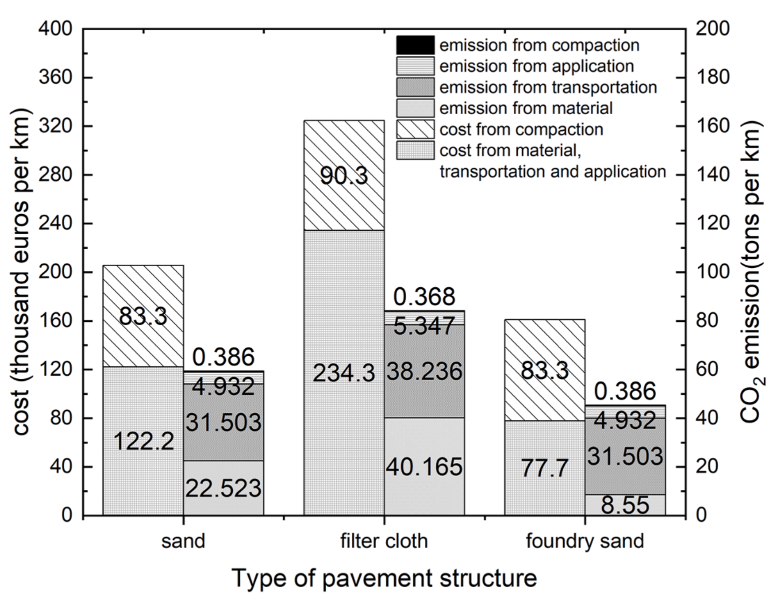

Fig. 8. Cost and emission assessment.

emissions are presented in Fig. 8.

The results show that the total cost savings are 22% and up to 50% by using foundry sand in filter layer compared to the conventional natural sand structure and the structure of filter cloth with a thicker separation layer. The reduction in CO_2 emissions are also as high as 24% and 46% by using foundry sand. Detailed subsections in costs and emissions further show that the cost savings are mainly from the cost of materials and its application and compaction, where foundry sand has the great benefit of zero material cost. In emissions, one of the main sources is processing of the structural materials. Since foundry sand does not need to be processed at all for reuse, the structure with foundry sand filter layer has the lowest calculated emission. When a filter cloth is used, a thicker separation layer of crushed rock should be applied to satisfy the frost resistance requirements, which increase the emissions significantly from processing of the crushed rock. In should be noted that due to the poor availability of natural sand especially in southern Finland, costs in transport may in fact be significantly higher than that in this comparison. Therefore, in many projects natural sand is replaced by crushed rock due to scarcity, but the emissions are still high. The foundry sand structure, however, has clear benefits in both cost and emission in comparison with the conventional choices.

5. Conclusion and discussion

In order to improve the mechanical properties of the stabilized WFS and enable its high-volume applications in pavement structural layers, coarser aggregates were added to fabricate stabilized WFS mixtures. Sustainable stabilizers containing one or several kinds of the quick cement, fly ash, bio ash or lime were adopted for the mixtures. The viability of such stabilized WFS mixtures for applications in pavements was evaluated in terms of strength and durability by series of laboratory tests. Generally, the mixtures have shown great potentials for the intended applications even though further study is necessary in enhancing the early-stage strength for the mixtures by activated fly ash and bio ash-based stabilizers.

- The flexural tensile and uniaxial compressive strength of binders are found to be in line with the UCS of the WFS mixtures stabilized by the respective binder. Quick cement is the most effective binder to improve strength, followed by the Ecolan's binder which is a combination of coal ash, cement and lime. The activated fly ash and activated bio ash have shown similar binding effects for stabilizing the WFS.
- Curing time has been found to be a significant factor to the unconfined compressive strength development for the WFS mixtures stabilized by activated fly ash or bio ash. Quick cement has obvious advantages where short-term strength development is required, since the majority of the compressive strength has been achieved already at 7-day age. Constant growth of compressive strength of mixtures stabilized by activated fly ash or bio ash might be related with the slow pozzolanic reactions to provide cementitious products to bind the granular particles in the mixture. At the age of 91 days, the difference in compressive strength is little among the mixtures with cement, fly ash or bio ash as binders, indicating the potential of activated fly ash and bio ash in strength development for a comparatively long term. However, since the strength of fly ash- or bio ash-stabilized WFS is slightly lower than the requirements at 28-day age, special measurements might be necessary for the applications where early strength is important.
- Compared with unbound granular materials, the resilient modulus of stabilized WFS mixture is higher, but much less dependent on stress state. The resilient modulus of the studied WFS mixtures is much lower than that of hydraulically bonded material as recommended in the Finnish Agency's design guidelines, indicating that the selection of the modulus for this stabilized WFS mixtures in design procedures should be carefully considered, and probably corresponding to realistic stress status.
- The stabilized WFS mixtures can be classified as non-frost-susceptible material. Compared with virgin WFS of no coarser aggregates added, the stabilized mixtures with coarser aggregates are less frost susceptible due to larger nominal maximum particle size, as well as the binding effects of the stabilizer. Freezing-thawing cycles were found to significantly affect the strength of the WFS mixture stabilized by activated fly ash. The poor freeze-thaw resistance of specimens stabilized by activated fly ash could be related to its slower development of compressive strength.
- The cost and emission analysis have shown clear competitions of using the foundry sand in filter layer, in comparison with the investigated conventional options. Increasing the use of foundry sand could be accelerated by using various incentives such as a material tax on natural aggregates. Local foundries can also increase the attractiveness by further reducing the material pricing. For example, the price could be a quarter of the foundries' current landfill fees so that the cost to foundries could also be significantly reduced, or the contractor can be paid for the use of foundry sand. Another option could be to provide free material delivery to the construction site.

Credit author statement

Investigations into stabilized waste foundry sand for applications in pavement structures

Resources, Conservation and Recycling

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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