Wood fly ash stabilization of unbound pavement layers

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ABSTRACT: Modification and stabilization of road structure unbound layers has extensively been studied both at laboratory and field for decades. The most commonly used binders for soil modification and stabilization are cement and quicklime (CaO), but alternative pozzolans and their mixtures are of economical, technical and environmental interest.
This study presents soil stabilization with wood fly ash (WFA) at laboratory. Typical forest road surface structural unbound aggregate and aggregate mixed with 10%; 20% and 30% of WFA was tested and the optimal moisture content for each mixture determined according to the standard Proctor test procedure. Immediate bearing index was determined for fresh mixtures of unbound and WFA stabilized aggregate. The unconfined compression strength and modulus of elasticity for compacted soil - WFA mixtures were determined in unconfined compression test. Unconfined modulus of elasticity was used for vertical stress on top of the road subbase layer comparison in case of typical forest road structure with unbound aggregate surface layer and alternative one with stabilized fractioned dolomite breakstone and fractioned gravel.

RÉSUMÉ : La modification et la stabilisation des couches non liées à la structure routière ont été étudiées à la fois au laboratoire et au champ pendant des décennies. Les liants les plus couramment utilisés pour la modification et la stabilisation du sol sont le ciment et la chaux vive (CaO), mais d'autres pozolanes et leurs mélanges présentent un intérêt économique, technique et environnemental.
Cette étude présente la stabilisation des sols avec des cendres volantes de bois (WFA) au laboratoire. Agrégats et agglomérés non structuraux structuraux de surface de la route forestière typiques mélangés à 10%; 20% et 30% de WFA ont été testés et la teneur en humidité optimale pour chaque mélange a été déterminée selon la procédure d'essai standard de Proctor. On a déterminé l'indice d'appui immédiat pour les mélanges frais d'agrégats stabilisés non liés et de WFA. La résistance à la compression non confinée et le module d 'élasticité pour les mélanges de sol - WFA compacté ont été déterminés dans un essai de compression non confiné. Le module d 'élasticité non isolé a été utilisé pour la contrainte verticale au - dessus de la couche de sous - couche de route dans le cas d' une structure de route forestière typique avec couche de surface agrégée non liée et d 'une roche de dolomie fractionnée stabilisée et de gravier fractionné.

KEYWORDS: soil stabilization, wood fly ash (WFA), hydraulically bound mixtures, forest road.

1 INTRODUCTION

Renewable energy sources (RES) accounted for a 36.8% (approx. 69PJ) share of the gross inland energy consumption in Latvia, 2014 (CSP 2015). 82.1% of renewable energy was produced by different kind of wood fuel, but 24.3% of it was produced in cogeneration plants (CSP 2015). It was estimated that approximately 52ktons of wood fly ash (WFA) was generated as a by-product by cogeneration of electricity and heat in 2014.

Although, previous studies have confirmed that most of biomass fly ash (also WFA) are suitable for various construction sub-sectors, most of WFA is deposited and rarely used as a construction material. WFA has been effectively used in several projects (Bohrn and Stampfer 2014; Bjurström and Herbert 2009; Mácsik and Svedberg 2006; Mácsik et al. 2012; Lahtinen et al. 2005a; Supancic and Odernberger 2012; Vanhanen et al. 2014; Vestin et al. 2012), showing enhanced durability and bearing capacity relative to the conventionally designed road sections in the same circumstances. Frost susceptibility, heave, deformation and cracking problems are reduced.

There are newly constructed or rehabilitated approximately 300km of forest roads annually in Latvia, being important part of forest management and operated with a maximum one axle load of 10 tons throughout the year, except spring/autumn thaw/slush. Typical forest road section is shown in Figure 1.

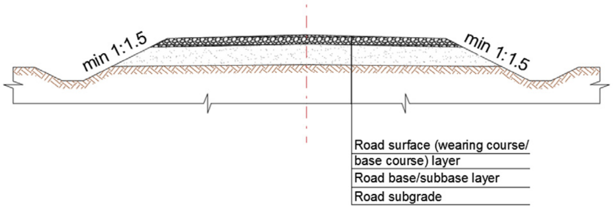

Figure 1. Typical forest road section.

JSC Latvia's State Forests owns and maintains >11000km forest road network in Latvia, and there is economical, technical and environmental concerns how to reuse existing or how to reduce usage of new raw unbound granular soil material for road rehabilitation and construction. At the same time LCC FORTUM Latvia (LCC FL) bubbling fluidized bed furnace cogeneration plant in Jelgava city with maximum capacity of 77MW exposes approx. 4ktons of WFA annually. It is all dumped in landfills, so heavily overloading them. This study proposes to use WFA from LCC FL combustion plant in forest road rehabilitation and construction as stabilizer of road surface unbound material.

It was found that WFA from LCC FL chemical composition is characterized by high SiO_2 (>43.10%), $Al_2O_3 + Fe_2O$ (R_2O – (> 5%)) and CaO (> 19.67%) content. Calculated hydraulic modulus (m = 1.74–2.8), distinguishing WFA as an active pozzolan or highly hydraulic material (Skels et al. 2016).

Conventionally, forest road surface is constructed by either compacted crushed gravel or fractioned dolomite breakstone with defined particle distribution. Compacted aggregate is a flexible material and it tends to deform plastically under the load and accumulation of this deformation is seen as rutting. There are two main rutting contributory mechanisms – which are labelled as Mode 1 and Mode 2 (Kolisoja 2013). Mode 1 rutting is mainly as a result of inadequate granular material shear strength in the aggregate close to the pavement surface, while Mode 2 occurs due to shear deformation within the subbase/subgrade with the granular layer replication.

Stabilized aggregate not only is able to sustain higher tyre imposed stresses, but also reduces the vertical and shear stresses below the road surface layer. Crushed gravel and fractioned dolomite breakstone and mixtures with 10%; 20%; 30% WFA was tested at laboratory. Obtained parameters was used for analytical comparison between typical forest road structure and one with WFA stabilized road surface layer.

2 MATERIALS AND METHODS

Typical 3-layer forest road structure (see Figure 1) was used in this study as a reference with unbound surface, subbase and subgrade layer (see Table 1). Tabular elastic modulus values was assumed in accordance to the National Pavement Design Guide (Zarins et al. 2014).

Table 1. Typical forest road structure

Layer	t, mm	E, MPa	Poisson's ratio
Aggregate (Gr)	200	200	0.35
Subbase (Sa)	500	100	0.3
Subgrade	-	50	0.3

Wood fly ash (WFA) stabilized aggregate (crushed gravel and fractioned dolomite breakstone) was studied at laboratory and the optimal mixture design proposed for alternative surface layer. Both typical and alternative 3-layer forest road structure was compared in terms of performance under the 50kN tyre load (over 0.3m diameter circular area), representing heavy wheel load in-situ. Comparison was done in BISAR 3.0 software, calculating vertical normal stress on top of the sand (Sa) subbase layer both for typical and alternative (with WFA stabilized road surface) 3-layer forest road structure.

2.1 *Wood fly ah (WFA) properties*

BFB furnace WFA from LCC FL combustion plant was collected in July 2016 and January 2017 for this study, but previously monitored from November 2015 to January 2016. The WFA chemical composition, hydraulic modulus and loss of ignition (LoI) is given in Table 2.

Table 2. WFA chemical composition

Component	**Content, %**	**Accuracy, ±%**
SiO_2	43.1–55.60	±0.7
$SiO_{2\ active}$	2.84–5.0	±0.7
$R_2O_3(Al_2O_3+Fe_2O_3)$	5.6–10.48	±0.7
CaO	19.67–24.7	±0.5
MgO	1.6–3.2	±0.3
Fe_2O_3	1.1–1.41	±0.1
K_2O	1.77–4.9	±0.3
Na_2O	0.6–1.39	±0.1
Al_2O_3=$R_2O_3Fe_2O_3$	4.4–9.07	±0.5
SO_3	4.6–8.3	±0.5
Hydraulic modulus	1.74–2.8	–
LoI (1000^{0}C)	4.5–5.1	–

Calculated hydraulic modulus (m = 1.74–2.8), characterizes WFA as highly hydraulic material and according to LVS EN 144227-4:2013 can be classified as calcareous fly ash.

2.2 *Unbound aggregate properties*

Conventionally forest road surface is constructed by either compacted crushed gravel or fractioned dolomite breakstone with defined particle distribution. Both crushed gravel and fractioned dolomite breakstone was used in this study with specific particle distribution (see Figure 2 and 3).

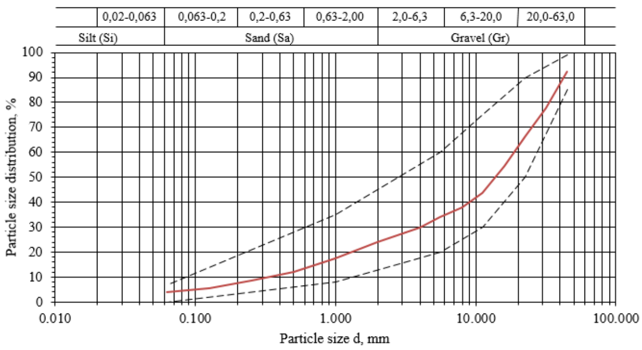

Figure 2. Particle size distribution of fractioned dolomite breakstone

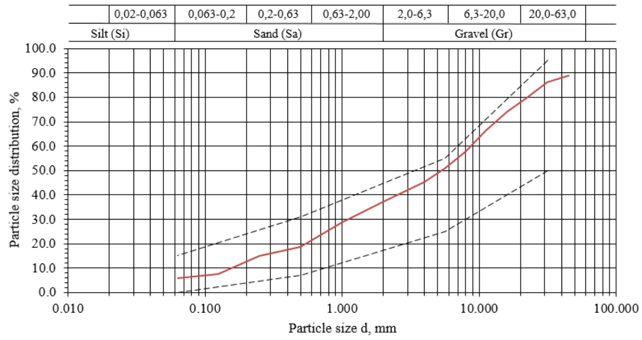

Figure 3. Particle size distribution of fractioned gravel

2.3 *Unbound aggregate – WFA mixture design*

Optimal moisture content for natural unbound and stabilized granular material with 10%; 20% and 30% wood fly ash was determined by standard Proctor compaction test in accordance to LVS EN 13286-2:2012 (see Figure 4 and 5).

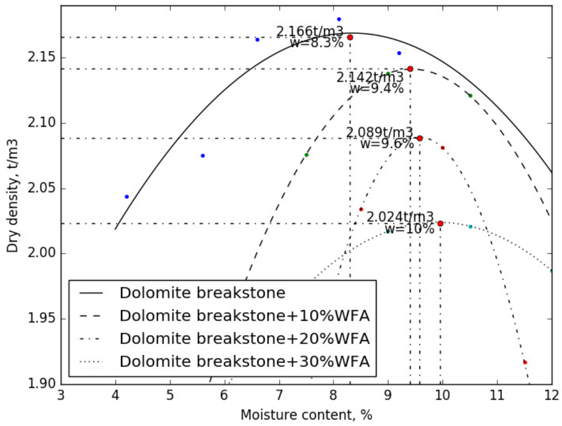

Figure 4. Standard Proctor curves for unbound and WFA stabilized dolomite breakstone

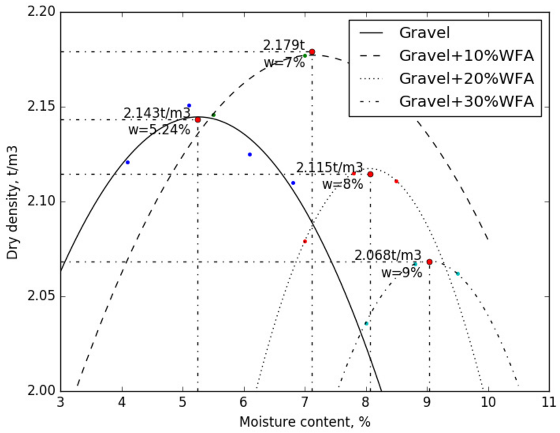

Figure 5. Standard Proctor curves for unbound and WFA stabilized gravel

The shift to the right in moisture content is caused by the fact that some amount of water is immediately affined in hydraulic chemical reactions. Defined optimal moisture content for each unbound aggregate – WFA mixture was used for further mechanical tests.

2.4 *Unbound aggregate – WFA mixture mechanical tests*

Immediate bearing index (IBI) was determined for unbound and wood fly ash stabilized aggregate according to LVS EN 13286-

47:2012 in California bearing ratio (CBR) test, so evaluating the fresh mixture.

Mechanical performance for unbound and wood fly ash stabilized aggregate was determined by compressive strength in unconfined compression test (UCT) according to LVS EN 13286-41:2003 curing samples sealed in 20°C±2°C temperature for 7 and 28 days. Six equal aggregate – WFA mixtures were tested at each testing set. Furthermore, also modulus of elasticity was determined by using LVDTs in UCT test according to LVS EN 13286-43:2003 as tangent modulus at $0.3q_u$, where q_u – maximum unconfined compressive strength (UCS). Although, it is common practice to derive modulus of elasticity from q_u (Murphy et al. , Indrarata 1990, ARA Inc. 2004), it was assumed that E-modulus can be found directly from the stress-strain function.

3 RESULTS

3.1 *Immediate bearing index (IBI) test results*

Immediate bearing index (IBI) test results are shown in Figure 6 and 7. It can be seen that fresh mixture both for WFA stabilized fractioned dolomite breakstone and gravel indicate maximum CBR values with 10% WFA. This follows the trend of standard Proctor test results – the maximal dry densities was exactly for 10% WFA – unbound aggregate mixtures, although for fractioned dolomite breakstone it was just below the unbound dolomite dry density.

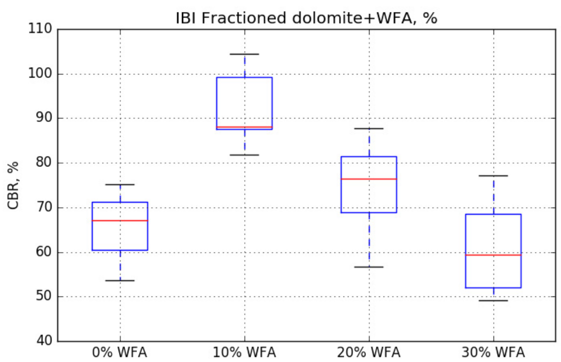

Figure 6. Immediate bearing index (IBI) for unbound and WFA stabilized fractioned dolomite

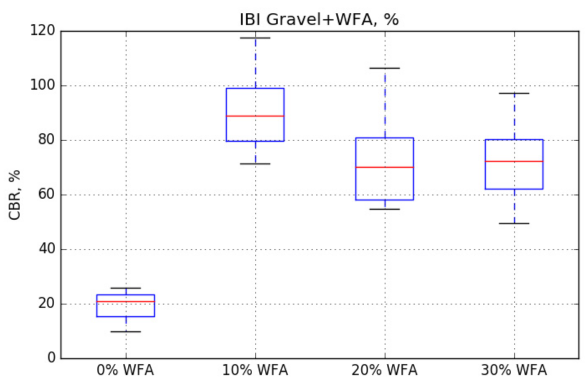

Figure 7. Immediate bearing index (IBI) for unbound and WFA stabilized gravel

3.2 *Unconfined compression test results*

Even the immediate bearing index test indicated that optimal fresh unbound aggregate mixtures are with 10% WFA, unconfined compression strength (UCS) test results showed that it is compensated in UCS values after 7 and 28 days hardening for 20% and 30% WFA mixtures. The highest UCS values for both stabilized fractioned dolomite and gravel after 28 days hardening was for mixtures with 20% and 30% WFA (see Figure 8 and 9).

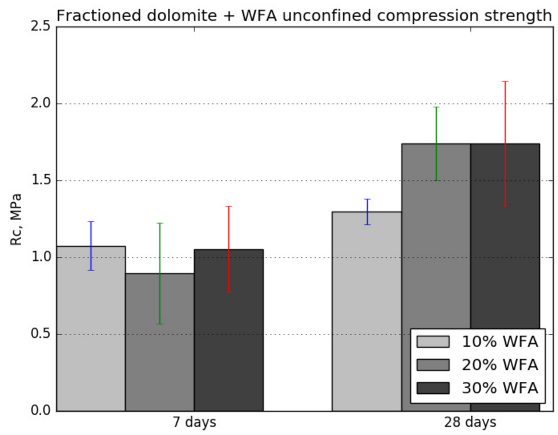

Figure 8. Unconfined compression strength (UCS) for bound fractioned dolomite after 7 and 28 days

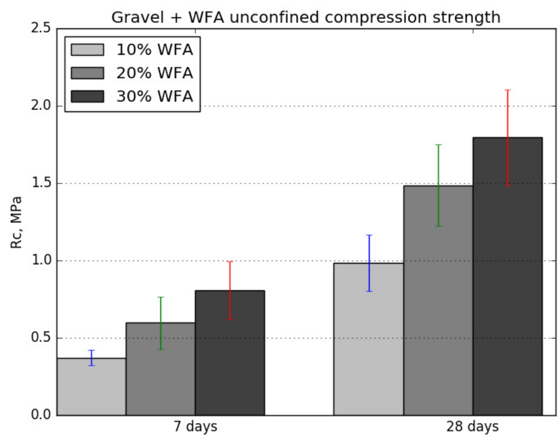

Figure 9. Unconfined compression strength (UCS) for bound gravel after 7 and 28 days

Modulus of elasticity was determined by using LVDTs in UCS test according to LVS EN 13286-43:2003 as tangent modulus at $0.3q_u$, where q_u – maximum UCS. Elastic tangent modulus E_{30} from stress-strain curve for WFA stabilized aggregate after 28 days hardening is shown in Figure 10.

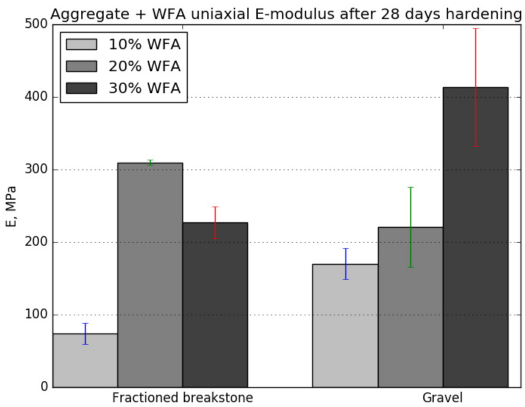

Figure 10. Uniaxial elastic modulus for fractioned dolomite breakstone and gravel after 28 days curing

Modulus of elasticity determined from UCS test only for aggregate mixtures with 20% and 30% WFA showed higher values than tabular E=200MPa for unbound aggregate in accordance to the National Pavement Design Guide (Zarins et al. 2014). However, maximal average values for fractioned dolomite breakstone – 20% WFA E_{30}=309.75MPa and gravel – 30% WFA E_{30}=413.75MPa were assumed for comparison with typical 3-layer forest road structure with unbound aggregate surface layer with E=200MPa in BISAR 3.0.

3.2 *Comparison between typical and stabilized forest road structure*

BISAR 3.0 software was used (SRDC 1998) to calculate and compare vertical normal stress and strain on top of the sand (Sa) subbase layer both for typical and alternative (with WFA stabilized road surface) 3-layer forest road structure (Poisson's ratio assumed 0.2 for WFA stabilized layer). The vertical stress and strain rate comparison on the top of the subbase for typical and two alternative structures is shown in Table 3.

Table 3. Stress and strain on top of subbase

Surface layer	Vertical stress, kPa	Vertical strain, μstrain
Unbound aggregate	-284.7	-2.887E3
Fractioned dolomite + 20% WFA	-249.4	-2.504E3
Gravel + 30% WFA	-223.5	-2.262E3

It was found that vertical stress on top of the subbase layer in case of alternative stabilized forest road surface is reduced by 12.4% and 21.5% for structure with fractioned dolomite breakstone + 20% WFA and gravel + 30% WFA, respectively.

4 CONCLUSIONS

Data obtained in this study verified that WFA from LLC FL BFBF combustion plant is good hydraulic binder for forest road surface layer stabilization both with fractioned dolomite breakstone and gravel.

Even the standard Proctor test and immediate bearing index test indicated that optimal fresh unbound aggregate mixtures are with 10% WFA, unconfined compression strength (UCS) test results showed that it is compensated in UCS values after 7 and 28 days hardening for 20% and 30% WFA mixtures.

Unconfined compression strength (UCS) test results for gravel consistently showed that by increased WFA content and curing time UCS is higher. The maximum UCS for 30% WFA stabilized gravel and fractioned dolomite after 28 days curing was 1.79MPa and 1.74MPa in average, respectively.

Although, it is common practice to derive modulus of elasticity from q_u, it was assumed that E-modulus can be found directly from the stress-strain function. The maximum uniaxial elastic modulus for stabilized fractioned dolomite was with 20% WFA (E_{30}=309.75MPa), but E_{30}=412.75MPa for fractioned gravel with 30% WFA, so giving the optimal design parameters.

Elastic 3-layer analytical calculation in BISAR 3.0 was performed to analyse the vertical stress reduction below the road surface comparing typical forest road structure to the alternative with stabilized road surface aggregate. Results showed that vertical stress is reduced by 12.4% and 21.5% for structure with fractioned dolomite breakstone + 20% WFA and gravel + 30% WFA, respectively.

5 ACKNOWLEDGEMENTS

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