Stabilization of road structures with fly ash as binder component – through demo projects to full scale use

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Abstract – Stabilization of unbound layers of road structures is a promising technique from technical, economical and environmental point of view. The method is sparsely used in Sweden for public roads, though this method is believed to have good potential as it increases the road construction's bearing capacity and durability in cold climate. The most common binder used is cement, but also alternative binder components like fly ash are of interest. Laboratory and field studies show that stabilized unbound layers with fly ash as binder components increase the roads bearing capacity and are environmentally sound. Quality control of the fly ash (mostly from bio-fuels) and the stabilized unbound layers degree of compaction (density) in the road construction are essential and of great importance to insure durability of the construction. An assessment of stakeholder's opinion on stabilization and fly ash as binder component shows that stabilization as a method and fly ash has good potential as it improves durability of the construction. However the objectives against the stabilization technique and the use of fly ash as binder component is the lack of extended field experience regarding operator aspects and durability in cold climate.

Keywords: Maximum 5 keywords. Fly ash, road stabilization, durability, binder, frost

INTRODUCTION

Stabilization of subgrades and unbound layers is not commonly in practice in Sweden for public roads outside Skåne [1]. Although this method is believed to have good potential as it increases the road constructions bearing capacity [2]. The most common binders used are construction cement (CEM II/A-LL 42,5R) Merit 5000 (ground granulated blast furnace slag) and lime, though alternative binders components, like fly ash are of interest in binder mixes [1] and [2].

Follow up studies of earlier built constructions are few and mostly limited to environmental properties such as leaching [3], [4] etc. Economy and maintenance have not been a priority in investigations [5].

Fly ash producers try to find environmentally sound use for fly ash, for example in stabilization of subgrades. [3] and of unbound layers in road constructions and industrial areas. Several objects were constructed using best practice guidelines [6] as guide. One important driving force of ash producers is to find applications where large quantities of fly ash can be used, such us in sub-base layers typically > 10 000 ton fly ash at one site. In these applications fly ash is used as ballast material with some hardening capacity, which depends on moister content, storage time, fuel etc.

During the last ten years a series of laboratory and field investigations were conducted with the aim of increasing experience on using fly ash from different mixtures of wood, used wood, peat bark, paper mill slimes and some coal as binder component. The aim of this paper is to evaluate what parameters should be measured in order to show how bearing capacity of the road develops and to evaluate the durability of the construction. The objectives were to aid the use of stabilization of unbound layers with fly ash as binder component. The target groups of the project were The Swedish Road Administration, entrepreneurs and environmental authorities.

METHODS

This study uses experience and data from different laboratory studies conducted between 1999 and 2011. These studies include general characterization of different fly ashes for potential use as binder components, [5] [7], [8], a full scale study where fly ash were used as binder component [9] and a follow up study on several pilot tests including a stakeholder opinion assessment [10].

Laboratory investigations

In a series of laboratory tests fly ash from several producers from the Paper Industry and energy producers were characterized [8] and [9]. The laboratory investigations included geotechnical characterization of fly ash, such as particle size distribution, compaction properties (proctor), density, porosity and void ratio. Shear strength after compaction and after curing during 14, 28 and 90 days. In this paper only shear strength after 28 days curing are shown.

Field test

Field tests were performed at Ehnsjövägen, Hallstavik, Holmen Paper [9]. A 1200 m long road section was stabilized with fly ash from Holmen Paper Hallstavik as binder component. A reference section of 400 m was used as comparison. During the stabilization ca 10 – 30 cm of gravel on the road was stabilized with 30 % fly ash (dry solid weight). The mixture's water content was optimized in order to optimize compaction and maximize density of the stabilized gravel. This pilot road was constructed September 2004 and followed up during the next five years [10]. The roads technical and environmental properties were investigated [10].

Stakeholder opinion

Assessing stakeholder's opinion is important to find problems and possibilities of the method. An interview was conducted with participants from fly ash producers, forestry industry, binder producers, operators, local environmental agencies, consultants, universities and participants from the Swedish Geotechnical Institute (SGI) and Swedish National Road and Transport Research Institute (VTI) [10].

RESULTS AND DISCUSSION

Results from several investigations are included, from laboratory characterization of fly ash as binder component to field test at Ensjövägen, Hallstavik where unbound layer was stabilized with fly ash as binder, and a stakeholder opinion assessment, where stakeholders were interviewed about their attitude and view of stabilization of unbound layer and fly ash as binder, [5] – [10].

Characterization

A total of different fly ashes from incineration of bio fuels (Heating Plants and Forest Industry Boilers) are included in this paper, [7] and [8], Table 1. The investigated fly ash were all sampled dry, with water contents between 0.1 % and 1.5 %, apart from two which originated from landfill and had a w 78.3 % and 65.8 %, Table 1. The fuel used are wood, recycled wood chip, bark chip, fiber sludge, peat and in some cases coal.

Table 1 Original water content (w), combustion and industry type [7].

	Fly ash producers	W [%]	Boiler type	Industry
BV	Holmen Paper Braviken, Norrköping	1.5	Grate Furnace	Forest industry
HV	E.ON Händelöverket, Norrköping	1.1	Circulation Fluid Bed	Heating plant
TVL	Tekniska Verken, Linköping	78.3	Grate Furnace	Heating plant
ÅV	E.ON Åbyverket, Örebro	65.8	Circulation Fluid Bed	Heating plant
SEF	StoraEnso Fors AB	0.4	Circulation Fluid Bed	Forest industry
ME	Mälarenergi, Västerås	0.1	Circulation Fluid Bed	Heating plant
VVU	VattenfallHeat Nordic, Uppsala	0.3	PowderBoiler	Heating plant
SEAB	Sandviken Energi AB Sandviken	0.4	Bubbling. FluidBed	Heating plant
FV	Fortum Värtan Stockholm	0.1	Pressurized Circ Fluid Bed	Heating plant
HPH	Holmen Paper, Hallstavik	0.1	Bubbling Fluid Bed	Forest industry

Grain size distributions of the studied fly ash are presented in Figure 1. The fly ash from Åbyverket and Braviken are well graded, (D_{60}/D_{10} – large coefficient), and has a larger range of grain sizes, while the rest of the fly ash are considered as uniform ($D_{60}/D_{10} < 4$).

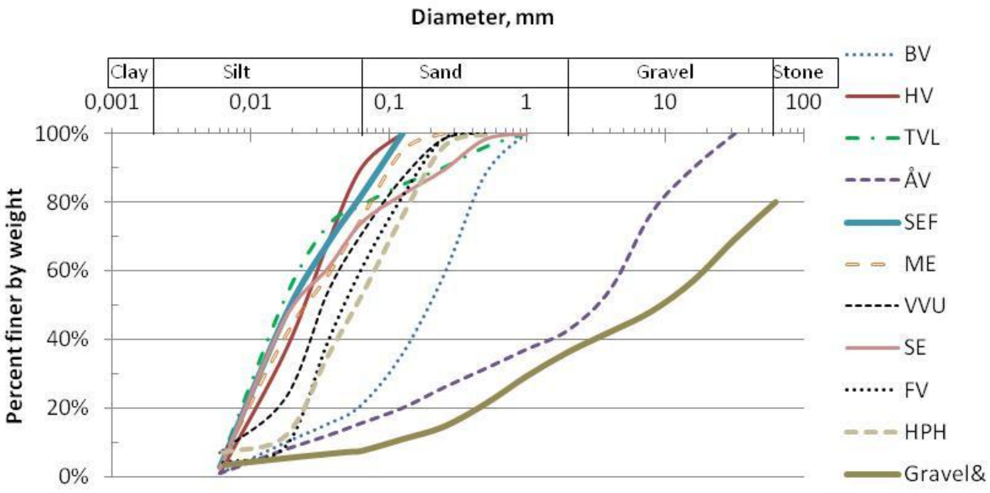

Figure 1 Grain size distribution curves of investigated fly ash [7],[8], and for gravel material stabilized at Ensjövägen, Hallstavik [9]

Compaction properties vary between different fly ash, Figure 2. Fly ash from FV and VVU has dry density of 1,6 – 1,7 ton/m^3 and an optimal water content (w_{opt}) of 15 – 20 %. While roster boiler type generates fly ash with lower dry densities in the range of 0,9 – 1 ton/m^3 and a higher w_{opt} (30 % – 55 %). Due to the great difference in compaction properties between different fly ash these properties are of interest when fly ash is used as binder component.

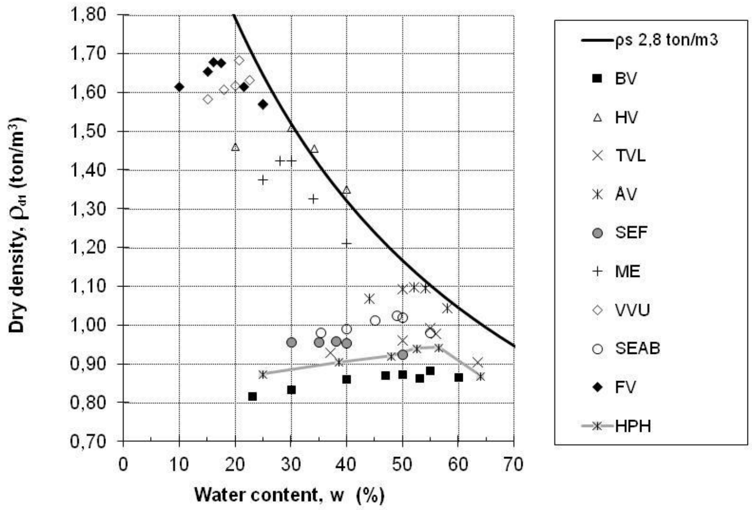

Figure 2 Proctor results for fly ash from earlier studies, [7] and [8].

Basic cementation properties were determined for the investigated fly ash after a curing time of 28 days. Unconfined compression tests were conducted to establish a trend for the gain in strength with different fly ash. Based on these results fly ash was characterized as binder component. Samples with fly ash were compacted at w_{opt} . As shown in Table 2 the undrained shear strength of the fly ash varied between 0,8 MPa to 12.2 MPa. Fly ash from landfill, TVL and ÅV had the lowest undrained shear strength as these had a low binder capacity left after curing with water before compaction. The next group of fly ash had undrained shear strength (τ_{fu}) between 2 and 5 MPa.

Based on the results fly ash were divided into three main groups A, B and C, with regard of potential as binder component in stabilization of gravel roads, Figure 3, [7]:

Group A fly ashes have poor curing properties and need stabilization agents such as other fly ashes with higher curing capacity or cement (Portland cement, Merit etc.). Fly ash which has been stored in landfill and has a low content of quick lime is also part of this group. Fly ash in this group should be used with caution without addition of stabilizing agent if they are to be used in applications where percolating water and frost-thaw cycles occur. After stabilization with fresh fly ash and/or cement, fly ash from this group can be used in sub-base road applications.

Table 2 Specification of measured parameters. [7]

	w [%]	LOI [%]	pH	CaO, [%]	Dry density [kg/m^3]	w_{opt}, [%]	τ_{fu}, [MPa] [5]
BV	1.5	13.3	12.6	5.2	885	55	3
HV	1.1	4.2	12.7	12.2	1510	30	4.1
TVL	78.3	30.3	9	1.1	980	56	0.8
ÅV	65.8	10.5	12.6	10	1100	52	1
SEF	0.4	7.1	12.8	12.4	960	38	4.5
ME	0.1	4.5	12.6	4.6	1425	28	12.2
VVU	0.3	7.6	12.8	9.9	1684	20.6	2
SEAB	0.4	8.4	11.9	1.7	1025	49	1.4
FV	0.1	11	12.5	1.8	1680	16	8.1
HPH	0.1	9	12.2	9	945	55	-

Group B fly ashes have medium-high to high content of quick lime and good development of shear strength. These fly ashes can be used without being stabilized with cement. In fact, adding cement can reduce properties of compaction thus reducing the strength of a construction. The frost-thaw durability of these fly ashes is also expected to be good but can be further improved by addition of cement [8]. Potential civil engineering use of fly ashes from this group are as liners in landfills, sub-base and base course in secondary roads such as gravel roads or low trafficked paved roads or as stabilizing agent in soils (compare to Lime Cement – columns or mass stabilization).

Group C fly ashes have high shear strength. These fly ashes can be used without addition of cement. Cement can, however, increase shear strength and frost-thaw durability. The need of a stabilizing agent should be investigated for each fly ash separately. Potential examples of applications correspond to group B and furthermore they can, for example, be used for stabilizing of hazardous waste (such as fly ash originating from household waste) or contaminated soils.

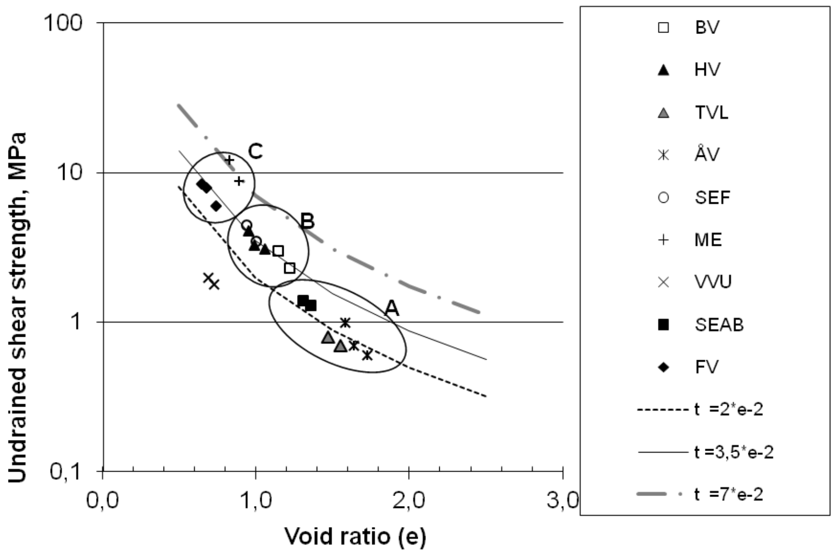

Figure 3 *Correlation between void ratio and shear strength. t stands for* τ_{fu} *(undrained shear strength)*

Results shown in [7] indicate that a limited set of properties can identify potential applications. Properties such as grain size distribution, compaction properties, void ratio and shear strength give a good indication of fly ash properties and use in appropriate applications. The investigation have furthermore shown, for fly ashes in group B and C, that the optimum water content for compaction is lower than the water content needed to achieve a maximum development of strength. Dry storage of fly ash is important to enable use without need of adding stabilizing agents.

In other corresponding projects, in Sweden and Finland, curing properties of fly ash have been used in order to renovate gravel roads [10] - [15]. At the same time supplies of dry fly ash is limited, especially in comparison with the supplies of traditional road materials. On the other hand, now ongoing projects indicate that no more than 15% of fresh fly ash applied to the bearing course is adequate to give the road better performance [15]. It is therefore important to investigate how added water (15-30%) reduces the curing properties with time and to study future storage and handling of fly ashes. In [16] it is shown that an addition of 10 – 20 % of water to fly ash from VVU and ME reduces CaO (active) content of the material radically. The study [16] shows that fly ash should be used within days and weeks after water addition.

Stabilized road section

Based on laboratory studies [11] a field test was conducted at Ehnsjövägen, Hallstavik. A 1200 m long road section was stabilized with fly ash from Holmen Paper Hallstavik (HPH). Gravel material was well graded, Figure 1. In a laboratory investigation, the curing properties of fly ash stabilized gravel (road material) was investigated, Figure 4. The highest value of shear strength after curing of 28 days had a mixture where 90 % of gravel was stabilized with 5 % fly ash and 5 % cement. The results indicated that 20 % to 30 % fly ash gives appropriate shear strength required for Ehnsjövägen which is a road with low traffic load [11], [9].

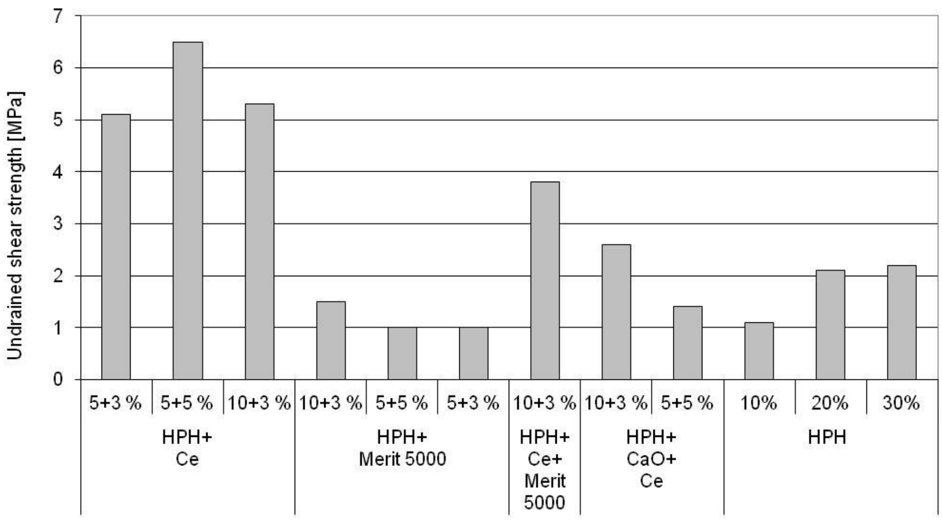

Figure 4 Effect of different binders on the stabilised gravel, after curing time 28 days. FA is Flyash from Holmen Paper, Hallstavik (HPH), Ce is addition of cement and CaO is addition of lime. [8]

Based on the results presented above, compaction properties of the stabilized gravel (road material) were investigated. As shown in Figure 5, fly ash from HPH has a low dry density, 0.945 ton/m^3 at w_{opt} 56 %. Gravel stabilized with 10 % fly ash has a maximum dry density of ~ 2 tons/m^3 at w_{opt} 9 %, while 30 % fly ash gives a dry density of 1.75 ton/m^3 at w_{opt} 15 %. As content of fly ash increases dry density decreases and w_{opt} increases, Figure 5. Hallstavik is an example where stabilization of unbound layer/ subgrade was used based on laboratory works including geotechnical properties of the stabilized layer. Total content and leaching properties were investigated and followed up on site during a six year period [10]. The road was stabilized during 2004, partially based on the Finnish guidelines [19] for stabilization of unbound layer. After admixture [9] of the binder, water content was increased to the level required by the optimum water content of compaction. After compaction the road surface was leveled and an additional compaction followed. Control of the density of the stabilized road show that section 1 (0 – 400 m) and section 2 (400 – 800 m) has a dry density median near that of 30 % fly ash, Figure 6. On section 3 (800 – 1200 m) a layer of fly ash was used and less gravel was mixed to the fly ash. Low dry density on this section indicates that the stabilized road contains between of 10 – 100 % fly ash.

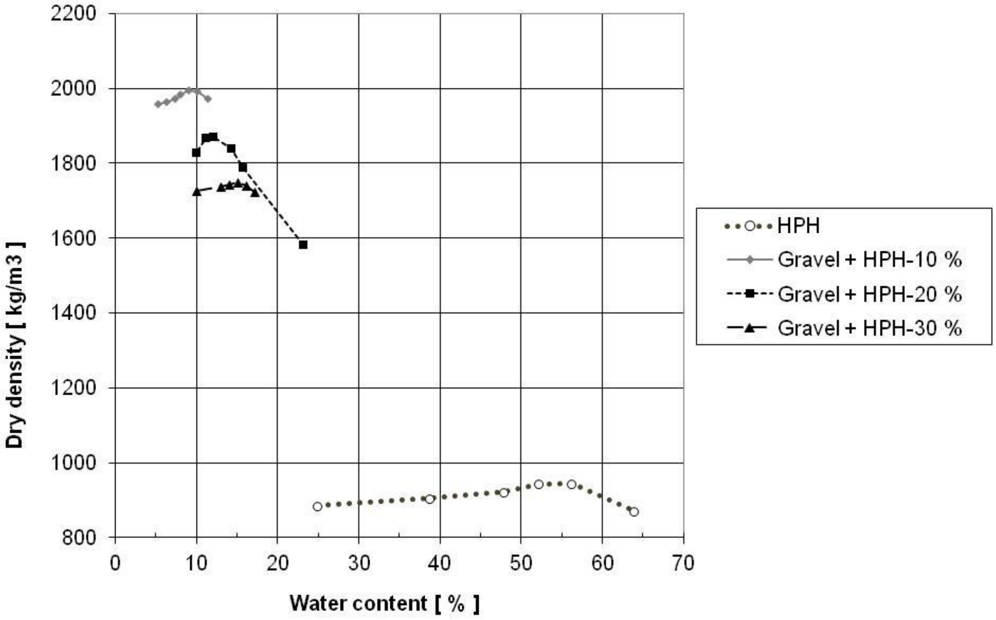

Figure 5. Dry density of stabilized gravel (subgrade material) with 10 %, 20 % and 30% fly ash (HPH) and dry density of fly ash from Holmen Paper, Hallstavik (HPH).

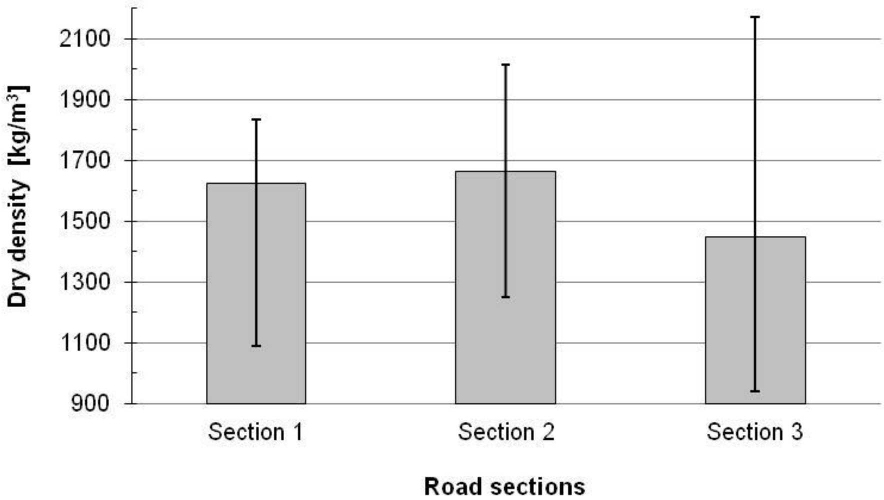

Figure 6. Dry density of fly ash stabilized gravel from quality control of the road section, median, maximum and lowest values are presented.

Before the road was stabilized, eight lysimeters were installed 0,5 m below the surface of the road and one below the reference section [10]. Amount of water collected in the lysimeters were measured as well as metal contents, pH and electric conductivity. Results show that metal contents, like Cu, Cd, Pb, Zn are between 1 – 10 µg/liter in the percolated water in both reference and stabilized sections [10]. The only noticeable difference between reference and stabilized sections is the lysimeters electric conductivity and sulfate contents. Lysimeters electric conductivity is shown in Figure 7. During 2005 electric conductivity (κ) values ranged between 83 mS/m and 453 mS/m with a median value of 151 mS/m. Results from 2009 show that κ-values were between 85 mS/m and 98 mS/m with a median value of 88 mS/m. The investigation showed that percolation though the stabilized road construction was less than 20 liter/(m^2 and year) [10]. Fly ash stabilized road construction has after 5 years marginal effect on ground water quality and there are indications that this is also valid for other Swedish bio fly ashes. [10]. It is also is corresponding to Bendz et al [4]

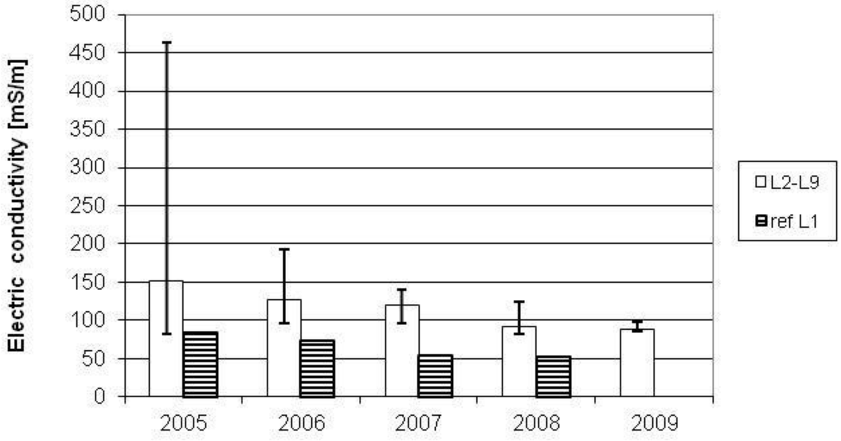

Figure 7 Electric conductivity of lysimeter water. Median values and max/min values are shown for lysimeters 2 – 9 (L2 – L9) and for the reference lysimeter. The reference lysimeter was dry during sampling 2008. [10]

Ehnsjövägen was investigated with a falling weight deflectometer (FWD) in May 2004 before stabilization, during May 2005 and autumn 2009, periods when the road has a low bearing capacity. The FWD device delivers a transient impulse load to the road surface. The subsequent pavement response (deflection basin) is measured by a series of sensors. Results of the median deflection values (D_0) for the road sections are showed in Figure 8. Major decrease in deflection can be seen for road sections 1, 2 and 3, while the reference section shows no improvement. Each section was 400 m long. It should be observed that road sections 1 – 3 were in greater need of renovation before 2004 than the reference section.

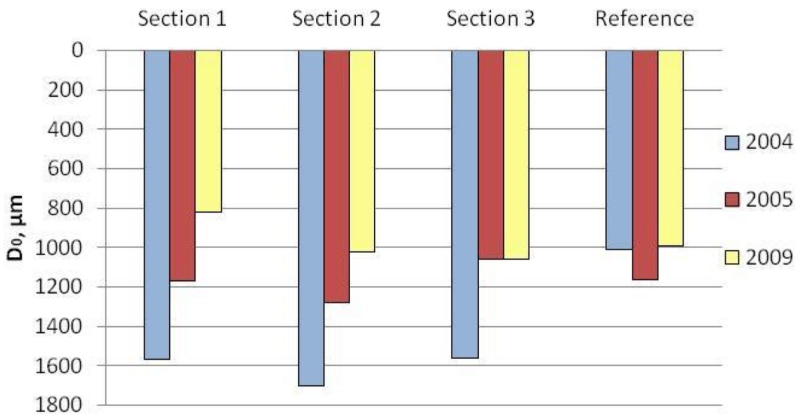

Figure 8. Registered average deflection values, D_0, for each road section before (2004) and after stabilization (2005 & 2009). [10]

Figure 9 Ehnsjövägen, a) before stabilization (2004, b) five years after stabilization (2009) and c) a typical reference road section 2009.

The investigation shows that stabilized road can have a designed quality [10]. Quality of the road or subgrade material (gravel), water content of the gravel and the admixture, compaction depth, and achieved compaction grade as well as stabilizer quantity admixed are of importance. Observance has to be paid to quality and checked upon by measurements in order to secure road quality. Results from Hallstavik indicate that the quality of the road, five years after construction is good. No potholes or unevenness could be observed, while the reference section is of poor quality, littered with potholes, Figure 9. [10]

Stakeholder opinion assessment

The opinions of several actor´s are involved in a successful use of fly ash as binder component in stabilization of unbound layers and subgrades. Producers of fly ash and binders, as well as the forestry industry, consultants, operators and local environmental protection agencies were interviewed and their opinion on fly ash as binder component were assessed [10]. The interview result concludes that the manual for stabilization of gravel roads with fly ash, [6] is used, though mostly in pilot studies. Furthermore it is well understood that control and follow up during construction is an important instrument to get good road quality after stabilization. Compaction and water content are important to control in order to secure high bearing capacity, frost and frost heave resistance of the stabilized road. Experience shows that fly ash gives a good function. The follow up study at Hallstavik [10] shows that permeability of the stabilized road construction is low and groundwater samples from the road section indicates that metal contents in the water is the same or lower than in reference samples [10]. An assessment of the roads surface conditions show that stabilized sections had no occurrence of cracks, unevenness or potholes and was generally in good condition after 5 years in use in contrast to the reference road section with poor road conditions.

The development of stabilization of road constructions is driven by the Swedish Road Administration and the forestry industry. These stakeholders have focus on technical and economical issues, and the major driving force is to improve a road construction's function and durability [17]. The development in stabilization of unbound layers and subgrades are examples where increased bearing capacity, low permeability and/or improved frost and frost heave resistance gives a better construction. Binders used in these cases are cement, Merit 5000 and or lime. In some cases fly ash is used as binder component. In these cases only fly ash with good binder quality is used and storage which conserves these properties is required. This requires dry storage. However, fly ash is mostly stored after adding minor quantity of water, up to water content of 20 % or more. Wet stored fly ash is losing its binder qualities with time. Storage time > 2 weeks is enough to reduce binder qualities to a minimum [15]. The quality of fly ash as binder is dependent on incineration processes, fuel, storage (dry/wet) and storage time.

Fly ash producers try to find environmentally sound use for fly ash, for example in stabilization of subgrades and of unbound layers in road constructions and industrial areas. Several objects were constructed using [6] as guide [13] and Vestin [10]. One important driving force of ash producers is to find applications where large quantities of fly ash can be used, such us in sub-base layers typically > 10 000 ton fly ash at one site. In these applications fly ash is used as ballast material with some hardening capacity, which depends on moister content, storage time, fuel etc. Earlier studies, such as [5], [7] and [11] showed that fly ash in these applications are not frost lifting and that durability against frost and thaw cycles are acceptable. Resistance against frost can be improved by addition of 3 – 7 % cement to the fly ash. Follow up studies of earlier built constructions are few and mostly limited to environmental properties such as leaching. Economy and maintenance are not priorities today. Results from laboratory and field studies as well as interviews indicate improved durability of the road and that the life cycle costs are likely to be 15 – 25 % lower for the applications than traditional road construction techniques over a considered time span of 40-years and an interest rate at 4 % [5]. Comparison with [4] shows that it is low risk to environment and health to use the tested fly ashes in sublevels. Leaching is less critical than dusting to crops that we eat unwashed in more than small volumes for rather long times. Ashes are not hardwearing and shall not be in the top layers even after the road is disused.

Fly ash quantities required in different road applications are listed in Table 3. Notable is that the limited quantity of fly ash is restricting the use of fly ash in bigger projects. This is due to small quantities falling out daily and limited dry storing capacity. Thereby the use of fly ash as binder component is restricted to shorter road sections with geotechnical problems like low bearing capacity roads with frost/thaw related problems. Together with other binders fly ash has good potential as binder component in subgrade stabilization and in stabilization of unbound layer. In these applications fly ash is used together with cement and/or lime. The quantity of fly ash required for these applications are much lower than to use fly ash in monolithic layers, though dry storage is not required in the latter application.

Table 3. Use of fly ash in base and sub base layers in gravel road (after [6])

	Fly ash as construction material	Fly ash as construction material with binder[$]	Fly ash stabilized gravel	Fly ash/cement stabilized gravel
Layer thickness	0.2-1.5 m	0.2-1.5 m	0.1-0.2 m	0.1-0.2 m
Amount of fly ash in a 5m broad road section.	1.5 -11 ton/m	1.5 -11 ton/m	1- 1.5 ton/m	0.2-0.5 ton/m
Example of mixing relation (TS%)	100 % (only fly ash)	Fly ash/binder[$] 90/10% - 97/3%	Fly ash/gravel 30/70% – 50/50%	Fly ash/binder[$]/gravel 10/3/87% - 15/5/80%

[$] cement

Different key actor's viewpoints were congregated to point out important issues to 1) motivate the use of stabilization as a technique and 2) use binders partially based on fly ash. The interview results show that control of the quality of different sites is limited. Key actors agree on that stabilized road sections should be followed up and controlled and road quality and maintenance documented. Empiric knowledge, accumulated from several road projects, is missing today. This leads to limited knowledge of life span, economy, environmental issues and maintenance. The following parameters were suggested to be of importance to follow up:

- Design – Laboratory and field parameters [5]
- Life time and durability of the construction – Mechanical degradation and frost resistance [5]
- Environment – Environmental assessment and recourses used [18]
- Economy – Binder quality and quantity, binder development, maintenance costs and investments [5]

Two main ways have been identified, 1) where fly ash is used as a construction material/binder component with or without cement and 2) where focus is on the development of stabilization as a method:

1) New roads and industrial sites are built with fly ash as construction material. Slowly, acceptance increases. Ash producers are in close cooperation with entrepreneurs. The driving force is cost efficient use of fly ash combined with high bearing capacity of the construction, instead of land filling. No continuity, which means that different producers "invent the wheel" over and over again. Fly ash is stabilized with cement (0 – 30 %).

2) Stabilization of unbound layer in road constructions is prioritized. Fly ash is used as binder component in addition to other binders. Fly ash has to be stored dry. Driving force is to produce cost efficient roads and to develop binders for less cost, decrease CO_2 release etc . Volume of fly ash can be adjusted to the need. Stabilization as a method for unbound layers has to be established first.

CONCLUSIONS

In all; using the method of stabilization unbound layers is expected to enhance the bearing capacity of the road construction as a whole. The applications developed are expected to be durable against frost, will not heave due to frost and their insulation properties are not far from traditional materials in an unbound layer. The proposed solutions, for both the paved road and gravel road, are expected to be favorable in a life cycle cost perspective and it is low risk to environment and health.

Cement, lime and Merit 5000 are binders usually used in stabilization of soft soils. The binders are dry and quality is well defined. In order to find acceptance for fly ash as binder component together with cement, lime it is essential to ensure the quality of the fly ash. The following applications with fly ash in road constructions have good potential:

- As monolith layer, where fly ash layer between 0,2 – 1,5 m is packed in layers. This application gives good bearing capacity and a lightweight construction, however requires big quantities of fly ash. The fly ashcan be stored wet or preferably dry.
- As binder when stabilizing unbound layer in road constructions. The unbound layer is usually gravel or bottom ash.
- Subgrade stabilization where road material, mostly till and clay is stabilized in situ with cement and/or lime with fly ash as a binder component.
- Deep stabilization of soft soils, where fly ash is used as a binder component, only used in pilot studies /tests.

Results from field studies and interviews indicate that fly ash as binder component has a positive effect on the constructions life span. Life span, economy, environment, and cost for maintenance are not followed up today. In order to promote the use of stabilization of subgrade and unbound layer in road construction a better understanding is needed of the correlation of laboratory and field results and a documentation of different objects from planning to drift in order to improve design. Thereby more reference roads with laboratory and long term follow up studies are needed.

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