Utilization of waste incineration bottom ash in bound construction materials

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Abstract – Waste incineration bottom ash, bound with fly ash and cement, was tested as a construction material both regarding environmental and technical properties. A bound material with waste bottom ash has several advantages compared to unbound bottom ash as well as cement stabilized fly ash. The hydraulic conductivity is reduced compared to non bound materials, which reduces the risk for contaminant leaching. Unconfined compression test showed that the strength properties are sufficient for utilization in roads and industrial storage areas. Non destructive testing methods indicated reduced risk for crack formation due to drying compared to stabilized fly ash. The transport of contaminants was evaluated through diffusion tests.

Keywords: Waste incineration, Bottom ash, Utilization.

INTRODUCTION

In an international perspective waste incineration is common in Sweden and increasing every year. This gives rise to an increased amount of by-products, bottom ash being one. The waste incineration bottom ash in Sweden is today utilized almost exclusively as a construction material inside landfills. Many landfills in Sweden will be closing in the near future, making other markets for the material a top priority.

Several attempts have been made to use bottom ash as a construction material also outside landfills, for building roads and parking lots, as a substitute for natural aggregates. The limiting factor in utilization is usually not the technical properties, but rather the risk of environmental effects. There are ways to reduce that risk. Contaminations can be removed from the bottom ash through e.g. washing. Treatment methods are however often expensive. Another way is to stabilize the material chemically, forming stable compounds, or mechanically, creating a dense material with low hydraulic conductivity, a so called bound material. Bound materials can be created by mixing the bottom ash with fly ash, cement or other reactive materials. Outside of Sweden waste bottom ash is also used as aggregates in asphalt [1], as aggregates in concrete [2], as mineral addition in cement clinker manufacture [3] etc. In Sweden utilization as construction material in unbound constructions has been used in car park and road construction [4-6], this is an application used in other European countries as well [7-10]. Research on waste bottom ash in bound material is needed to evaluate if this is a suitable method to utilize waste bottom ash in construction.

The goals were to:

- Evaluate waste incineration bottom ash in laboratory as a bound construction material, regarding both environmental and technical properties.
- Evaluate laboratory methods for testing of bound ash materials in laboratory.

MATERIAL AND METHODS

Bound ash material in industrial storage areas and roads

Fly ash from bio fuel and peat combustion mixed with cement and water is today utilized as a bound construction material for industrial storage areas or roads. A part of the fly ash could be replaced with waste incineration bottom ash and the material utilized the same way.

Description of materials in laboratory testing

The waste incineration bottom ash used in the testing was originating from Vattenfall in Sweden, from combustion of household and industrial waste in a grate boiler. Scrap metal and coarse particles were sorted away from the bottom ash and the resulting bottom ash fraction (0-10 mm) was stored outside in a large pile for more than a year prior to testing. The fly ashes used in testing originated from peat combustion and bio fuel combustion from Mälarenergi. The cement used in the testing was building cement. Both fly ash and cement was stored dry in closed containers prior to testing.

Experimental design

Test samples were prepared according to three mixtures, R, SB and ST, see Table I. Test samples were prepared using proctor packing in tubes 100 mm long 50 mm in diameter. For both mixture R and SB the optimum water content was determined in proctor packing tests to 15 %. This water content was used throughout the tests for sample preparations if nothing else is noted.

Table I Proportions of the three material mixtures used in the laboratory testing. Numbers are the ratio in percent of total dry matter.

[Mass-% by dry matter]	R Reference	SB Test material	ST Test material
Waste incineration bottom ash	1	64	64
Fly ash from bio fuel combustion	94	31	
Fly ash from peat combustion			31
Cement	5	5	5

Testing of leaching properties

Diffusion tests were carried out according to the standard NEN 7345 for mixture R and SB after 28 days of hardening, this also includes availability tests according to the standard NT ENVIR 003. Percolation tests were carried out according to the standard CEN/TS 14405:2004 for non-bound bottom ash as well as mixture R and SB after 28 days of hardening. In percolation tests all test samples are crushed to <10 mm before testing.

Testing of technical properties

Non-destructive testing of the modulus of elasticity (E-modulus) was done using a GrindoSonic MK5I. Both mixture R and SB was tested. Samples were extracted from their tubes after 14 days, and then stored in a climate chamber at 89 % RH. During testing the sample was knocked and a piezoelectric accelerometer registered the vibration, giving the Eigen frequency, which was used to calculate the E-modulus. Unconfined compression tests were carried out according to the standard EN 12390-3. Hydraulic conductivity was tested using cell pressure permeameters, with back pressure.

RESULTS

Hydraulic conductivity

Bound material of mixture SB packed at 15 % water content showed a hydraulic conductivity of $6.35\ 10^{-6}$ m/s (mean of two samples) after hardening in 7°C during 28 days. Bound material of mixture ST packed at higher water content showed a hydraulic conductivity of $7.05\ 10^{-10}$ m/s (mean of two samples) after hardening in 20°C during 167 days.

Unconfined compression tests

Mixture SB showed higher strength development in unconfined compression tests than mixture R (Figure I), on average 3 times the strength of mixture R. Strength development was higher for samples hardened in 20°C than for samples hardened in 7°C (Figure II). Higher water content gave higher strength development.

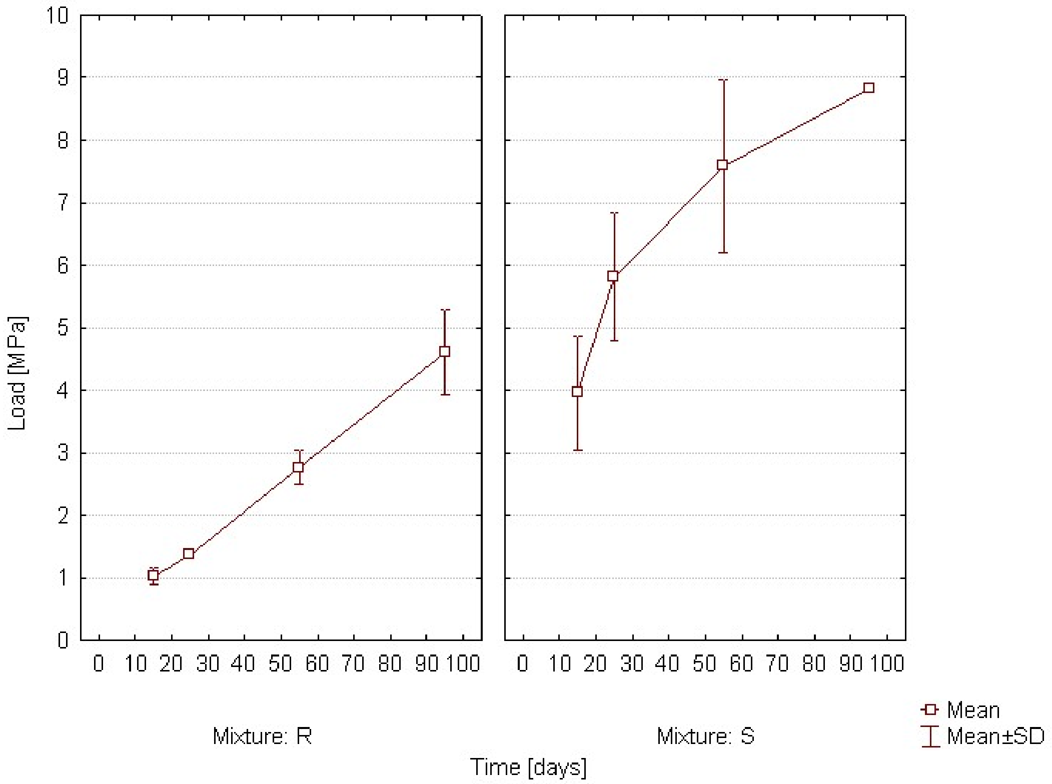

Figure I Unconfined compressive strength in MPa for mixture R and mixture SB. The bars represent the standard deviation. Results are the mean of three samples

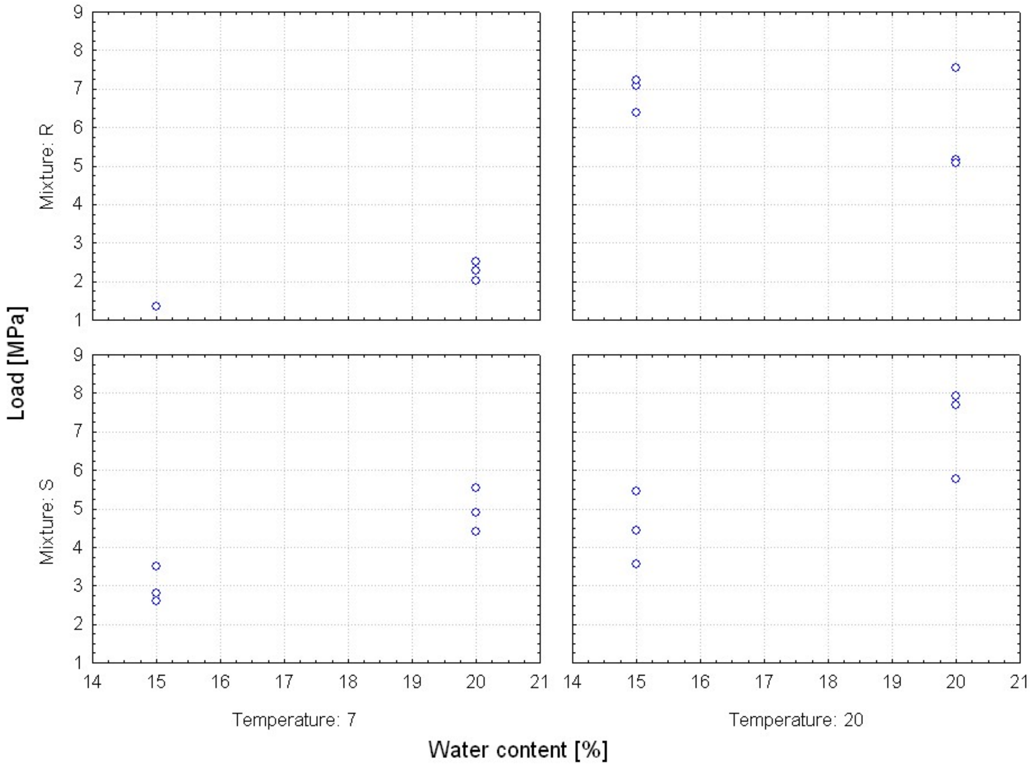

Figure II Unconfined compressive strength in MPa after 28 days of hardening for mixture R and SB. Both temperature during hardening and water content was varied

Mobility of contaminants in bound ash materials

A number of elements were below the detection limit, As, Cd, Hg, Ni, Pb, F and SO4 for one or more samples. For non-bound bottom ash only Cl and SO_4 is above the guideline values for unrestricted utilization in Sweden, in handbook "Recyling of waste in construction works" [11]. For bound waste bottom ash also Cu, Pb and Cr was above the guideline values (Table II). The pH-value was higher in the bound material compared to non bound waste bottom ash.

Table II Leaching from percolation tests on non-bound bottom ash and bound material of mixture SB and ST. Values are the mean of 3 samples for non-bound bottom ash and mixture ST and the mean of 2 samples for mixture SB. Values marked with < signifies that one or more measurements were below detection limit. Unit for concentration in leachate is mg/l. Unit for electric conductivity is mS/m. Unit for cumulative leaching is mg/kg dry matter (DM).

	Concentration in leachate L/S 0.1 [mg/l]					**Cumulative leaching at L/S 10 [mg/kg DM]**			
	Guideline values in handbook Recycling of waste in construction	**Non-bound waste bottom ash**	**Bound waste bottom ash Mixture ST**	**Bound waste bottom ash Mixture SB**		**Guideline values in handbook Recycling of waste in construction**	**Non-bound waste bottom ash**	**Bound waste bottom ash Mixture ST**	**Bound waste bottom ash Mixture SB**
As	0.01	<0.00833	<0.005333	<0.0075		0.09	<0.0160	<0.0110	<0.0100
Ba	-------	0.0101	0.173	1.180		-------	0.0269	3.00	12.5
Cd	0.01	<0.0003	<0.0006	<0.001		0.02	<0.000477	<0.0007	<0.0008
Cr	0.2	0.0868	0.190	1.180		1	0.107	0.145	0.725
Cu	0.2	0.172	1.820	1.960		0.8	0.186	1.131	0.891
Hg	0.001	<0.00002	<0.00002	<0.00002		0.01	<0.0002	<0.0002	<0.0002
Mo	-------	1.14	3.20	4.00		-------	1.115	2.030	2.268
Ni	0.1	0.00350	0.0305	0.0262		0.4	<0.00638	<0.0205	<0.0106
Pb	0.05	0.000595	0.144	0.161		0.2	<0.00200	0.361	0.422
Sb	-------	0.0506	0.0184	0.00985		-------	0.383	0.0590	0.0285
Se	-------	0.00906	0.151	0.0588		-------	0.0129	0.139	0.0442
Zn	1	0.0892	0.231	0.449		4	<0.0282	0.495	0.463
Cl	80	2653.3	2293.3	2370.0		130	1754.5	1916.6	815.2
F	-------	0.513	<4.33	<1.50		-------	4.84	<7.22	<7.24
SO_4	70	1606.7	1034.7	<6.00		200	2407.5	885.4	<101.6
DOC	-------	20.67	197.7	372.5		-------	127.1	122.5	148.2
pH		10.3	12.7	13.0					
Cond		1097.3	1687.0	24.75					

The diffusion coefficient, D_e, varied for different elements in the two mixtures R and SB (Table III). Cl was the element with the highest diffusion coefficient. For mixture R Ba, Cr, DOC and F had average diffusion coefficients ($11.0<pD_e<12.5$ according to standard). For mixture SB no diffusion coefficients were average or high,($pD_e>11.0$). For mixture SB Cl was not found to be diffusion controlled. Instead surface wash off dominates in the initial test phase and depletion in the mid and end phase of the test. The cumulative leaching of Cl at the end of the test was however equivalent for both mixture R and SB.

Table III Results from diffusion tests and availability tests, all values are the mean of duplicate tests. Diffusion coefficients (D_e) from diffusion tests according to NEN 7345. "Det limit" means concentration was to close to detection limit to calculate diffusion coefficient. "Not diff" means that the leaching was not diffusion controlled. Gray background indicates high diffusion coefficients. Bold font indicates average diffusion coefficient. Numbers marked with < indicates that at least one value was below detection limit.

	Diffusion coefficient D_e [m^2/s]		**Cumulative leaching at end of test [mg/m^2]**		**Availability test [mg/m^2]**	
Mixture	**R**	**SB**	**R**	**SB**	**R**	**SB**
As	Det limit	Det limit	<0.275	<0.298	13.10	<33.46
Ba	**3.8E-12**	1.4E-14	628.3	75.8	1491.4	3124.6
Cd	Det limit	Det limit	<0.0138	<0.0147	11.20	14.47
Cr	**4.1E-13**	1.6E-13	7.58	7.01	49.28	52.34
Cu	4.8E-17	5.1E-18	0.735	8.281	422.6	12131.5
Hg	Det limit	Det limit	<0.00550	<0.00589	<0.0653	<0.100
Mo	1.4E-13	2.8E-13	12.3	14.7	135.4	84.8
Ni	Det limit	Det limit	0.161	<0.149	133.3	216.3
Pb	1.2E-14	2.4E-17	0.513	0.947	25.0	947.3
Sb	1.7E-13	4.9E-15	0.140	0.848	2.30	69.6
Se	Not diff	2.8E-13	0.364	0.438	16.27	4.15
Zn	Not diff	3.5E-18	2.31	5.72	760.9	23692.2
DOC	**2.9E-12**	Not diff	1084.1	2291.3	4242.9	4355.2
Cl	**2.9E-11**	Not diff	20142.1	20212.6	30465.6	55531.8
F	**4.4E-13**	2.2E-13	549.9	471.8	6530.5	6350.3
SO_4	1.1E-16	6.8E-16	1678.1	3915.4	1078226	812181

Non-destructive laboratory testing

Samples were found to have a RH of 96-99% in the sealed tubes. After extraction from their tubes after 14 days they were stored in 89 % RH. The E-modulus of samples of mixture SB increased during the first month, after that the increase stopped and the values stabilized (Figure III). The E-modulus of the samples of mixture R increased initially only to fall later during the test. At the time of fall in E-modulus the outside of the samples showed no difference. Later on cracks were beginning to show in the surface of the samples of mixture R, but not for the samples of mixture SB. The deviation of the E-modulus values was greater for mixture R than for mixture SB.

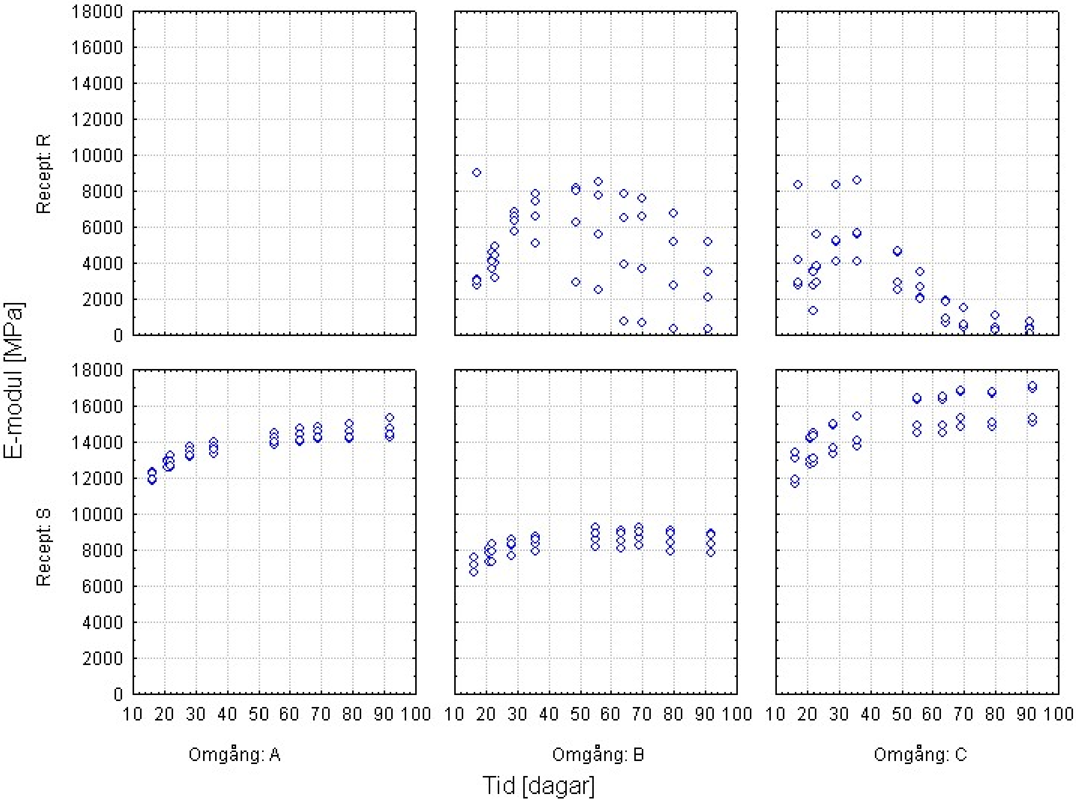

Figure III Development of E-module over time from non destructive testing for both mixture R and SB. Batch A, B and C had different varying addition of water.

DISCUSSION

Technical properties of bound material

High levels of chlorides has been found to be a problem when utilizing waste bottom ash as aggregates in concrete due to corrosion on reinforcement iron, chlorides can limit the amount of bottom ash that can be utilized without some type of washing [12]. Since there is no reinforcement iron in the intended application of the bound bottom ash (roads and industrial storage areas), this is a minor issue in this type of application.

Another challenge when utilizing waste bottom ash in concrete applications could according to literature be gas development due to metallic aluminium at high pH-values [2, 13]. Such tendencies were observed but no effect on technical properties could be validated. Bound bottom ash has concrete like properties. Unconfined compression tests show strength of 1-8 MPa depending on hardening temperature and water addition. This is lower than for concrete, but considering the small amount of cement, 5 %, added in the mixture it is expected. Waste bottom ash could be used as aggregate in concrete, but since chloride removal treatment might be needed, the market for the bottom ash is probably greater as a construction material, where the demands are slightly lower.

The speed of the hardening reactions is highly dependent on temperature, increased temperature during hardening gives significantly higher strength development. Concrete is usually tested after hardening in 20°C. Samples were hardened at 7°C to not overestimate results compared to field conditions. When samples were stored at 20°C, the rate of strength development increased. The hardening reactions are also dependent on water. With to little water the hardening process will be hampered. Similar results were obtained for hydraulic conductivity where significantly lower values, as low as 10^{-10} m/s, were measured after hardening at high water content and high temperature, compared to 10^{-6} m/s for lower water content and lower temperature.

The water content giving the maximum dry density (the water content giving the best packing of particles) is often used for testing of soil materials to determine the optimal water content for test sample manufacture regarding strength and stability. For hardening materials, like ash and cement, reactions between water and solid matter is important for strength development, these reactions consume water. Lack of water will hamper these reactions. The unconfined compression test results showed that water content higher than the optimal water content for maximum dry density was needed during test sample manufacture to fully take advantage of the strength development originating from fly ash and cement. Higher water content than the water content giving maximum dry density is needed for optimal strength development in hardening materials.

Environmental properties of bound materials

Many cation metals have high mobility at high and low pH-values and a minimum in mobility at neutral pH-values [14]. During storage of waste bottom ash outside pH is reduced due to carbonation reactions, this reduces the leaching of several cations. Storing is commonly used in Sweden to improve environmental properties of waste bottom ash through carbonation. Carbonation is effective for Cu [15].

The aged bottom ash used in the testing had pH 10, which indicates that it had carbonated. When the aged waste bottom ash was mixed with fly ash and cement, the pH rose from 10 to 12-13. According to Dijkstra et al. [14] the mobility of Ni, Zn, Cu and Pb are most likely to increase if pH is increased, which agree well with the test results. This could be one explanation why leaching of a number of cations in percolation tests increased. The fly ash and cement added contains metals and salts which could also be a reason for the increased levels in the percolation tests. It is however very important to note that percolation tests are not representative to an actual construction with bound material, since the sample according to the test standard needs to be crushed prior to testing. The percolation test shows the amount of leaching from large particle surfaces and water flow through the material, none of which is true for hardened dense materials. A low hydraulic conductivity means a low flow of water through the material and thus a low net risk of leaching. A hydraulic conductivity of 10^{-1} m/s can be considered very low.

A better method to evaluate leaching from hardened material is diffusion tests, since the material can be tested in the form it is going to be used. This method was used to compare mixture R and SB. The pH was equivalent for both mixtures, differences in pH can therefore not explain any leaching differences. Chlorides had the highest diffusion coefficient of all elements tested. The number of elements with high or average high diffusion coefficient is larger for mixture R than for mixture SB. Mixture R showed a higher cumulative leaching in diffusion tests compared to mixture SB for Ba, Cr and F, while mixture SB was higher for Cu, Mo, Pb, Sb, Se, Zn, DOC, SO_4. Chlorides are equivalent for both mixtures.

Evaluation of non-destructive laboratory testing

The samples tested in non-destructive testing were stored under conditions causing them to slowly dry, however, the two mixtures reacted differently to this. The initial increase in E-modulus in sample of mixture SB stabilized during the test, while the initially increasing E-modulus in samples of mixture R dropped drastically during the test. The E-modulus decreased before distinct cracks were visible on the surface of the samples, indicating that the method is useful to identify cracks in bound ash materials before they can be seen. Waste bottom ash reduced the risk of crack formation due to drying. Unconfined compression tests also show that strength increase significantly if bottom ash is part of the material. Furthermore non-destructive methods enable to follow the same sample throughout the testing, reducing errors between samples and saves money because fewer samples needs to be made compared to destructive testing.

CONCLUSIONS

This paper evaluated waste incineration bottom ash as a bound construction material. To stabilize waste bottom ash with fly ash and cement is a good way to use waste bottom ash in the construction of industrial storage areas and roads.

Bound ash materials containing waste bottom ash were found to be stronger than fly ash based bound materials already used in construction today.

Manufacturing of test samples at optimal water content for maximum dry density is not optimal for hardening material. Higher water content is needed when hardening reactions consume water, if the reactions are not to be hampered. Temperature during hardening also affects the speed of hardening reactions.

Bound ash materials has a low hydraulic conductivity and will let very little water pass through the material, which reduces the risk of negative environmental consequences compared to non bound ash. Solubility of chlorides is not affected if waste bottom ash is bound or not, the mobility however decreases as the material has a low hydraulic conductivity. Diffusion testing is preferable to percolation and batch tests in environmental risk evaluations.

Bound ash materials containing waste bottom ash reduce the risk of crack formation due to drying compared to bound materials mostly consisting of fly ash. Non-destructive testing works to detect crack formation in bound ash materials.

In order to create a market for waste bottom ash as a construction material further work is needed to demonstrate utilization of waste bottom ash under at demonstration scale under field conditions.

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