New Material Treatment Technologies in Management of the Effect of Seasonal Variations

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ABSTRACT: In the recent years, it has been considered more to use lower quality aggregates in road construction. This has become necessary mostly due to smaller supply of good quality materials available within a reasonable transportation distance and higher transportation costs. Non-traditional stabilisers have been marketed as economical and promising to improve the properties of poor quality materials. In the regions with long frost periods, such as Scandinavia, open-graded aggregates containing a small amount of fines have been used in road construction in order to prevent frost heave. As fines content increases, the moisture susceptibility of aggregate becomes greater, leading to problems with bearing capacity in spring when frost thaws. The research was done to find out if non-traditional stabilisers would provide a toolbox for decreasing the moisture susceptibility of coarse-grained aggregates having, except for spring-time frost thawing, a sufficiently good bearing capacity. Polymeric and ionic stabilisers and resins have been tested. This paper presents the effects of the stabilisers on four different aggregates. The laboratory research consists mainly of Tube Suction tests. The literature studies and test results indicate that ionic and enzymatic stabilisers can hardly be used for decreasing moisture susceptibility in aggregates having a fines content of less than 15%. The tests showed that polymeric stabilisers and resins were the most promising stabilisers. It must be noted that the same stabiliser might act in a different way from one aggregate to another. Therefore it should always be checked whether the stabiliser is applicable in connection with the aggregate in question.

KEY WORDS: Non-traditional stabiliser, aggregate, moisture susceptibility, Tube Suction test, unbound material

1 INTRODUCTION

Taking into account the effect of seasonal variations has a major effect on the selection of materials that can be used in the unbound layers of road structures in the areas of seasonal frost. Usually the materials have been chosen from among those having a low fines content and an open graded grain size distribution. There is an increasingly restricted supply of good quality materials and the costs have risen because of longer transportation distances. Since industry and trade require just-in-time delivery of materials in order to optimise the cost structure, pressure has become higher to remove, or at least to minimise, load restrictions during seasonal frost. As the basic government allowance for the maintenance and repair of the road system at least in Finland has been cut down, it has become increasingly important to find cost-effective methods so that poor materials can also be utilised. This is particularly important in repair of existing road structures, in which a whole structural layer should be replaced with a new material or stabilised using rather expensive traditional methods. Non-traditional treatments methods can have potentiality for the improvement of structural layers, aimed primarily to decrease the water susceptibility properties of the materials. Remaining sufficiently dry, the material would also behave well in spring.

Since the mid-1990s, the Laboratory of Foundation and Earth Structures at the Tampere University of Technology has been doing research on the water-susceptibility properties of problematic base course materials. It started with research into the effects of the seasonal variations on the mechanical properties in problematic materials with different fines and low bitumen contents (Kolisoja et al., 2002). More recently, the effects of some non-traditional stabilisers have been tested as part of a more wide research (Vuorimies et al. 2004). The encouraging results contributed to obtaining funds for the research into the effects of non-traditional stabilisers on the moisture susceptibility of the problematic aggregates.

2 PURPOSE OF THE RESEARCH

The purpose of the research lasting about one year was to find potential non-traditional stabilisers suitable for the conditions in Finland and to establish their applicability and mechanisms of action. The laboratory tests were restricted to problematic materials used in the unbound bases, the fines contents of which varied 5-20%.

For getting an overall view of the different types of stabilisers, efforts were made to obtain as many types of stabilisers as possible for the tests, even though the agents were not primarily intended for use in open graded materials with low fines contents. Finnish aggregate itself has usually rather good mechanical properties, and so it was not higher strength that was sought in the non-traditional stabilisers but, instead, capability to prevent water from being bound and migrated into the aggregate.

Literature and Internet were used to find such stabilisers that might be suitable for the research and earlier experience in their utilisation. In the laboratory tests, the primary testing method applied was the TS test, which had proved a promising tool in research work done previously for evaluating the effects of non-traditional stabilisers (Saarenketo et al 2000, Vuorimies et al. 2004). Also, the effect of the stabilisers on the surface properties of the fines in the aggregates was examined.

3 NON-TRADITIONAL STABILISERS

The literature study showed that most of the rather few publications dealt primarily with the effects of the non-traditional stabilisers in fine-grained soils. The research into more coarse-grained materials was mostly focused on the dust suppressants. There are only few more comprehensive published researches or series of research into non-traditional stabilisers. The source most frequently referred to comprises Scholen's research report from the early 1990s and the articles focused on the same source material (Scholen and Coghlan 1991, Scholen 1995). In the recent years several articles have been written by U.S. Army Engineer Research and Development Center dealing with the strength impact of the non-traditional stabilisers from silty sand to clay (Newman and Tingle 2004, Santoni at al. 2003, Tingle and Santoni 2003, Santoni et al. 2002).

The lack of reliable published research material and properly documented test sites monitored long enough poses a major problem. In addition, the information given by the stabiliser manufacturers on Internet pages is often too general and superficial, sometimes even contradictory. Further, most of the researches relevant to this research are dealing with the stabilisers in arid and relatively warm climates and few publications contained references to freeze-thaw behaviour.

The non-traditional stabilisers are most often divided at least into 1) polymer, 2) enzymatic and 3) ionic stabilisers. In addition to these, the classification comprises 4) lignins, 5) petroleum products, and 6) stabilisers based on organic resin emulsions. Furthermore, it might be sensible to divide the agents into compound stabilisers, combined stabilisers and other non-traditional stabilisers.

Polymers come in a very wide range. Usually they come in liquid emulsions, of which a little less than half is polymer. Polymer-coated fly ash, for one, is available in powdery form. Most of the polymer products made for stabilisation have been vinyl acetates or acryl-based copolymers (Newman and Tingle 2004). Since polymers come in a very wide range, the mechanisms of action vary from one type to another. The latex acryl-copolymers, for example, stabilise the soil through their non-chemical covering impact (Petry and Little 2002). Powdery polymer-coated fly ash, again, forms hydrophobic soil matrix with the treated aggregate and this decreases water permeability and restricts water penetration into treated soil; in addition, its polymers replace water molecules on the surfaces of clay particles and cover them (Wilmot and Rodway 1999).

The basic structure of enzymes consists of proteins which in biological systems act as catalysts. If a soil is to be stabilised with enzymes there should be a lot of silt and clay sized particles and organic material. The enzymes are very specific in synthesising certain groups of chemical compounds and limiting their action to specific bonds in the compounds with which they react. The reaction can include breaking of the clay lattice and combining of cations and other compounds with the aid of organic molecules. Breaking of the lattice decreases the grain size of clay particles and helps them to combine with organic materials. In the case of enzymatic stabilisers a very important issue is compaction, which enables close contact between the soil particles and thus initiation of the cementation process. (Scholen 1995)

The electrolytes contained in ionic stabilisers affect the basic nature of clay minerals. According to the information provided by the manufacturers ionic stabilisers are only effective if the fines content is at least 35% and a certain proportion of the fines must be clay minerals. After stabilisation and compaction drying-wetting and freeze-thaw cycles should have no effect on the treated soil material. Treatment with ionic stabiliser should be done when the soil material is at the optimum water content or near full saturation. Ionic treatments can even be done deep below the ground surface through an injection method where the electrolytes are transported by osmosis. (Scholen and Coghlan 1991)

Lignin derivates are often made of by-products from the forest industry. They are generally used as dust suppressants. However, lignosulphonate, for instance, provided good short-term bearing capacity in some test series but the stabiliser was water soluble (Scholen and Coghlan 1991)

The petroleum products are made of cut-back bitumen, modified or unmodified bitumen emulsions, oil emulsions or mineral oils (Bolander and Yamada 1999). One of the traditional stabilisation methods is bitumen stabilisation, which is not, however, counted in this group. The soil particles are mainly covered by petroleum products, which bind the particles to each other after the emulsion has broken up.

The organic resin emulsions usually consist of resin emulsion made from softwood. Wood-based resin can also contain binding components added to it (Santoni and Webster 2001). The action of binding components is based on hardening during drying and their capability of binding particles to each other.

The agents included in compound stabilisers consist of at least two components of a different type, which have an intense impact and which are equally important for successful treatment. Stabilisers can be called combined agents when the combined action of at least two different agents is utilised so that these different agents are not simultaneously mixed in the layer to be treated. One of the agents can be mixed only in the uppermost part of the soil to be treated, for giving it more bearing capacity or durability.

4 TEST METHODS

The most important test method used in the laboratory was the Tube Suction (TS) test method, originally suggested by Saarenketo and Scullion. It is an easy-to-perform laboratory test method for assessing the water suction properties of various types of aggregates (Saarenketo 1995, Scullion and Saarenketo 1997). The test includes compaction of a 180 to 200 mm thick aggregate sample in a plastic tube with an internal diameter of 150 mm. After drying the specimen is put into a plastic tube with a layer of water at the bottom. The absorption of water into the specimen is then monitored by measuring the dielectric value and electrical conductivity at the top of the specimen at frequent intervals. The report by Saarenketo includes a more detailed description of the method (Saarenketo 2000). The directions were changed in one respect: the absorption vessel was covered with a box to decrease any direct evaporation from the surface of the specimens as relative air humidity was kept above that of room air. As for storing of the specimens before absorption, it was done deviating from the method if required in the stabiliser manufacturer's directions. The assessment of the unbound crushed base material in terms of quality grades based on the values of dielectric value of the TS test is presented in Table 1 (Saarenketo 2000). Roughly, the dielectricity measured at the top of the specimen represents the amount of free water at the top of the specimen.

Syed et al. had also used the method when testing the effect of the enzymatic stabiliser on four moisture susceptible base course materials (Syed et al. 2000).

Immediately after the TS test, the CBR number was determined by a penetration of 0.1 inch. The specimen was loaded according to ASTM D-1883 (ASTM 2001), although the manufacture and treatment of the specimen before loading deviated from the standard. The CBR number was indicating when the effects of the stabilisers were compared with the stiffness of the materials.

The specific surface areas and adsorption indexes of water were determined for the fines from the specimens taken after the TS tests, and the cation exchange capacities were determined for the gradings below 2mm taken. The cation exchange capacities have been calculated from six exchangeable cations (Al, Ca, K, Na, Mg and H). The mineralogy of the fines was determined using the X-ray diffraction method mainly for the untreated aggregates.

Table 1: Assessment of the unbound crushed materials of the base into quality classes on the basis of the dielectric value of the Tube Suction tests (Saarenketo 2000).

Dielectric value of the Tube Suction test	Classification
< 10 *)	Good-quality crushed material of the base
10 – 16	Questionable crushed material of the base
> 16	Inappropriate crushed material in the base

*) In Finland the dielectric value 9 in the Tube Suction test has also been used as the limit for the crushed material that can be classified as good.

5 MATERIALS

Figure 1 shows the grain size distributions of non-plastic materials determined from the top of the TS test specimen after the TS test. Lillby and Emet were crushed rocks. The Norvajärvi aggregate has been taken from the top of a gravel road near Rovaniemi. The Troms aggregate comes from the base of a local road in the island of Senja in Norway. The specific gravities of the aggregates, the percentages of the three most common elementary compounds and the main minerals of the fines are presented in Table 2.

The basic content for the commercial stabilisers on the market was chosen according to the manufacturer's recommendations. For stabilisers, which have not been used for the treatment of soils, the dosage was one weight per cent of the stabiliser concentrate. Stabilisers I – M have not been used in soils before. Some of the stabilisers were also tested with quantities twice or one and a half times the basic dosage. The optimum grain size distribution appropriate for the use of stabilisers A, B, D and F contains fines more than 25%, and so these were not expected to act effectively in the aggregates tested.

Polymers A and B were liquid acrylcopolymer-based emulsions. Polymer C was a dry powdered polymer, which also contained lime. Ionic stabiliser D could also be called a compound or lignin stabiliser due to its lignin content. The primary effective component of ionic stabiliser E was sulphonated D limonene. One part of combined agent F was mostly lime and cement. Resins I and J were so-called resin adhesives. Polymers K – L were liquid polymers, which should give hydrophobicity to the materials treated.

Table 2: The specific gravities of the analysed aggregates, the percentages of the three most common elementary compounds and the main minerals analysed in the fines.

Aggregate	Specific gravity, g/cm^3	Main minerals of fines (over 5%)	The most common elementary compounds		
			SiO_2, %	Al_2O_3, %	FeO, %
Lillby	2.70	Quartz, plagioclase, orthoclase, mica	70.7	14.9	3.7
Emet	3.04	Plagioclase, amphibole, quartz, calcite	48.3	11.3	20.6
Troms	2.72	Plagioclase, orthoclase, quartz, amphibole, mica	58.0	13.9	8.0
Norvajärvi	2.66	Quartz, plagioclase, orthoclase	67.1	13.5	4.8

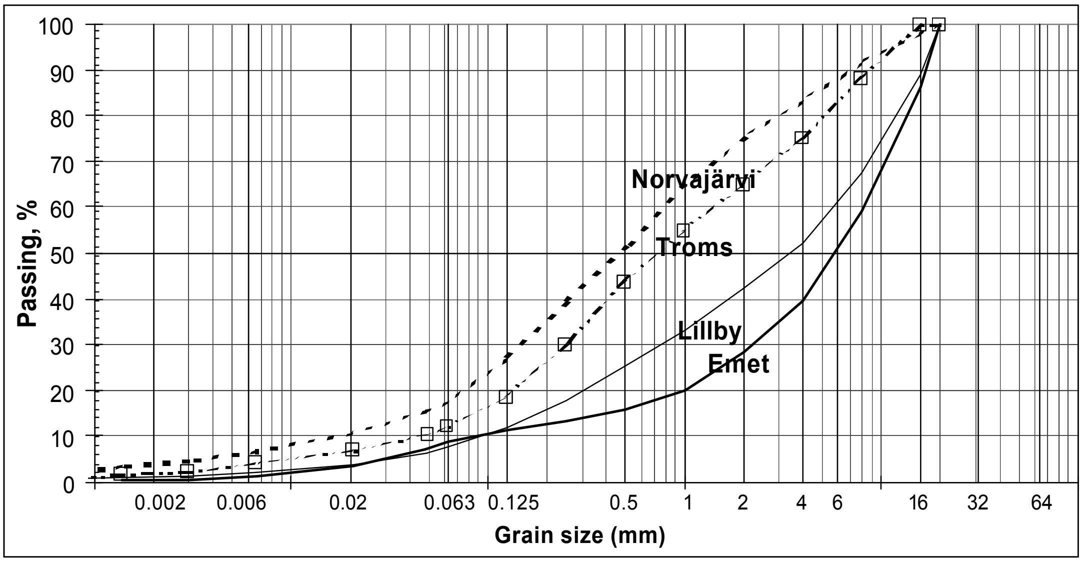

Figure 1: Grain-size distribution analysed from the top of the specimens after the TS test.

6 TEST RESULTS

Table 3 shows the dielectric values determined in the Tube Suction tests by 10 days and the water absorbed into the specimens in about 14 days during the test. The table shows that the untreated materials, except the Troms aggregate, are inappropriate as crushed aggregate in the base. Figures 2 and 3 show that in the Emet crushed rock almost all stabilisers have decreased the dielectric values and retarded water absorption into the specimens, since the dielectric values increased more slowly in the treated than in the untreated specimens. Half of the polymers decreased dielectricity below 9, which is the value to be recommended, and as for the rest of the stabilisers resins I and J effectively decreased dielectricity measured in the TS tests. In the Troms and Lillby aggregates the stabiliser did not always decrease the dielectric values, as can be seen from the red colour spots in Table 3. Table 3 shows that polymer stabilisers C and K and resin J decreased most effectively the moisture susceptibility of the tested aggregates, as becomes evident from the dielectricities measured and the water contents determined at the tops of the specimens at the end of the tests.

Table 3: The values of dielectricity (e_r) determined in the TS test specimens after ten days and the water content of the top of the specimen determined after the TS test and CBR test (w_{35mm}). The green colour indicates that dielectricity is less than nine or the measured quantity has decreased by more than 40% and the red colour indicates that the quantity has increased by more than 20% compared with the untreated aggregate.

Aggregate	Lillby		Emet		Troms		Norvajärvi	
Stabiliser	e_r	w_{35mm} %	e_r	w_{35mm} %	e_r	w_{35mm} %	e_r	w_{35mm} %
Untreated	17	4.9	24	3.7	11.5	5.0	30	6.3
Polymer A	20	5.0	19	4.0	10.5	5.2	18.5	5.2
Polymer B	17	4.9	17	3.2	12	5.6		
Polymer B *2	16	5.5	18	3.4			15	5.3
Polymeric C	8.5	3.7	6	1.7	8	2.7	17	3.8
Ionic D	22	5.0 *)	14	3.1 *)	15.5	5.2 *)		
Ionic D *2	19.5	4.3 *)	21	3.2 *)			15	5.3 *)
Ionic E	17	4.0	15	2.8	10.5	4.0	25	5.5
Combined F	15	4.7 *)	15	3.5	11.5	4.9		
Oil Resin G	18	4.7 *)	12.5	2.5	12.5	4.9		
Oil Resin G *1.5	16	4.7 *)	18	3.3			17	5.1
Resin I	23	3.5 *)	6	0.4	11	2.8	10.5	3.1
Resin J			7	0.9	5.5	1.5	10	2.5
Polymer K	9.5	1.8 *)	6	0.7 *)	5.5	1.9	7.5	3.1
Polymer L			24	3.5	5.5	1.7	18.5	5.1
Polymer M	20	4.0 *)	7	1.6 *)	5.5	2.2 *)	9	3.4 *)

*) The water content of the specimen was clearly higher after drying in the oven than those of the rest of the specimens, i.e. the water content of the specimen was higher in the initial phase of absorption.

Table 4 shows the CBR numbers determined in the specimens after the TS test and the cation exchange capacities determined in the specimens taken. The CBR numbers indicate that polymer stabiliser M would not be suitable for use due to its detrimental effect on the mechanical properties. The table also shows that the cation-exchange capacities of combined stabiliser F and polymer stabiliser C, which both contain lime or cement, are among the highest. In regions with long seasonal frost, the increase of strength is not, however, of much benefit if the material turns into something similar to the bound layer; in that case, uneven heaving by frost in the lower layers might result in roughness, which is more difficult to repair.

Table 5 shows the specific surface areas and adsorption indexes of water determined in the specimens taken from the TS specimens. Generally, a small specific surface area and a low adsorption index of water also indicate lower moisture susceptibility of the aggregate. It can be seen from the table, however, that oil resin G decreased these quantities most effectively. The test results show that a low adsorption index of water and a small specific surface area did not guarantee any considerable decrease in moisture susceptibility.

Tables 3-5 show that among the four aggregates analysed the Lillby rock aggregate was the most problematic.

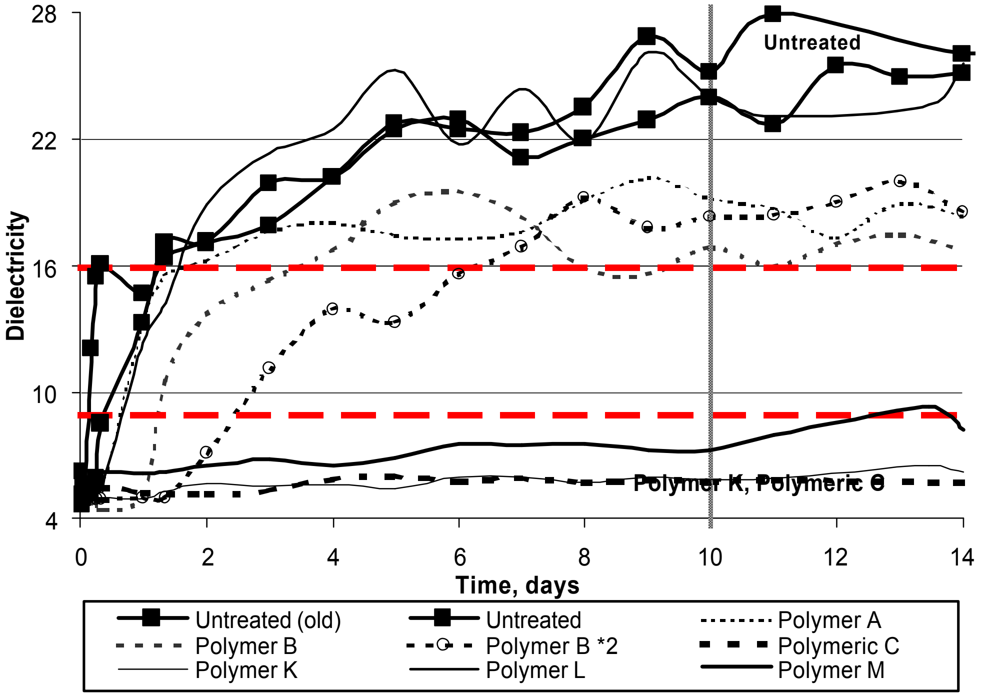

Figure 2: Diagrams of dielectricity in the TS tests in the Emet crushed rock specimens treated with polymer stabilisers vs. untreated Emet crushed rock.

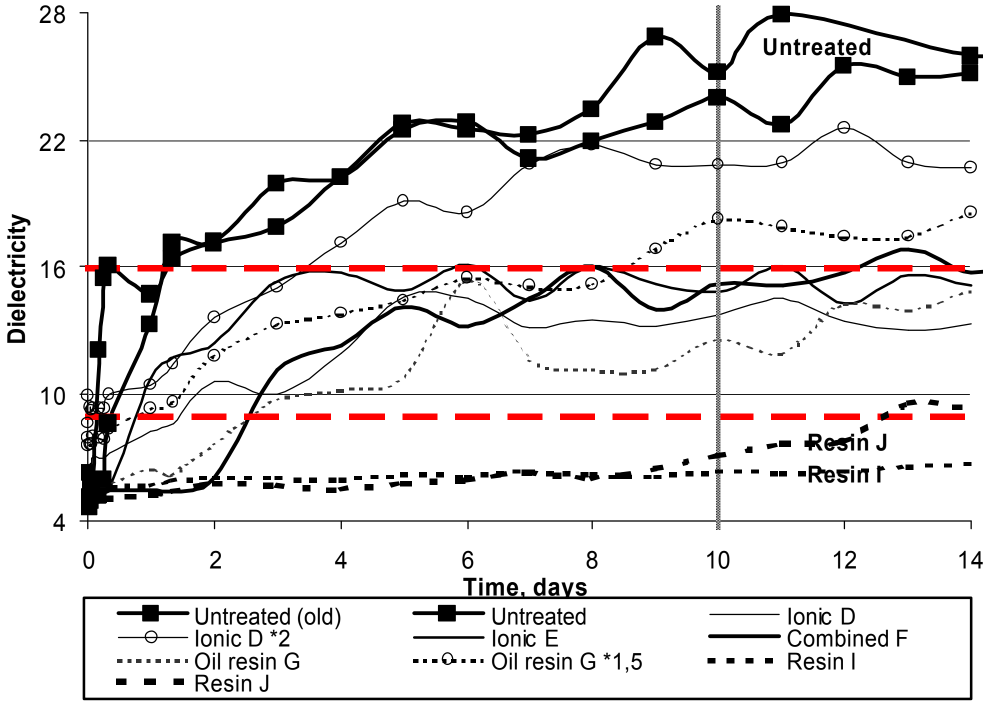

Figure 3: Diagrams of dielectricity in the TS tests in the Emet crushed rock specimens other than those treated with polymer stabilisers vs. untreated Emet crushed rock.

Table 4: The CBR numbers determined after the TS test and the cation-exchange capacities (CEC) determined in the specimens taken from the TS test specimens. The red colour by the CBR number indicates that the quantity has decreased by more than 20% compared with the untreated specimen.

Aggregate	Lillby		Emet		Troms		Norvajärvi	
Stabiliser	CBR	CEC cmol/kg	CBR	CEC cmol/kg	CBR	CEC cmol/kg	CBR	CEC cmol/kg
Untreated	138	1.8	140	7.4	132	1.7	84	2.5
Polymer A	119	2.4	143	7.6	115	2.0	85	2.1
Polymer B	127	1.6	138	7.7	119	1.7		
Polymer B *2	119		138				68	
Polymeric C		8.6		21.4	146	6.8	138	8.6
Ionic D	131	1.6	144	7.0	111	1.5		
Ionic D *2	131		122				49	
Ionic E	131	1.6	139	7.5	121	1.6	112	2.0
Combined F	182	19.4	151	12.7	165	11.0		
Oil Resin G	🟥 100	1.3	🟥 105	4.7	122	1.2		
Oil Resin G *1.5	133		122				108	
Resin I	🟥 96	2.4	128	2.8	121	2.4	104	3.2
Resin J			178	12.6	111	2.1	92	2.3
Polymer K	127	2.8	129	11.3	141	2.5	74	3.8
Polymer L			134	15.5	154	1.5	82	2.2
Polymer M	🟥 103	3.2	146	23.0	🟥 88	3.2	🟥 63	2.7

Table 5: The specific surface areas (SSA) and adsorption indexes of water (AIW) determined in the TS test specimens. The green colour indicates that the measured value has decreased by more than 30% and the red colour indicates that the measured value has increased by more than 30% compared with the test result obtained with the untreated aggregate.

Aggregate	Lillby		Emet		Troms		Norvajärvi	
Stabiliser	SSA m^2/kg	AIW %	SSA m^2/kg	AIW %	SSA m^2/kg	AIW %	SSA m^2/kg	AIW %
Untreated	1560	1.17	12500	2.46	4570	2.08	3350	3.35
Polymer A	🟥 2910	1.16	🟩 3325	🟩 1.24	🟩 2330	🟩 1.44	🟩 2130	🟩 1.13
Polymer B	1280	0.96	🟩 3070	1.97	3530	1.88		
Polymer B *2	1138	🟩 0.60	🟩 4095	2.14			🟩 2145	2.52
Polymeric C	🟥 2320	1.45	🟩 2440	2.40	🟩 2898	1.66	2380	🟩 1.98
Ionic D	1240	🟩 0.56	🟩 2950	2.20	🟩 2670	🟩 1.12		
Ionic D *2	1475	1.34	🟩 3385	1.76			🟩 2055	🟩 1.78
Ionic E	🟥 2220	1.17	🟩 5720	2.62	4660	2.14	🟩 2012	🟥 5.21
Combined F	🟥 4450	🟥 2.97	🟩 4090	🟥 5.2	4340	2.33		
Oil Resin G	🟩 550	🟩 0.65	🟩 470	🟩 1.42	🟩 1310	🟩 1.45		
Oil Resin G *1.5	🟩 845	🟩 0.38	🟩 558	🟩 1.70			🟩 1218	🟩 1.54
Resin I	🟩 788	🟥 2.31	🟩 494	🟩 0.74	3320	🟩 1.40	2570	🟩 1.68
Resin J			🟩 1238	1.82	🟩 2398	🟩 1.30	🟩 2070	🟩 1.46
Polymer K	1338	🟩 0.51	🟩 1668	1.83	🟩 1868	🟩 1.28	🟩 1614	🟩 1.10
Polymer L			🟩 5106	2.27	3645	🟩 1.50	3010	🟩 1.90
Polymer M	1164	0.92	🟩 1528	2.05	🟩 1430	1.48	🟩 1338	🟩 1.22

7 CONCLUSIONS

There is only very little published independent research data available of the non-traditional stabilisers. Most of the publications deal with the results of researches into materials that are finer grained than silty sand. The biggest problem is the lack of profound data from test sites, which is obtained through long-term monitoring.

The most promising non-traditional stabilisers suitable for decreasing the moisture susceptibility of the non-plastic coarse-grained materials are found among polymers. The Tube Suction tests show that polymer stabilisers C and K and resin J act best in the problematic base materials tested.

On the basis of specific surface area, adsorption index of water and cation exchange capacity it was not possible to anticipate what stabilisers will decrease the moisture susceptibility of coarse-grained materials best.

Treatment with some of the stabilisers decreased the stiffness of the aggregates in the CBR test as compared with the untreated aggregate, though the water content of the specimen had decreased. In that case the stabiliser will be hardly suitable for decreasing the moisture susceptibility of the aggregates as the mechanical properties of the aggregates deteriorate too much.

The intention is to continue research into whether the stabilisers that have proved promising are suitable for the purpose in question by carrying out tests, such as frost tests, to find out their long-term behaviour. For more experience, it would be important that long-term monitoring of the test site treated with non-traditional stabilisers could be arranged.

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REFERENCES

ASTM D1883–99, 2001. *Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils.* The American Society of Testing and Materials.

Bolander, P. and Yamada A., 1999. *Dust Palliative Selection and Application Guide*. USDA, San Dimas Technology and Development Center. Available: http://www.wsdot.wa.gov/TA/T2Center/DustGuide.pdf. [Referred to 28.4.2004].

Kolisoja, P., Saarenketo, T. Peltoniemi, H. and Vuorimies, N., 2002. *Laboratory Testing of Suction and Deformation Properties of Base Course Aggregates*. Transportation Research Record 1787.

Newman, K. and Tingle, J., 2004. *Stabilization of Silty Sand Using Polymer Emulsions.* Transportation Research Board 2004 Annual Meeting CD-ROM Paper No 04-3108.

Petry, T. and Little, D., 2002. *Review of Stabilization of Clays and Expansive Soils in Pavement and Lightly Loaded Structures – History, Practise and Future*. Journal of Materials in Civil Engineering, Vol 14, No 6.

Saarenketo, T., 1995. *Using electrical methods to classify the strength properties of Texas and Finnish base course aggregates.* Center for Aggregates research, 3rd Annual Symposium Proceedings, Austin, Texas.

Saarenketo T., 2000. *Tube Suction test – results of round robin tests on unbound aggregates.* Finnish National Road Administration, Lapland Region, Report number 19/2000.

Saarenketo, T. Kolisoja, P. Vuorimies, N. Yliheikkilä, T, and Ylitapio, S. 2000. *Suction and Deformation Properties of Base Course Aggregates: parts I and II.* Tampere University Of Technology. Geotechnical Laboratory. Research Report 51. In Finnish

Santoni, R., Tingle, J. and Nieves, M., 2003. *Accelerated Strength Improvement of Silty Sand Using Nontraditional Additives.* Transportation Research Board 2003 Annual Meeting CD-ROM, Paper No 03-2889

Santoni, R., Tingle, J. and Webster, S., 2002. *Stabilization of Silty Sand with Nontraditional Additives.* Transportation Research Record 1787, Paper No 02-3756.

Scholen, D., 1995. *Stabilizer Mechanisms in Nonstandard Stabilizers.* 6th International Conference on Low-Volume Roads. Vol 2. Minneapolis, Minnesota, June 25-29,1995. Conference Proceedings 6, National Academy Press, Washington, D.C.1995.

Scholen, D. and Coghlan, S., 1991. *Nonstandard Stabilization of Aggregate Road Surfaces.* Transportation Research Record 1291.

Scullion, T. and Saarenketo, T., 1997. *Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials*. Transportation Research Record 1577.

Syed, I., Scullion, T. & Randolph, R., 2000. *Tube Suction Test for Evaluating Aggregate Base Materials in Frost- and Moisture –Susceptible Environments.* Transportation Research Record 1709, Paper No 00-1147.

Tingle, J. and Santoni, R., 2003. *Stabilization of Clay Soils with Nontraditional Additives.* Transportation Research Record 1819, Vol. 2, Paper No. LVR8-1136

Wilmot T. and Rodway B., 1999. *Stabilised pavements - Selecting the additive: cementitious, polymer or bitu*men. The International Conference on Local Engineering & Public Works, Sydney, 22–26.8.1999. Available: http://www.auststab.com.au/tp25.pdf. [Referred to 26.1.2005]

Vuorimies, N., Kolisoja, P., Saarenketo, T. & Peltoniemi, H. 2004. *Studies of Seasonal Behaviour of Route Aggregates in 2001-2003.* Finnra reports 4/2004 [Internet publication]. In Finnish. Available: http://alk.tiehallinto.fi/julkaisut/pdf/thselv0404.pdf

Vuorimies, N., Kolisoja, P., Saarenketo, T. and Peltoniemi, H., 2004. *Test Results of Studies in Seasonal Behaviour of Route Aggregates in 2001-2003.* Tampere University of Technology, Laboratory of Foundation and Earth Structures, Research Report 56, In Finnish.