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The Environmental Impact of Using Fine-Grained Cements as Injection Materials for Soil Grouting - A Mini Review

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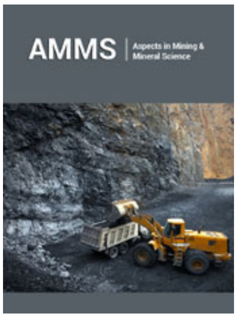

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Abstract

Common cement-based suspensions are capable of penetrating coarse-grained soil materials effectively (e.g. gravel and coarse-grained sands) with a permeability of 10^{-1}cm/sec and above. Various types of chemical solutions are used to reinforce lower permeability soils (up to 10^{-4}cm/sec) that can penetrate into soil formations such as fine sands and sludges. Materials of this type have significant disadvantages, such as high cost, unsatisfactory durability, low strength and can also cause environmental pollution due to their toxicity. In the last thirty years, new materials have been developed, which are presented as a counter-proposal to the use of chemical solutions for the above problems. These are extremely fine-grained cements whose suspensions have the ability to penetrate and reinforce even fine-grained sands. The main advantage of these materials over chemical solutions is that they are composed entirely of minerals and thus do not cause adverse environmental effects. The aim of this work is to review the utility of applying cement grouts to soil formations in order to improve their mechanical properties and highlighting their environmental friendliness.

Keywords: Permeation grouting; Fine-grained cements; Injectability; Sands

Introduction

The safe construction and operation of many technical projects often requires the improvement of the properties and mechanical behavior of the soil formations. The shear behavior of a soil material is of particular interest because it has a direct impact on practical bearing capacity problems [1,2], stability of slopes and embankments [3,4] as well as permanent seismic movements of slopes [5,6]. Permeation grouting is commonly used in geotechnical engineering either to reduce the permeability or improve the mechanical properties of soil and rock [7]. Success in a given grouting operation requires that the grout is capable of being injected into the soil formation and that the desired improvements in the properties of the formations are attained. Grouts are generally categorized as suspension, or particulate grouts, which are prepared with ordinary Portland or other cements, clays, or cement-clay mixtures, and fine sands in some cases, and solution, or chemical grouts which include sodium-silicate formulations, acrylamides, acrylates, lignosulfonates, phenoplasts and aminoplasts as well as other materials that have no particles in suspension. Chemical solutions can be injected in fine sands or coarse silts but are more expensive and some of them pose a health and environmental hazard. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradations [8-15].

Permeation Grouting

The use of permeation grouting is a method of improving the properties and mechanical behavior of the soil. The method is generally expensive, and its choice depends on the relative cost with respect to other alternative solutions. It is based on the replacement of water (or air) of soil voids or rock mass cracks by a grout, that is pressed under low pressure, so as not to disturb the soil formation. It is the oldest method of injection and is usually applied to relatively small areas of soil that are far from the soil surface. The method is used in technical projects, aiming at controlling underground flows, increasing the shear strength of soil formation, reducing deformation or subsidence and filling gaps [16].

Injection categories

There are many criteria by which injection methods can be classified; they are related to the type of injection, the application cases, the 'grid' of the injection points and the sequence of the manufacturing steps. The categories of injections as defined by European standards EN12715: 2000 and EN12716: 2000 are as follows: (a) Permeation Grouting, (b) Compensation Grouting and (c) Jet Grouting.

Suspensions types

As mentioned above, suspension-type grouts can even be soil-water mixtures. These grouts are the most economical solution, but at the same time they show many important disadvantages such as the inability to develop strength along with the difficulty of penetration. The most popular suspension - type grouts are those based on cement, whose main components are the common Portland cement and water. Depending on the needs of each application (high initial strength, resistance to chemical environment) it is possible to use different types of cement (aluminum, slag, etc.) instead of common cement. In addition, it is possible to add to the grouts some solids (sand, clay) with the main purpose of reducing the cost of injections, while the use of admixtures such as fly ash, slag silica fume and addition of chemical improvers (i.e. water reducers, superplasticizers, coagulation accelerators etc.) aims to improve some properties. The following sections list all the ingredients used in the manufacture of cement grouts and additionally indicate how they act on the properties of grouts. Cement is a mortar, which, when mixed with water, can thicken and harden both in air and in water. It is mainly an excellent hydraulic mortar, which combines high hydraulicity and strength. Common Portland cements are mainly used for permeation grouting. The raw materials, which are necessary for the preparation of the main phases of Portland cements, are those that contain the oxides of calcium (CaO), silicon (SiO_2), aluminum (Al_2O_3) and iron (Fe_2O_3). Limestone gives CaO, while clay gives SiO_2, Al_2O_3 and Fe_2O_3. Marls contain all four oxides in varying amounts depending on their composition. Furthermore, silica sand contains SiO_2 and bauxite Al_2O_3. The main phases of Portland type cements are the following [17]:

a. C_3S silica

b. Calcium silicate C_2S

c. C_3A alumina

d. Aluminum-iron calcium C_2 (A,F)

The above phases are not present in the cements completely pure, but with small admixtures of MgO, TiO_2, K_2O, Na_2O, Mn_2O_3 etc. Portland cement consists of clinker and gypsum (or gypsum and anhydride), which are collected in a very fine powder with a special surface of Blaine 2200-6000cm^2/gr. The amount of gypsum that grinds together with the clinker depends on the fineness and type of cement and is necessary to regulate the setting. However, for reasons of volume stability, the amount of cement must be limited. Clinker is a product of firing (shells or extruders) of blast furnaces and the materials from which it is made are usually limestone and clay or marls that contain both materials. To improve the proportions of the firing mixture, silica sand and iron oxides can be added [17]. Cements have standard mechanical, chemical and physical properties, which are determined by performing standard tests. According to the European Standard EN 197-1: 2000, these properties are: strength after 2, 7 and 28 days, the initial setting time and the swelling after setting. Important properties of Portland cements are also Blaine fineness, density and loose weight. The most important property for choosing the right cement for injections is its fineness, which is expressed by the special Blaine surface (in cm^2/gr and m^2/gr). The finer the cement is ground, the larger the surface to react with water and therefore the reaction (hydration) takes less time. The cement grains react with the water on their surface and this reaction proceeds gradually towards the center, until the grain is completely hydrated. If the fineness is low, the cement grains are not fully hydrated, while in cements with very high fineness we have the appearance of cracks in the hardened cement paste. The German Regulations define only a lower limit (minimum limit) for fineness at 2200cm^2/gr [17]. In general, in common Portland cements the fineness ranges from 350 to 800m^2/gr [18]. However, the fineness is not enough to ensure the optimal choice of cement but should be combined with the knowledge of its granulometric curve. Most common cements have a maximum grain diameter ranging from 50 to 200 μm, thus limiting the scope of application of cement injections in coarse-grained soils with $D_{10}\geq 1$mm and $k\geq 5\cdot 10^{-2}$cm/sec and in rocks presenting cracks of thickness $\alpha\geq 160$μm [19]. Due to these limitations, arose the need for the production of new fine-grained cements that would be the basis for the preparation of grouts with improved properties, able to penetrate into finer formations.

Fine-Grained Cements as Injection Materials

Common cement-based suspensions -as defined by the various standards (ASTM C 150-04, EN 197-1: 2000, etc.)- are capable of penetrating coarse-grained soil materials effectively (e.g. gravel and coarse-grained sands) with a permeability of 10^{-1}cm/sec and above [20]. Various types of chemical solutions are used to reinforce lower permeability soils (up to 10^{-4}cm/sec) that can penetrate into soil formations such as fine sands and sludges. However, it has been shown that materials of this type have significant disadvantages, such as high cost, unsatisfactory durability, low strength and can also cause environmental pollution due to their toxicity [20-23]. In the last thirty years, new materials have been developed, which are presented as a counter-proposal to the use of chemical solutions for the above problems. These are extremely fine-grained cements whose suspensions have the ability to penetrate and reinforce even fine-grained sands [8-11,24-27]. The main advantage of these materials over chemical solutions is that they are composed entirely of minerals and thus do not cause adverse environmental effects. For the reinforcement of soils, characterized as medium or fine-grained sands, various types of solutions have been developed in the last thirty years that are able to penetrate effectively into soil formations with a permeability coefficient of up to 10^{-4}cm/sec. These solutions, which are mainly chemical, have significant disadvantages associated with high cost, unsatisfactory durability and environmental impact due to their toxic behavior [22,28]. On the other hand, mortars developed on the basis of common cements can penetrate effectively into coarse-grained soils (e.g. gravelly and coarse-grained sands) with a permeability of 10^{-1}cm/sec [20]. Therefore, in order to achieve satisfactory penetration with the least possible impact on the natural environment, the use of fine-grained cements for the preparation of suspensions that are capable to permeate fine-grained formations has been proposed in recent years [9,16,24].

Fine-grained cements categorization

The categorization of cements into "fine-grained" along with their clear separation is based on the establishment of certain criteria and standards that are applied. The Norwegian standard separates the fine-grained cements into: microfine with d_{95}<30μm and ultrafine with d_{95}<15μm [29]. In the USA, according to the ACI Committee 552, fine-grained cements are those that show a maximum grain size, d_{max}=15μm [30], while the European standard EN 12715: 2000, defines as fine-grained (microfine cements) those with d_{95}<20μm and Blaine fineness>8000cm^2/gr. Finally, in Britain, ultrafine cements are defined those having a maximum diameter of grain d_{max}<6μm [31].

Methods of preparation

The preparation of suspensions from fine-grained cements is carried out by two methods: the dry and the wet grinding process [32]. Most fine-grained cements are produced by the dry method and are products of grinding Portland common cement, blast furnace slag or some pozzolan. Grinding takes place in special mills, in which the size of the maximum grain is reduced [33]. The second method of making fine-grained cements, referred to in the literature as the wet method, grinds the cement in mills in the presence of water, on site. Efforts in this direction have led to the production of suspensions called Microsol [20] and Cemill [34], although there are other standard methods of preparing suspensions, such as Ahrens [35] and Huang et al. [32]. However, Cemill suspensions appear to have a very short workability and require a complex manufacturing process, while Ahrens suspensions do not exhibit satisfactory rheological properties and result from extremely slow process [33]. Naudts & Landry [36] introduced the PASREM grinding machine which enables the preparation of suspensions in a short period of time along with satisfactory rheological properties. In general, the wet method allows the production of the desired amount of suspension by reducing waste, favors more accurate project budgets and requires much lower costs compared to the preparation of fine-grained cements with the dry method. However, it does not allow the production of materials with a maximum grain size of less than 18μm [36].

Fine-grained cements as commercial products

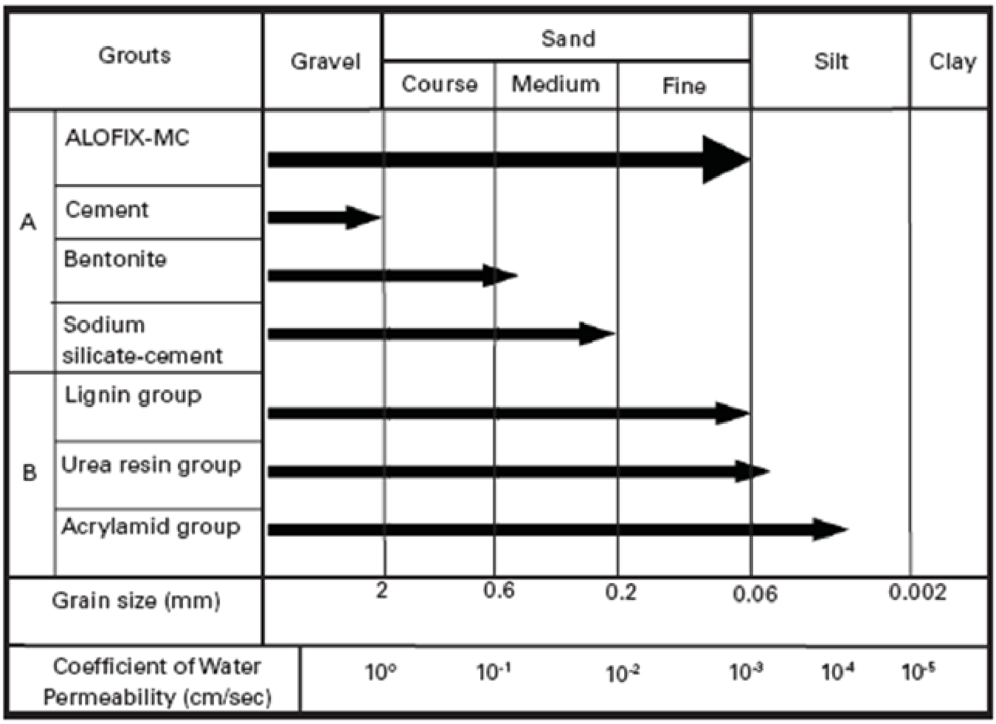

Figure 1: Comparison of the penetration of MC-500/Alofix MC cement suspensions with other grouts [48].

A significant number of commercially available fine-grained cements has been developed in recent years. Specific information on the production method and composition of these fine-grained cements is not available from the producers. The MC-500 is the oldest fine-grained cement in the international literature and is produced by the Japanese cement company Onoda Cement. Following the absorption of the company by Taiheiyo Materials, this product is available in the market of Southeast Asia and Australia under the brand name Alofix MC, while in the USA under the name MC-500. It is a mixture of finely ground Portland cement and slag in a ratio of 4:1 [37], which consists only of minerals and has a specific gravity of 3.0±0.1gr/cm^3. Its manufacturers recommend its combined use with the NS-200 hyper plasticizer at a dose of 2% by weight of dry cement. From Figure 1 it yields that MC-500/Alo fix MC based cement suspensions can achieve penetration comparable to that of chemical solutions. Super Fine and Super Fine-L are fine-grained, slag cements manufactured by the Japanese company Nittetsu. They have an average grain size of 3μm and a specific gravity of 3.0gr/cm^3 and 2.92gr/cm^3, respectively [38]. The use of Nittetsu Super Fine has been reported by several researchers [39-41]. Clarke introduced later the MC-500 to the U.S.A. under the trade name M5 and then manufactured M1 and M3 cements [42-44], giving them the trade names MC-100 and MC-300 respectively. MC-100 is a fine-grained slag, while MC-300 is a fine-grained Portland cement [45-47].

The U.S. Company Grout prepares cement-based injection materials by both dry and wet methods. The fine-grained cements Type V Premium and Type V Standard have a specific weight of 2.63gr/cm^3 and 2.70gr/cm^3 and an average grain size of 2.50μm and 4.0μm, respectively. Their chemical composition includes 55% Thera earth and 45% super grounded type IV Portland cement. In the dry state, their combined use with a hyper plasticizer in doses of 1.5% and 2.5% by weight respectively of dry cement is required [48]. The specific materials are the basis for the production of suspensions with a ratio W/C of 0.6:1 and 0.8:1, respectively, following the wet method and a very specific process in terms of the manner and time of mixing and stirring. The use of Type V Premium cement is noted in their research efforts by Henn et al. [39] and Henn et al. [40]. Important references in the international literature are related to the Spinor cements (A6, A12 and A16) of the French company Soletanche-Bachy [49,50]. Their main representative is the fine-grained cement A12, which is slag having a specific weight of 2.94gr/cm^3. The manufacturer proposes the use of a superplasticizer in a dosage of 3% by weight of dry cement along with W/C ratios from 1:1 to 3:1. Spinor A12 can also be used for the preparation of Microsol grouts, which are prepared by the wet method. It is also reported that MC 20 RC fine cement is manufactured in Brazil by Holcim Brazil [51]. A significant part of the international market is occupied by fine-grained cements under the brand name Mikrodur, which are sold by Dyckerhoff AG. These are products consisting of either pure Portland (with the mark P) or pure slag (with the mark R). Finosol products are also available from the same company, which are suspensions resulting from the mixing of blast furnace slag, clinker, coagulation and admixtures controller in field applications.

Table 1: Typical chemical compositions of fine-grained cements [39-55].

Chemical Ingredient	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)
MC–100	35.4	16	0.3	43.3	3.5	0.3
MC–300	17.9	4.9	3.5	61.6	2.6	2.4
MC–500	29.0	13.2	1.2	49.2	5.6	1.2
Fine Hard	31.6	13.6	0.7	46.4	6.1	1.6
Micro A	28.8	11.3	1.0	48.9	5.4	1.4
Micro N	30.9	12.9	0.5	44.3	6.3	1.6
Micro S	26.9	10.4	1.4	51.1	4.6	2.0
Spinor A12	31.0	9.5	1.3	44.0	6.5	
MC 20 RS	24.3	7.7	2.0	52.7	3.8	3.7
Micro Matrix	20.4	6.4	2.7	62.3	1.0	3.3

Characteristic of these suspensions is the individual preparation of their ingredients before the final mixing. Depending on their fineness, Mikrodur and Finosol materials are divided into F (Fine), U (Ultrafine) and X (EXtrafine). Mikrodur and Finosol cements have been used in various research efforts [20,52-54]. Products of the company BASF Construction Chemicals are the fine-grained cements under the brand name Rheocem, which are based on pure Portland cement. Depending on their fineness, they are divided into products 650, 800 and 900 [55]. The manufacturer recommends their use in combination with the plasticizer Rheobuild 2000PF in a dosage ranging from 1.0% to 3.0% by weight of dry cement. Henn et al. [39], used in field applications, suspensions based on the fine-grained Microcem A and Microcem B cements of Addiment company. These are fine-grained pure Portland cements that have a specific weight of 3.20gr/cm^3. The Swedish company Cementa AB is also active in the production of fine-grained cements, introducing on the market the fine-grained cements Ultrafin 12 and Ultrafin 16 with a specific weight of 3.10-3.20gr/cm^3. The Norwegian company Elkem ASA Materials proposes the product Ultrafin 12 as a basis for the preparation of fine-grained suspensions available in the market under the brand name MultiGrout System. The Cemill designation identifies the wet method by which cement suspensions are prepared on site using Portland conventional cement as a base. The method was proposed by De Paoli et al. [34] and aims at developing an on-site production process of fine-grained material using common cement. This process made it possible to produce not only unstable grouts (Cemill-I), but also fixed grouts using bentonite (Cemill-S). These objectives were achieved with a special device, which has two functions: (a) achieves very strong dispersion of cement granules without the addition of a corresponding anticoagulant and (b) implements a progressive procedure of elaborating the coarse cement fraction until it reaches the desired levels of fineness without the need for this coarse material to be removed [34]. Regarding the chemical composition of fine-grained cements, it is emphasized that, mainly, they consist of the same oxides as Portland cements, but in different proportions. Another element, which promotes the use of fine-grained cements for permeation injections, is the fact that they are composed of inorganic and non-toxic materials, an element that is particularly beneficial in preventing environmental pollution. Table 1 below gives typical chemical compositions of commercially available fine-grained cements.

Conclusion

a. This paper reviews constituent materials, properties and applications of grouts for soil grouting and especially permeation grouting. The effectiveness of grouting process requires proper skills, understanding, meticulous attention and intuitive perception.

b. The improvement of properties and the mechanical behavior of soil formations can be achieved on the spot by performing an appropriate injection program. The injection program may: (a) be performed as a part of the preliminary field work prior to the commencement of a project's construction, (b) be a part of the construction of the main project, or (c) be designed and executed as a "treatment" when unforeseen circumstances arise during the construction of a project.

c. Injections are generally intended either to increase the shear strength, density and stiffness of the soil or to reduce compressibility and permeability.

d. The grouts used to make permeation injections are mainly suspensions and chemical solutions.

e. The suspensions penetrate satisfactorily in soils with granulometry up to coarse sand.

f. Chemical solutions penetrate satisfactorily in more fine-grained formations up to fine-grained sands or coarse-grained sludges.

g. Because some chemical solutions are toxic or generally harmful to the environment and humans, an effort has been made internationally in recent years to replace them with inorganic fine-grained cement-based suspensions.

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References

1. Lokkas P, Papadimitriou E, Alamanis N, Papageorgiou G, Christodoulou D, et al. (2021) Significant foundation techniques for education: A critical analysis. WSEAS Transactions on Advances in Engineering Education 18(2): 7-26.

2. Lokkas P, Chouliaras I, Chrisanidis T, Christodoulou D, Papadimitriou E, et al. (2021) Historical background and evolution of soil mechanics. WSEAS Transactions on Advances in Engineering Education 18(10): 96-113.

3. Alamanis N (2017) Failure of slopes and embankments under static and seismic loading. American Scientific Research Journal for Engineering, Technology and Sciences (ASRJETS) 35(1): 95-126.

4. Alamanis N, Zografos C, Papageorgiou G, Xafoulis N, Chouliaras I (2020) Risk of retaining systems for deep excavations in urban road infrastructure with respect to work staff perception. International Journal of Scientific & Technology Research 9(2): 4168-4175.

5. Alamanis N, Dakoulas P (2019) Simulation of random soil properties by the local average subdivision method and engineering applications. Energy Systems 12: 841-861.

6. Alamanis N, Dakoulas P (2021) Effect of spatial variability of soil properties on permanent seismic displacements of slopes with uniform load. 14th Baltic Sea Geotechnical Conference, Helsinki, Finland.

7. Zebovitz S, Krizek R, Atmatzidis D (1989) Injection of fine sands with very fine cement grout. Journal of Geotechnical Engineering 115(12): 1717-1733.

8. Christodoulou DN, Droudakis AI, Pantazopoulos IA, Markou IN, Atmatzidis DK (2009) Groutability and effectiveness of microfine cement grouts. In: Hamza et al. (Ed.), Proceedings, 17th International Conference on Soil Mechanics and Geotechnical Engineering: The Academia and Practice of Geotechnical Engineering, Alexandria, Egypt, 3: 2232-2235.

9. Pantazopoulos IA, Markou IN, Christodoulou DN, Droudakis AI, Atmatzidis DK, et al. (2012) Development of microfine cement grouts by pulverizing ordinary cements. Cement and Concrete Composites 34(5): 593-603.

10. Markou IN, Christodoulou DN, Petala ES, Atmatzidis DK (2018) Injectability of microfine cement grouts into limestone sands with different gradations: Experimental investigation and prediction. Geotechnical and Geological Engineering Journal 36(2): 959-981.

11. Markou IN, Christodoulou DN, Papadopoulos BK (2015) Penetrability of microfine cement grouts: experimental investigation and fuzzy regression modeling. Canadian Geotechnical Journal 52(7): 868-882.

12. Christodoulou D, Lokkas P, Markou I, Droudakis A, Chouliaras I, et al. (2021) Principles and developments in soil grouting: A historical review. WSEAS Transactions on Advances in Engineering Education 18(18): 175-191.

13. Christodoulou D, Lokkas P, Droudakis A, Spiliotis X, Kasiteropoulou D (2021) The development of practice in permeation grouting by using fine-grained cement suspensions. Asian Journal of Engineering and Technology 9(6): 92-101.

14. Markou IN, Kakavias CK, Christodoulou DN, Toumpanou I, Atmatzidis DK (2020) Prediction of cement suspension groutability based on sand hydraulic conductivity. Soils and Foundations 60(4): 825-839.

15. Santagata MC, Santagata E (2003) Experimental investigation of factors affecting the injectability of micro cement grouts. In: Johnsen FL, Bruce AD, Byle JM (Eds.), Proceedings, 3rd International Conference on Grouting and Ground Treatment, New Orleans, USA, 2: 1221-1234.

16. Atmatzidis DK (1990) Soil improvements with injections. University Notes, University of Patras, Greece.

17. Sideris K (1998) Technology of building materials. Department of Civil Engineering, Democritus University of Thrace, Greece.

18. Bruce AD, Littlejohn S, Naudts CA (1997) Grouting materials for ground treatment: A practitioner's guide. In: Vipulanandan C (Ed.), Proceedings, Conference on Grouting: Compaction, Remediation, Geotechnical Special Publication, USA, 66: 306-334.

19. Markou IN (1995) Grinded greek lignite fly ash as a suspension-type injection material for on-site soil improvement – reinforcement. PhD Thesis, Department of Civil Engineering, University of Patras, Greece.

20. Legendre Y, Hery P, Vattement H (1987) Microsol grouting, A method for grouting fine alluvium. Proceedings, 6th International Conference Offshore Mechanics and Arctic Engineering Symposium, Houston, Texas, USA, pp. 433-440.

21. Karol RH (1982) Chemical grouts and their properties. In: Baker WH (Ed.), Proceedings, Conference on Grouting in Geotechnical Engineering, New Orleans, Louisiana, USA, pp. 359-377.

22. Shimoda M, Ohmori H (1982) Ultrafine grouting material. In: Baker WH (Ed.), Proceedings, Conference on Grouting in Geotechnical Engineering, New Orleans, Louisiana, USA, pp. 77-91.

23. Dupla JC, Canou J, Gouvenot D (2004) An advanced experimental set-up for studying a monodirectional grout injection process. Ground Improvement, Thomas Telford Ltd, 8(3): 91-99.

24. Arenzana L, Krizek RJ, Pepper SF (1989) Injection of dilute microfine cement suspensions into fine sands. In: Balkema AA (Ed.), Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, The Netherlands, 2: 1331-1334.

25. Clarke WJ (1984) Performance characteristics of microfine cement. ASCE Preprint 84-023, Atlanta, USA, pp. 1-14.

26. Dano C, Hicher PY, Tailliez S (2004) Engineering properties of grouted sands. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, New York, USA, pp. 328-338.

27. Mollamahmutoglu M (2003) Treatment of medium to coarse grained sands by fine grained Portland cement (FGPC) as an alternative grouting material to silicate-ester grouts. Cement, Concrete and Aggregates 25(1): 1-6.

28. Karol RH (1985) Grout penetrability. In: Baker WH (Ed.), Proceedings, Issues in Dam Grouting, Denver, Colorado, USA, pp. 27-33.

29. Tolpannen P, Syrjanen P (2003) Hard rock tunnel grouting practice in Finland, Sweden, and Norway: Literature study. Technical Report, Finnish Tunnelling Association.

30. Perret S, Palardy D, Ballivy G (2000) Rheological behavior and setting time of microfine cement-based grouts. ACI Materials 97 (4): 472-478.

31. Littlejohn S (2003) The development of practice in permeation and compensation grouting: A historical review (1802-2002): Part 1 Permeation Grouting. In: Johnsen FL, Bruce AD, Byle JM (Eds.), Proceedings of the 3rd International Conference on Grouting and Ground Treatment, New Orleans, USA, Geotechnical Special Publication 120(1): 50-97.

32. Huang Z, Chen M, Chen X (2002) A developed technology for wet-ground fine cement slurry with its applications. Cement and Concrete Research 33(5): 729-732.

33. Naudts A, Landry E, Hooey S, Naudts W (2003) Additives and admixtures in cement-based grouts. In: Johnsen FL, Bruce AD, Byle JM (Eds.), Proceedings of the 3rd International Conference on Grouting and Ground Treatment, New Orleans, La, USA, Geotechnical Special Publication 120(2): 1180-1191.

34. De Paoli B, Bosco B, Granata R, Bruce DA 1992) Fundamental observations on cement-based grouts (2): Microfine cements and the Cemill process. In: Borden RH, Holtz RD, Juran I (Eds.), Proceedings, Conference on Grouting, Soil Improvement and Geosynthetics, New Orleans, Louisiana, USA, Geotechnical Publication 30(1): 486-499.

35. Ahrens HE (1997) A new and superior ultrafine cementitious grout. In: Vipulanandan C (Ed.), Proceedings, Conference on Grouting: Compaction, Remediation, Testing, Logan, Utah, USA, Geotechnical Special Publication 66: 188-196.

36. Naudts A, Landry E (2003) New on-site wet milling technology for the preparation of ultrafine cement-based grouts. In: Johnsen FL, Bruce AD, Byle JM (Eds.), Proceedings of the 3rd International Conference on Grouting and Ground Treatment, New Orleans, La, USA, Geotechnical Special Publication 120(2): 1200-1207.

37. Bruce DA (1992) Trends and developments in American grouting practice. In: Bell AL (Ed.), Proceedings, Conference on Grouting in the Ground, London, England, Thomas Telford, London, England, pp. 573-589.

38. Weaver KD (1991) Dam foundation grouting. ASCE, New York, USA.

39. Henn R, Ganse P, Bandimere S, Smoak G, Warner J (2001) Comparison of penetration test results of grouts made with various ultrafine cement products. Proceedings of the Rapid Excavation and Tunneling Conference, Elsevier Science BV, Amsterdam, pp. 345-361.

40. Henn R, Davenport R (2005) Ultrafine cement: A critical component of a grouting program. Tunnels and Tunnelling International, pp. 27-29.

41. Brachman RWI, Martin CD, Gilliss SA (2004) Grout field trials in outwash sands. Canadian Geotechnical Journal 41(1): 1-11.

42. Clarke WJ, Boyd MD, Helal M (1992) Ultrafine cement tests and dam test grouting. In: Borden RH, Holtz RD, Juran I (Eds.), Proceedings, Conference on Grouting, Soil Improvement and Geosynthetics, New Orleans, Louisiana, USA, Geotechnical Publication 30(1): 626-638.

43. Clarke WJ, Boyd MD, Helal M (1993) Ultrafine cement tests and drilling Warm Spring Dam. In: Anderson LR (Ed.), Proceedings, Geotechnical Practice in Dam Rehabilitation, Specialty Conference, Raleigh, North Carolina, USA, Geotechnical Publication 35: 18-732.

44. Clarke WJ, McNally AC (1993) Ultrafine cement for oilwell cementing. Rocky Mountain Regional Meeting/Low Permeability Reservoirs Symposium and Exhibition, Society of Petroleum Engineers (SPE), Richardson, TX, United States, pp. 291-298.

45. Weaver K, Coad RM, McIntosh KR (1992) Grouting against hazwaste. Civil Engineering, ASCE, New York, USA, 62(5): pp. 70-72.

46. Helal M, Krizek RJ (1992) Preferred orientation of pore structure in cement-grouted sand. In: Borden RH, Holtz RD, Juran I (Eds.), Proceedings, Conference on Grouting, Soil Improvement and Geosynthetics, New Orleans, Louisiana, USA, Geotechnical Publication 30(1): 526-540.

47. Schwarz LG, Krizek RJ (1992) Effects of mixing on rheological properties of microfine cement grout. In: Borden RH, Holtz RD, Juran I (Eds.), Proceedings, Conference on Grouting, Soil Improvement and Geosynthetics, New Orleans, Louisiana, USA, Geotechnical Publication 30(1): 512-525.

48. www.parchem.com.au

49. Saada Z, Canou J, Dormieux L, Dupla JC, Maghous S (2005) Modelling of cement suspension flow in granular porous media. International Journal for Numerical and Analytical Methods in Geomechanics 27(7): 691-711.

50. Bouchelaghem F, Vulliet L (2001) Mathematical and numerical filtration-advection-dispersion model of miscible grout propagation in saturated porous media. International Journal for Numerical and Analytical Methods in Geomechanics 25(12): 1195-1227.

51. Abreu JV, Mezzalira FA, Cruz LOM (2005) Brazilian special cements for shotcrete and injections in underground constructions. Proceedings, Conference on Waterproofing, ITA-AITES, Sao Paulo, Brazil.

52. Hakansson U, Hassler L, Stille H (1992) Rheological properties of microfine cement grouts with additives. In: Borden RH, Holtz RD, Juran I (Eds.), Proceedings, Conference on Grouting, Soil Improvement and Geosynthetics, New Orleans, Louisiana, USA, Geotechnical Publication 30(1): 551-563.

53. Reinhardt HW (1993) Ultra-fine cements for special applications. Advanced Cement Based Materials 1(3): 106-107.

54. Mittag J, Savvidis S (2003) The groutability of sands - results from one-dimensional and spherical tests. In: Johnsen FL, Bruce AD, Byle JM (Eds.), Proceedings, 3rd International Conference on Grouting and Ground Treatment, New Orleans, La, USA, Geotechnical Special Publication 120(2): 1372-1382.

55. Mollamahmutoglu M, Yilmaz Y, Kutlu I (2007) Grouting performance of microfine cement and silica fume mix into sands. Journal of ASTM International 4(4).