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¹A thukkaiah tukram.iit@gmail.com

²L mounika lmounika8591@gmail.com

Department of Civil Engineering,

Pallavi Engineering College Hyderabad, Telangana 501505

ABSTRACT

Large sinkholes happened in a residential suburb in the State of Kuwait, resulting to damage of houses and subsequently to partial evacuation of this residential neighbourhood. From fully completed inquiry programmes, the sinkholes were linked to the presence and proliferation of Karst voids in the limestone bedrock layer. Accordingly, a thorough treatment programme was created to limit the danger of sinkhole recurrence by decreasing the possibilities of collapse in the higher level holes inside the limestone bedrock. In this project, two distinct cement grout mixes were devised and employed for treatment of the Karst cavities; cavity filling grout and permeation grout. The examination of the employed mixes comprised frequent measurement of the compressive strength, slump, thermal conductivity, thermal resistance, bleeding, air content, loss of slump, flow and setting time. The treatment was followed by an assessment procedure by drilling control boreholes. Some cores of the hardened grout were retrieved from the control boreholes and their characteristics were assessed and compared to those of laboratory specimens. This document explains several kinds and mixes of cement grouts employed in the ground treatment, features of quality control programme, and frequency and types of testing. Assessment of the findings in addition to summary of the project is also offered. The findings proved the efficacy of the numerous cement grout mixtures utilised in this treatment operation.

Keywords: Permeation and permeation management are two of the most important aspects of karst, cement, grout, and sinkholes.

Introduction

It was discovered that eight sinkhole events happened in a Kuwaiti residential neighbourhood, four of which occurred between 1988 and 1989 and the other four in 2004 (Al-Rifaiy 1990; Abdullah and Mollah 1999; Abdullah and Kamal et al. (2005)). The first sinkhole was discovered when a 15-meter diameter and 31-meter deep cylindrical hole appeared in front of a residence. Another sinkhole of similar size and

depth appeared a few days later; this was followed by others in the same area. The diameters and depths of the sinkholes ranged from 1.5 to 15 metres. There was a partial evacuation after sinkhole episodes, and thorough research of the area's topography and geology led to the discovery of subsurface cavities (Al-Mutairi et al., 1998; Abdullah and Kamal, 2005; Abdullah and Kamal, 2005). Researchers discovered a 35-40-meter-thick layer of overburden soil, mostly made up of quartz sand, above the Dammam Formation Karst limestone bedrock in this residential area. Dissolution of limestone bedrock and subsequent ravelling into the underlying Karst voids are cited as the source of sinkholes. Therefore, it was decided to limit soil movement into the limestone cavities in order to fix those holes and avoid future sinkhole disasters. It was decided that cement grouting the Karst cavities would be the most effective remedy for the cavities issue in this research. Because of its low cost and simplicity of implementation, the chosen treatment method is regarded the most effective and cost-effective way to reduce sinkhole formation risk. Ground-level cement grout was injected into the limestone bedrock formation to fill up the holes and crevices underneath it. Grouts that were used in this treatment project are discussed in this study along with their compositions and amounts. Aside from a discussion of how to ensure that the treatment programme was successful, the report also explains how to conduct regular testing and what sorts of tests were used.

Background

Treatment techniques

Sinkhole restoration procedures include complete excavation and replacement, pin piles to bedrock, pressure grouting, polymer injection, and combinations of these techniques. Cost, practicality, timeliness, and efficacy of these strategies may all vary greatly (Schokker, 2008). For typical Karst sites with voids in the rock and the overlaying soils and modest to moderate facility loads, slurry grouting is usually the best option (Fischer, 1996). Using compaction grouting is most effective on sound and shallow rock since excessive grout will be injected

into the cavities of the rock and soil. There were also several reports of case studies (Gobin, 2010; Beck, 2003). Gobin explains how a bridge foundation in central Florida was built to avoid karst conditions. When a test pile was installed and following activities such as borings and grout injection were carried out, more sinkholes were formed, as was expected. Only when a significant amount of grout was pumped into the area did sinkhole development end.

Grouting methods

Grouting is a geotechnical process, which involves injection of cement or chemical grout for the purpose of filling cracks or voids in the rock mass or soil. Cement is the most common grout used in rock treatment. Before treatment, it is important to understand the rock condition and properties (Wallner 1976; Lombardi 1985). For choosing the proper grout, both the soil formation and grout characteristics should be considered.

The formation should have ability to receive grout, and the mechanical properties, such as permanence, penetrability and strength, of each grout determines its suitability for a specific job. For the long term requirements and durable grout, some properties should be observed which are water separation during hardening, hardening time, and solubility of the grout in the surrounding environment (Eklund and Stille, 2008). The most commonly used grout consists of cement and water with additives that reduce the cost or improve workability and applicability. When the voids are large and penetration is easy, fillers for bulking out are mixed with the grout. They weaken the grout but strength, however, is not an important issue in this type of application. Sand is a cheap filler but requires care to avoid segregation. Clay, such as Bentonite, could be used as grout filler or as a grout on its own, but it is more expensive and difficult to use than sand.

Methodology of Treatment Application

The main purpose of the treatment application considered in this study is to reduce the risk of sinkhole recurrence by minimizing the possibilities of collapse in the upper level cavities within the limestone bedrock.

The scope is filling up of the uppermost cavities in the rock formation at depths range from 30 to 50 m, i.e. the cavities that are close to the overburden sand, with stable cement mortar grout pumped from the ground surface. The work was carried out in a pilot treatment

area located within the affected residential area among total surface area of around 62,000 m². As shown in Figure 1, the treatment area under consideration is divided into six zones according to their risk factor, based on the previously conducted geophysical investigation programs (Kamal et al., 2007). Injection method from the ground surface is used with low pressures for proper filling of the underground cavities. The treatment is not intended to densify the rock or to improve its strength, but to fill up the existed voids and cavities and to prevent migration of sand from the overburden layer into the limestone bedrock. By closing cavities and voids in the limestone layer and preventing soil raveling, the thick overburden of dense sand will assure sufficient ground support for all structures above ground. The cavity filling grout, consisting of cement, sand, additives and water, is considered economical and efficient. The cavity filling grouting is replaced by a treatment called permeation grouting in locations where no open cavities are observed but the uppermost layers of the rock prove to be highly pervious due to open fissures or the presence of frequent small Karst features. Permeation grout consists of cement-water mix and additives without aggregates injected into the rock mass under pressures using packers. The applied treatment program is extensively used in the pilot area. All detected underground cavities and fractured rocks in the upper layer of the limestone bedrock during the drilling program are treated by either cavity filling or permeation grout. The treatment project started with an exploratory program, which consisted of drilling borehole and conducting in-situ testing and sampling to investigate the properties and characteristics of the soil. Then, grout mixes are designed and a meticulous quality control program is followed. The grouting program is started by utilizing two different treatment methods; the cavity filling of deep limestone cavities using cement based mortar and permeation grouting of remaining deep voids using cement based grout. The treatment requires extensive drilling of boreholes that is used for grout injection of the two methods. To ascertain the treatment and examine the soil status after treatment a control program is proceeded which consists of drilling boreholes accompanied by in-

situ and laboratory testing (Kamal et al., 2007 and b). The project also included a rigorous dilapidation survey to monitor the status of the existing structures before, during and after treatment application.



Figure 1: The six zones in the pilot area, TA1 to TA6

Results and Discussion

Grout types and materials

Two main mixes are utilized in the treatment project in this study, the cavity filling and permeation grouts. Constitutive materials are first inspected, tested and approved. Cement is supposed to satisfy the requirements of EN 197-1:2000, while the bentonite is supposed to have less than 10% sand and a liquid limit of not less than 300. Aggregates are checked routinely on each delivery for the grain size distribution, water soluble chloride salts, sulphate content and moisture content. Water and additives are also checked and approved. Based on the general project requirements, mixes are designed and tested as described hereafter.

Cavity filling grout

The cavity filling grout mix is designed to satisfy the requirements of decantation of less than 2% after two hours (ASTM C940), and cylinder compressive strength of more than 1 MPa (ASTM C39). Those requirements are checked as frequent as one series of three sets every 500 m³ and not less than one series every ten days. The utilized grout mix consists of 1,500 kg natural sand, 150 kg cement, 300 liters of water, 1.5 liters of retarders (per cubic meter), and 15 kg of bentonite. Slump is specified between 200 and 220 mm. The cavity filling mix is prepared offsite and submitted in truck mixers, Figure 2. The results of the testing program of

the cavity filling grout show that the compressive strength has a minimum value of 1 MPa, maximum value of 4 MPa and average value of 1.64 MPa (> 1 MPa), Figure 3. The results show that the saturated unit weight of cavity filling grout is ranging between 15.05 and 19.86 kN/m³ with an average value of 18.77 kN/m³, Figure 4. In addition to compressive strength and unit weight tests, other properties of the mix are determined including air content, setting time, bleeding, thermal conductivity, and thermal resistance coefficient, as a sample results of one series of tests is listed in Table 1.



Figure 2: Delivery of cavity filling mix

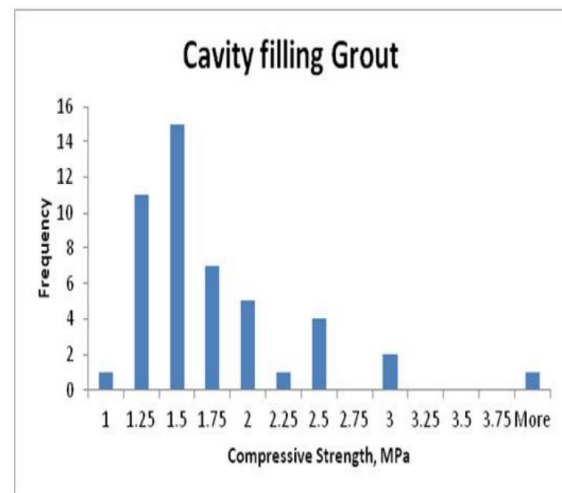


Figure 3: Histogram for the compressive strength results for cavity filling grout

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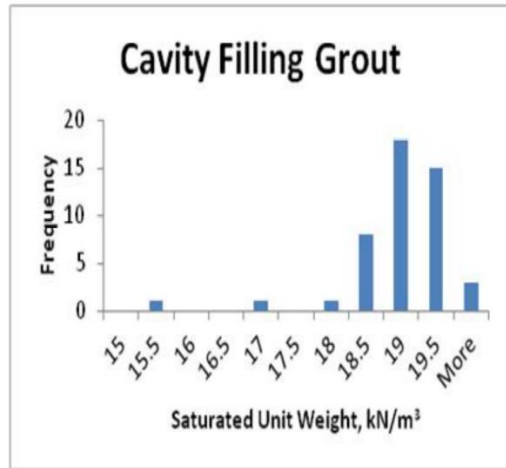


Figure 4: Histogram for the saturated unit weight results for cavity filling grout

Table 1: Properties of the cavity filling mortar

Property	Sample Test Results	Average Value
Compressive strength	(1.12, 1.09, 1.05 MPa)	1.09 MPa > 1 MPa
Bleeding	1.00%, 0.90%, 0.95%	0.95% < 2%
Air content	(2%, 2%, 2.1, 2%)	2%
Setting time	-	10 hours < Setting Time < 24 hours
Thermal conductivity	-	0.49365 w/m ⁰ K
Thermal resistance coefficient	-	0.163 m ² °K/w

Consistency of the cavity filling mortar is a measure of the workability of the cement grouts. Workability time of the cavity filling grout is increased by adding retarding admixture that allows the cement grout to have workable consistency for longer time. It is measured using two different methods: slump test method (ASTM C143) and flow table test method (ASTM C1437). Loss of consistency versus elapsed time is measured to confirm that the grout mix is workable during the pumping period and during the time needed to move from treatment of a cavity to another. As shown in Figure 5 and yet after 5 hours, the grouting mortar has slump of more than 100 mm and is workable and pumpable. This period is needed to consume the grout quantity in a mixing truck for treating a cavity and proper time to move to another treatment location. The flow table results as a measure for workability loss, also confirmed the same results of flowable and pumpable after 4 hours elapsed as shown in Figure 6.

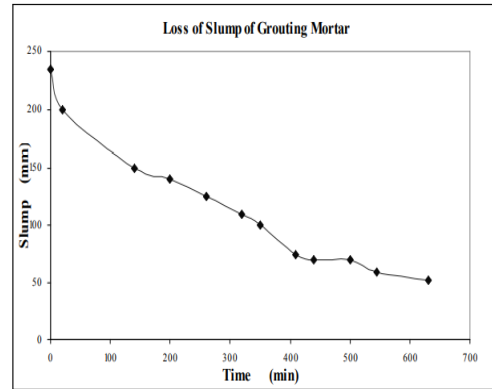


Figure 5: Slump of the cavity filling mortar

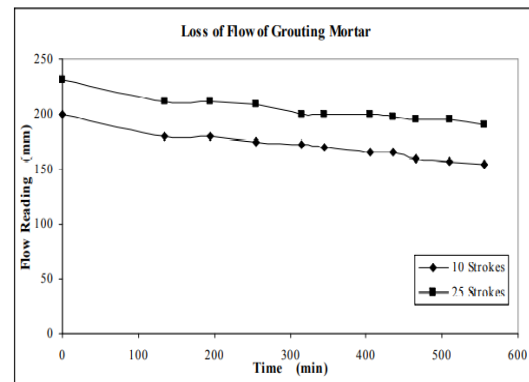


Figure 6: Flow table results of the cavity filling mortar

4.3 Permeation grout

The grout used for permeation is specified to have both cement and bentonite, water/cement ratio less than one, average cylinder compressive strength of not less than 5 MPa, bleeding at two hours after mixing less than 3% and March funnel flow time less than 50 seconds (ASTM D6910). The permeation mix consists of 800 kg of cement, 718 liters of water, 5 liters of retarders, and 15 kg of bentonite. The slurry is prepared on site in a batching plant as shown in Figure 7. Bleeding, density and viscosity are checked on site twice a day as part of the control and quality assurance program, Table 2. The compressive strength is checked not less than a series of three samples every seven working days. The permeation grouting results from the testing program show that the compressive strength is ranging between 5.6 and 16.4 MPa with an average value of 10.6 MPa (> 5 MPa), Figure 8. The results show that the saturated unit weight of permeation grouting is ranging between 13.11 and 17.75 kN/m³ with an

average value of 15.08 kN/m³, Figure 9. The bleeding of the grout mix at two hours after mixing and the March funnel flow time is measured to control the permeation grouting before injection. The results indicated that the bleeding is ranged from 0.5% to 2.5% with an average value of 1%. The results of March funnel flow time indicating a range of 30 to 39 s with an average value of 34

First test - at time: 10:45 am		Second test - at time: 1:30 pm	
Bleeding (%)	1.5	Bleeding (%)	1
Density (t/m ³)	1.52	Density (t/m ³)	1.51
Viscosity (sec.)	36	Viscosity (sec.)	35

Table 2: A Sample of daily tests of the permeation grout



Figure 7: Insite slurry preparation

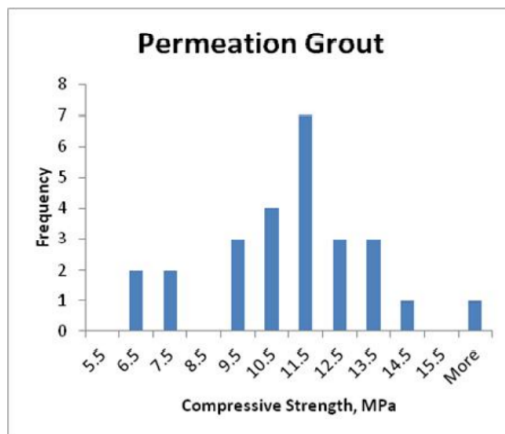


Figure 8: Histogram for the compressive strength results for permeation grout

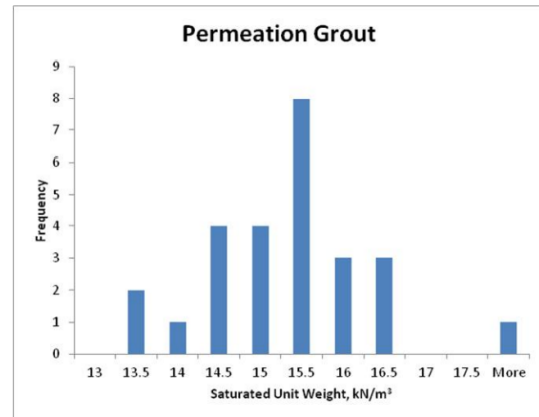


Figure 9: Histogram for the saturated unit weight results for permeation grout

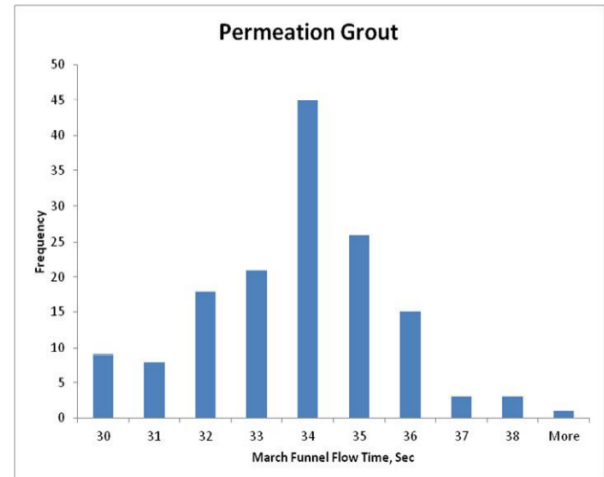


Figure 10: Histogram for the March funnel flow time for permeation grout

Control program

To verify the efficiency of the injected grouts, a control program is conducted after completing the treatment applications. The control program for the grout included determination of the compressive strength of the hardened grout cores extracted from the control holes for both grouting; cavity filling and permeation. The results of the cavity filling grouting indicate that the compressive strength has a minimum value of 1.69 MPa, maximum value of 5.49 MPa and average value of 2.72 MPa (> 1 MPa).

It is clear that grout compressive strength after treatment application is greater than

before treatment application. The average value of saturated unit weight for cavity filling grout is determined as 19.78 kN/m³. The grout extracted samples indicate that no washing out of the cement during grouting due to the existence of bentonite in the grout mix. The results of the permeation grouting indicate that the average compressive strength equals to 8 MPa which is greater than the designed strength. The results also show that the average value of the saturated unit weight of permeation grouting equals to 15.71 kN/m³.

Summary and Conclusions

In large projects, it is essential to utilize comprehensive quality control program in order to assure the quality and hence the adequacy and durability of the project. The lack of such program may jeopardize the credibility of the whole project. This is more apparent where soil treatment projects are involved, as the deterioration signs will not be visible. In the treatment application project under consideration, two grouting methods and mixes were used to treat underground deep cavities.

A comprehensive quality control program was adapted that included testing of constitutive materials, mix design and frequent evaluation of the mechanical and physical properties of the adapted mixes. The frequency of testing depends on the importance of the tested property and the mix size. Compressive strength and workability were considered the most important properties from the used grouts. Workability was selected to assure that the mix can be transferred, placed and still retain enough workability to fill the designated cavity. As a measure for slump loss and flow time, the cavity filling mortar retained more than 50 mm slump after more than 10 hours. The compressive strength was greater than the designed strength.

The close adherence to the quality control program assures the quality of performed treatment. It is highly unlikely that a major cavity still exists in the treated area after this comprehensive treatment project. The grout mixes used in this project can be used for areas and problems with similar nature.

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