Experimental Study of Chemical Grouting of Conglomerate Foundations

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Abstract: *A new chemical grouting method has been developed for conglomerate formations based on the experimental studies. Due to the lack of chemical grouting experience of conglomerate formations, the testing programs were performed to evaluate the performance of chemical grouting in the water sealing of part of conglomerate foundation of Karkheh earth dam using a combination of field and laboratory tests. First, the chemical grouts alone were examined with regard to viscosity-time behavior, gelation time, temperature-influence, stability, and deformability. These laboratory tests, led to the selection of the final chemical grout which was a solution of sodium silicate, water, and ethyl acetate as reactant. The second step tested grout-soil interaction: The injectability and permeability reduction of the selected chemical grout was examined in field injection tests. In this step two field tests were performed including shallow test holes without hydrostatic pressure and full scale tests under dam real hydrostatic pressure head. Based on these two field injection tests, performed in the conglomerate foundation of Karkheh dam, a new chemical grouting method for conglomerate formations is proposed and satisfactory results led to the recommendation of this method for eventually successful application.*

Keywords: *Chemical Grouting, Conglomerate Formations, Sodium Silicate.*

1. Introduction

This study originates from the technical problems caused by the concentration of seepage in part of conglomerate foundation of Karkheh dam.

Karkheh earth-fill dam and hydropower project is constructed on Karkheh River, the third largest river in Iran, is located 200 kilometers northwest of Persian Gulf at southwest of Iran. With a body volume of about 33 Mm3 and the useful reservoir capacity of 5600Mm3, Karkheh earthfill dam is the largest one in Iran. The dam height over foundation is 127m and the crest length is 3030m. The project includes the embankment placed across the Karkheh River, a powerhouse with total installed capacity of 400MW, at the left abutment and a gate-controlled chute type spillway with a crest width of 110m and length of 955m located at right abutment (Fig. 1).

Before discussing the details of this study, it seems worthwhile summarizing the main geological characteristics of the dam area.

The karkheh dam is placed on poor to fair permeable conglomerate beds, which are slightly-moderately cemented. The overall permeability of the conglomerate is estimated to be in the relatively high range of about $4^{-9} \times 10^{-4}$ m/s mainly caused by zones of discontinuity and open frame work gravels. The impervious horizontal mudstone layers stratify the conglomerate with 3 to 9 m thickness, estimated permeability of about 10^{-7} to 10^{-10} m/s, which are bedded horizontally in area of the project (Fig. 2). In the Fig. 2, it can be noted that the mudstone layers are numbered due to the river bed level

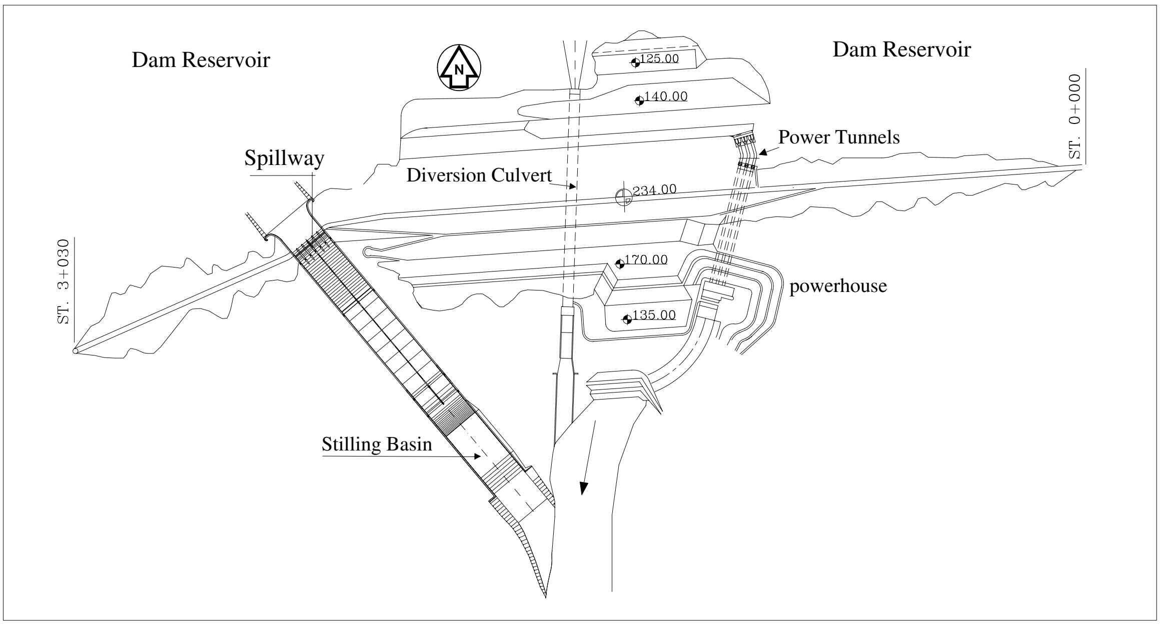

Fig.1 General plan of Karkheh dam project

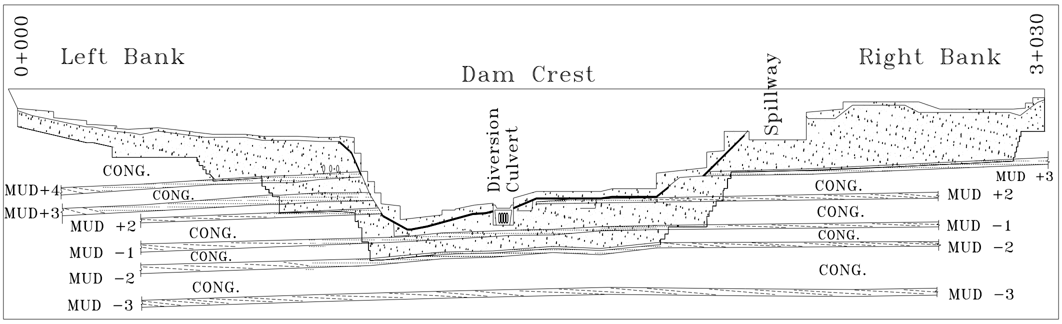

Fig.2 Karkheh dam longitudinal section. Hatched area represents the extension of cutoff wall. To clarify, the figure is exaggerated in the vertical direction.

so that the layers located above and below the river bed level are entitled with plus and minus numbers respectively.

Geotechnical investigations and observations were indicated that these layers are enough continuous at the location of Karkheh dam to provide different strata for each conglomerate layer confined by mudstone layers [1]. Due to the high permeability of conglomerate layers, a vertical foundation water sealing system was required to control water flow to downstream, to reduce exit hydraulic gradient, to prevent high measure of leakage, to decrease the uplift pressure, and finally to provide associate stability of the dam body and its hydraulic structures.

Different water sealing alternatives were considered for the Karkheh dam foundation. The first alternative was grout curtain, the selection of which was favored by the

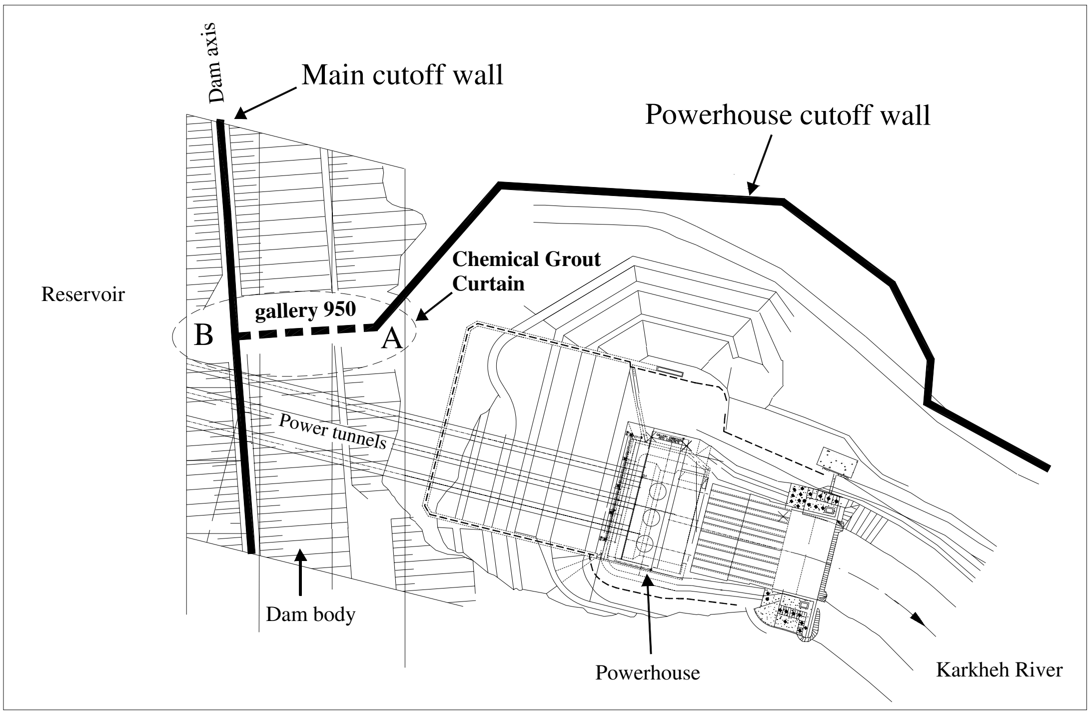

Fig.3 Karkheh dam cutoff walls and the location of the probable chemical grouting curtain.

availability and lower cost of grouting technology within the country and anticipating suitable performance speed on the one hand, and lack of other suitable technologies on the other hand. But all those theoretical advantages of grout curtain proved false by test grouting and economical studies. Hence, cutoff wall was taken into consideration as the second alternative. Enormous studies and investigations were carried out leading to design of a plastic concrete cutoff wall as the main part of the dam foundation water-tightening system.

Therefore a plastic concrete cutoff wall with thickness of 0.8 to 1.0 meter was performed throughout the dam axis. At different locations of dam, the depth of wall was determined regarding seepage analysis, construction ability and economical factors (Fig.2&3) [2].

In addition to the dam main cutoff wall, in the Fig.3 another cutoff wall, performed at the north and east of the powerhouse, can be seen. The excavation slope of the powerhouse area cut mudstone layers (+2), (+3), (+4) and the conglomerates between them. As mentioned before, the permeability of mudstone layers is much smaller than that of conglomerate layers. Hence, hydraulic conditions and the seepage pattern in each layer of conglomerate are different from others. The conglomerate between mudstone (+2) and (-1) outcrops at the riverbed on upstream side and at the powerhouse excavation area on the downstream. Therefore this layer is directly charged by the reservoir on the upstream, inducing pore pressure in the rock and applying great lateral pressure to the powerhouse building at the contact. This situation influences the stability of the powerhouse building and excavation slope [1]. Considering these facts, the powerhouse cutoff wall is designed to decrease seepage at the slope overlooking the powerhouse, to increase safety and to reduce the involved risk.

As shown in the Fig.3, this cutoff wall begins at the point A; near the entrance of access gallery No.1 or gallery 950 (this gallery is located at the station 0+950). Due to the existence of the dam body in this section and the destructive effects of cutoff wall construction on the dam zones which are subjected under the reservoir water head and other existing technical ambiguities such as interaction between the new cutoff wall and dam zones, the cutoff wall construction was not applicable in this section. Therefore, to connect the new cutoff wall to the dam main cutoff wall, a one-row cement based grout curtain was performed from inside of the gallery 950. With performing this grout curtain, a relatively continuous curtain was created around powerhouse.

The dam monitoring data indicate that this cutoff wall has rerouted the seepage flow into preferable paths (sufficiently far) and as a result reduction in the seepage discharge, hydraulic gradient and pore pressure in the rock masses was obtained which all together provide more suitable conditions for the stability of the powerhouse slopes.

But in the access gallery 950, the situation was not so successful. Observations showed water leakage in this section is higher than anticipated, indicating the unsatisfactory performance of the cement grout curtain.

To remedy the problem of seepage in this part of dam foundation, the other existing alternative was chemical grouting. As the permeability of the formation is around 10^{-5} cm/sec, a silicate-base chemical grout was assessed to be a suitable type of grouting of the conglomerate formation. Such grouts would have viscosity of up to 5 cp, which is suitable for the encountered formations [3]. However, there was no experience of chemical grouting in the country, also authors could not be able to find any published work on chemical grouting of conglomerate formations. Therefore, ambiguities were associated with the design and construction of the Karkheh dam chemical grout curtain.
To overcome part of these ambiguities, prior to the main chemical grouting, the testing programs were performed to evaluate the performance of this method in the water sealing of the area using a combination of field and laboratory tests. At first, extensive site trials and laboratory tests were carried out to develop an effective grout mix. In these laboratory tests the chemical grouts alone were examined with regard to viscosity-time behavior, gelation time, temperature-influence, stability, and deformability. These laboratory tests, led to the selection of the final chemical grout which was a solution of sodium silicate, water, and ethyl acetate as reactant.

The second step tested grout-soil interaction: The injectability and permeability reduction of the selected chemical grout was examined in field injection tests. In this step two field tests were performed including shallow test holes without hydrostatic pressure and full scale tests under dam real hydrostatic pressure head.

As a matter of fact, due to the existing unknowns about the performance of these grouts, it was necessary to use a combination of full-scale and shallow test holes. Based on these two field injection tests which were performed in the conglomerate foundation of Karkheh dam, a new chemical grouting method for conglomerate formations is proposed and satisfactory results led to the recommendation of this method for eventually successful application.

In this paper, an experimental study, concerning the mentioned situation, is outlined that was carried out in the Karkheh dam site.

2. A Short and Selective History

Chemical grouting was developed in response to a need to develop strength and control water flow in geologic units where the pore sizes in the rock or soil units were too small to allow the introduction of conventional Portland-cement suspensions [4].

Chemical grouts were developed around 1900. Jezlorsky (1886) and Francois (1914) [5] introduced the use of sodium silicate in conjunction with other reactive chemicals for strengthening sandy formations. There are different reports on the date of invention and first use of chemical grouting technology in the literature. Karol (1983) [6] in his book on chemical grouting has reported that the first practical use of chemical grouting was performed in Europe around 1800 to improve the characteristics of soils. Kutzner (1996) [7] believe that this method for first time was invented by Dutch engineer, Joosten in Germany in 1926. According to Terzaghi and Peck (1967) [8] and Nonveiller (1989) [9], the method of chemical grouting was invented by Joosten in 1925 which was based on successive grouting of sodium silicate and calcium chloride.

However, for many years the term chemical grouting was just synonymous with sodium silicate and the Joosten process [5]. But from the 1950s onwards, due to the advancement of polymer industries and production of a whole new group of chemical grouts, the range of chemical grout uses in civil and underground engineering has increased rapidly and the method of chemical grouting really became popular. In the last five decades a wide range of chemical grouts, such as sodium silicate, acrylamide, acrylate, aminoplast, phenoplast, crome lignin, polyurethane, epoxyresins, polyester resins and many others are introduced which provide a wide selection for the grouting engineer.

Simultaneous with such advances in the production of new chemical grouts, since the knowledge of grout properties and behavior during grouting process and after curing are necessary for the design and control of the chemical grouting technology, a lot of research has been conducted to study physico-chemical, mechanical and strength properties of these grouts. Einstein and Schnitter (1970) [10] presented the selection of chemical grout for Mattmark dam. Janin and Sciellour (1970) [11] presented the chemical grouting for Paris rapid transit tunnels. They reported that elaborate grouting procedures prove the efficiency of chemical grouts in supplementing or replacing modern tunneling methods when grouting is thought of, at the right time, as a reliable construction procedure. Warner (1972) [12] examined the results of over 2500 laboratory samples utilizing 12 mixes of 8 different grouts along with about 100 field samples to investigate strength properties of chemically solidified soils. O'Connor et al. (1978) [13] studied the micro characteristics of chemically stabilized granular materials. Also they assessed the usefulness and accuracy of sieve analyses, the changes in grout composition and concentration with distance from point of injection. Maksimovich and Sergeev (1983)

[14] investigated the effect of chemical injection stabilization on gypsum stability in the foundation of hydraulic structures. Krizek and Perez (1985) [15], based on data obtained from seventy-nine large-scale one-dimensional laboratory tests, established limiting conditions to define the transition zone between retention and elutriation of chemical grout injected into a cohesionless soil permeated by water. Vipulanandan and Krizek (1986) [16] investigated the mechanical behavior of chemically grouted sand. They proposed a theory to explain the behavior of grouted sand, and tensile strength and stiffness models were developed to predict the properties of the grouted sand from the properties of the constituents. Vipulanandan et al. (1997) [17] investigated the role of additives on the performance of the acrylamide grout and N-methylolacrylamide grout to control the shrinkage and swelling in the grouts. They also quantified the shrinkage and swelling of polyacrylamide grouts and grouted sands using nonlinear relationships. Lowther and Gabri (1997) [18] studied the viscosity, hydraulic conductivity and strength of urethane-grouted sand to explore its potential for the formation of in situ barriers. Persoff et al. (1999) [19] determined whether barriers formed by injecting colloidal silica could meet regulatory requirements for low permeability, and withstand the effects of contaminants, under conditions of perfect grouting. Mollamahmutoglu (1999) [20] described the results of a study on the stress-strain time dependent (creep) behavior of silicate-Hardener 600B grouted Leighton Buzzard sand specimens when subjected to incremental loading at certain time intervals. Sunparek and Soucek (2000) [21] developed some methods for laboratory testing of chemical grouts and presented the results of laboratory tests connecting to well known projects in the Czech Republic. Cividini (2001) [22] presented an experimental and numerical study of the low-pressure grouting of granular soils by diluted chemical solutions.

To the author's knowledge, based on the literature review, there is no published work especially discussing the experience of chemical grouting of conglomerate formations. Considering this fact, the aim of this study is to summarize results obtained from chemical grouting tests which were performed in part of conglomerate foundation of Karkheh dam.

3. The Results of Test Cement Grouting of Karkheh Dam Foundation

As briefly discussed before, in phase I study of Karkheh Dam project, a cement based grout curtain was considered as the main anti-seepage measure of the dam foundation. The main reasons for making such decision were: availability of the technology, lack of other suitable technique in the country, anticipating higher speed, and lower cost of the method than the other methods.

As it is necessary for large projects to perform a field grouting test to determine the groutability, borehole spacing and suitable required grout pressure, a series of comprehensive cement based grouting test including single hole and multi-hole (triangular shaped) tests were carried out. Results of these tests showed that even by using super-fine cement with Blaine value of about 8000 cm^2/g a continuous grouting curtain as an anti-seepage measure could not be achieved. Only the grouting of highly permeable zones (open framework gravel) was satisfactorily done.

The evaluation of results obtained from

cement grouting tests done in the conglomerate bedrock of the Karkheh dam gives the following results [23]:

1. Cement grouting has been able, except in two stages, to decrease the average permeability by 50-75 percent, and in some cases even 1/10. However, despite this, the achieved permeability was not in the acceptable range. In check holes the average remaining permeability has been in the range of 20- 50 LU. The permeability coefficient acceptable in the design has been 0-10 LU.

2. The samples procured from the check-holes by using the S.M. powder have not been, in many cases, influenced by cement grouting. This fact indicates that the distribution of cement has not been uniform, and it has been unable to affect a radius range of 1-1.25 m despite the use of fine-grained cement. This has been confirmed when the consolidation grouting of the foundation of the clayey core of the culvert was carried out. The distance between boreholes was 62.5 cm in this part.

3. Overall, it seems that it is not technically and economically practical to waterproof the conglomerate masses especially, the one underlying mudstone layer no. (-1) by executing a cement grout curtain.

Considering above-mentioned facts, in the access gallery 950, in one hand execution of cement grout curtain was not technically and economically useful, and in the other hand due to the placement of the dam body in this section, it was not practicable to develop cut-off wall. Consequently, to remedy the problem of seepage in this part of dam foundation, the other existing alternative was chemical grouting. As the permeability of the formation is around 10^{-5} cm/sec, a silicate-base chemical grout was assessed to be a suitable type of grouting of the conglomerate formation. As a result, the method of chemical grouting was considered and at first, two field grouting test were performed to examine the performance of this method. In the following sections of this paper, the results of these tests are presented.

4. Selection of Chemical Grout for Karkheh Dam

As the permeability of the conglomerate formation in the location of access gallery 950 is around 10^{-5} cm/sec, a silicate-base chemical grout was assessed to be the suitable type of grouting of the formation [3]. This grout system is widely known as sodium silicate system which according to [4] is the most popular chemical grout system because of its safety and environmental compatibility. There are various silicate systems which almost all systems are a mixture of sodium silicate and a reactant along with/without an accelerator that will cause the silicate to form a gel [4]. Therefore for the selection of the chemical grout, our objective was to develop a mix of sodium silicate and solution of water and an reactant along with/without an accelerator, which in a relatively small time provides some cohesion to the soil after rapidly penetrating it at a low pressure.

The concentration of the silicate solution which was selected for use in Karkheh dam ranged between 35 and 40 percent. Such grouts would have viscosity of up to 5 cP, which is suitable for the encountered formation [4].

For selecting the appropriate solution as reactant, extensive site trials and laboratory tests were carried out to develop an effective grout mix. In this order, four well known reactants including calcium chloride, acetate

Table 1 Physical and mechanical properties of some grout mixes

Grout Mix	Volume	Gelation Time (min)	Viscosity (cP)	Properties of the grouted conglomerate formation
Sodium Silicate (37%) Acetate Ethyl Water	60 % 20 % 20 %	120	3	High synersis of the gel Good resistence against water flow- Integrity of the gel
Sodium Silicate (37%) Formamide Sodium Alominate Water	52 % 16 % 19 % 13 %	48	4	Formation of uniform silicate gel- Low synersis- Strengthening with time- Good injectability of the grout
Sodium Silicate (37%) Formamide Calcium Chloride Water	43 % 2 % 26 % 29 %	10	5.5	Low strength non-integrity of the gel High synersis of the gel Poor injectability
Sodium Silicate (37%) Acetate Ethyl Water	61 % 24 % 15 %	12	5	Formation of the flaky gel at the beginning which resulted in unsatisfactory injectability
Sodium Silicate (37%) Acetate Ethyl Calcium Chloride Water	50 % 12.5 % 12.5 % 25 %	10	7	Poor injectability -Formation of a tough and uniform gel- Formation of an impermeable gel after some hours

ethyl, formamide and sodium aluminate were considered. Using these reactants, on the whole around 300 different silicate-based chemical grouts, each having certain mix design, were produced and underwent extensive laboratory evaluation. First, the grouts alone were examined with regard to viscosity-time behavior, gelation time, temperature-influence, and stability properties. The second step tested grout-soil interaction: The injectability of the grouts was examined in laboratory injection tests. Some of these grout mixes, as well as their physical and mechanical properties are presented in Table 1. In this stage, the chemical grouts were produced under the following conditions:

1. The water used for making chemical grouts had the temperature of 22 ^{o}C.
2. All experiments were performed at the temperature of 37 ^{o}C.
3. Grout combinations were mix manually.
4. The mixing time was about 5 minutes.

Based on the assessment of the physical and mechanical behavior of around 300 silicate-based grout samples which were made using four different reactants, the following practical conclusions about the performance of these reactants in conglomerate formations can be obtained:

1. The gelation time of grout samples containing sodium alominate as reactant, was rather uncontrollable. The results indicated that minor changes in the sodium alominate content, which would be expected during field operations, result in major changes in the mix setting time. However, it was observed that the use of sodium alominate makes the final grout more uniform and homogeneous. But due to its negative effect on the grout setting time, which is of indispensable importance in chemical grouting technology, it was decided to eliminate sodium alominate from the practice.

2. Some mixes prepared using calcium chloride as reactant, showed to produce non-uniform gels containing very small particulate materials which highly affected the ability to inject the grout in the sample

Table 2 The influence of variations in grout composition on the gellation time and viscosity of the grout

Grout Mix	Volume	Gelation Time (min)	Viscosity (cP)
Sodium Silicate (39.5%) Acetate Ethyl Water	58 % 20 % 22 %	24	4.5
Sodium Silicate (39.5%) Acetate Ethyl Water	59 % 19 % 22 %	36	4.5
Sodium Silicate (39.5%) Acetate Ethyl Water	60 % 16 % 24 %	48	4
Sodium Silicate (39.5%) Acetate Ethyl Water	61 % 16 % 23 %	59	4

formations in the laboratory. In other words, the injectability characteristics of the grout had been decreased by these particulate materials formed during gellation process. It is to be noted that, at the same time, some other grout samples with calcium chloride had better performance including acceptable injectability, synersis and strength properties. Regarding these results, it can be concluded that, grouts with the calcium chloride are very sensitive to the preparation process of the specimens.

3. A controllable gellation time and very good synersis, uniformity and integrity properties were observed in samples containing formamide. It must be added that such behavior is the case until accelerators such as calcium chloride and sodium alominate ware not included in the grout solution.

4. The behavior of grout samples having acetate ethyl was similar to that of samples made using formamide.

On the basis of the above mentioned results, it can be seen that formamide and acetate ethyl have a satisfactory performance as reactant in the chemical grout solution. Since formamide is not produced inside the country and its behavior is very similar to that of acetate ethyl, finally acetate ethyl was chosen as the reactive agent for use in the chemical grout.

After establishing the reactant component, the influence of variations in grout composition on the gellation time of grout was examined to obtain the right mix design. In this order another experimental study was conducted in which our objective was to obtain an appropriate mixture, a solution of sodium silicate, water, and acetate ethyl with gellation time around 40 min. It can be mentioned that with simple computations, considering the depth of the grouting holes and the amount of grout intake in each section, 40 min is the least required time to prevent the danger of gellation in the grouting equipments. Some of these test mixtures is presented in Table 2. The chemical grout samples for these experiments were prepared under the following experimental situations:

1. Water temperature was about 23 ^oC.
2. All experiments were performed at the temperature of 36 ^oC.
3. In this stage, automatic mixer was employed for mixing chemical grouts. Using automatic mixer it was possible to obtain uniform grouts with more stable properties.
4. The mixing time was about 3 minutes.

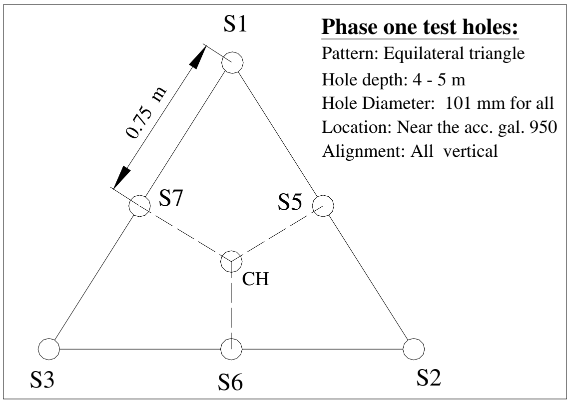

Fig.4 Sketch showing the triangular placement of shallow test holes in phase 1 of test chemical grouting.

As a result, the mix design and physical-mechanical properties of the selected grout mix were:

- Sodium Silicate: 35 %
- Acetate Ethyl: 12 %
- Water: 53 %
- Mix viscosity = 2 - 3 cp
- Gellation time = 40 min

5. First Phase of Test Grouting: Shallow Triangular Test Holes

As mentioned before, prior to initiation of the main chemical grouting in access gallery 950, two phases of test grouting were performed to verify effectiveness of this technique, to find solutions for probable geotechnical problems encountered during the chemical grouting, to optimize the whole process and ultimately to develop the appropriate method of grouting.

In phase 1 of test chemical grouting, shallow test holes with depths ranging between 4 to 5 meters were used which did not undergo any hydrostatic pressure. As shown in Fig. 4, these grouting holes each having 101 mm diameter were drilled in the corners and side midpoints of an equilateral triangle located near the access gallery 950. The center to center spacing of two neighboring grout hole was 0.75 m. As can be seen in Fig. 4, a test hole named CH (Control Hole) was drilled in the center of the triangle to be used for water-pressure test to assess the effectiveness of the process. All the test holes were water-flushed rotary-drilled and were equipped with tub-a-manchettes.

Before to proceed injection in these test holes, the permeability test taken in the holes located in the corner of the triangle was of the order of 163 to 255 Lugeons (Table 3). Then, chemical grouts, based on the grout mix obtained in section 3, were injected into these holes (S1, S2 and S3). In this stage, the permeability test taken in the intermediate holes (S5, S6 and S7) indicated that the permeability varied from 70 to 102.5 Lugeons (Table 3). Finally, after injection of chemical grouts in all test holes, the permeability at the Control Hole (CH) showed the value of 73 Lugeons, which was more than the acceptable limit of about 5 Lugeons.

Results of performed chemical grouting in triangular test holes indicated that improvement of conglomerate formation was not satisfactory. It can be inferred that some cavities or perforations remained untapped or untreated.

Table 3 Summary of grouting in phase 1 test holes

Hole Name	Depth (m)	Permeability		Comments
		Lugeon	Cm/s	
S1	5	163	$2.1*10^{-3}$	Before injection
S2	5	239	$3.1*10^{-3}$	Before injection
S3	4	225	$3.3*10^{-3}$	Before injection
S5	4	102.5	$1.3*10^{-3}$	After che.gro. in S1, S2, S3
S6	5	89	$1.1*10^{-3}$	After che.gro. in S1, S2, S3
S7	5	70	$9.1*10^{-4}$	After che.gro. in S1, S2, S3
CH	4	**73**	$9.4*10^{-4}$	After che.gro. in all holes

Table 4 Summary of grouting records in the test hole S4

Test Hole Name	Permeability before Treatment		Permeability after cement grouting		Permeability after cement and Chemical Grouting	
	Cm/s	Lu	Cm/s	Lu	Cm/s	Lu
S4	$9.1*10^{-4}$	70	$3.7*10^{-4}$	29	$1.5*10^{-5}$	**1. 2**

As it was mentioned in section 1, the karkheh dam geology contains zones of discontinuity and open frame work gravels which makes the overall permeability of the conglomerate to be in the relatively high range of about 4-9×10^{-4} m/s. Therefore it is believed that the poor performance of the performed chemical grouting is related to the dam geology conditions. It was observed that the technique of chemical grouting is effective for clogging of small voids and the developed silica gels can not resist against water flow in large openings. In other words, it was found that for treatment of a medium having both large and small voids like conglomerate formations, a combination of chemical and cementitious grouting must be employed in order to fill small and large openings respectively.

With regard to the above considerations and to examine the proposed hypothesis, in the next step, all of the test holes, previously injected by chemical grouts, were injected by cementitious grouts with a water:cement proportion of 2:1 along with 8 percent by volume of bentonite. After this stage of grouting the permeability test taken in the CH was of the order of 16 Lugeons, which proved the accuracy of the considered hypothesis but still it was more than the acceptable limit of about 5 Lugeons.

So far, as described above, employing a combination of chemical and cementitious grouting with giving priority to chemical grouting, succeeded in reducing the permeability of the formation to 16 lugeons. Since generally in the process of injection, at first, large openings are filled with grouts, it seems more coherent to inject cementitious grouts at first to fill large openings and remaining small voids will be filled using chemical grouting later. As a matter of fact it was at this point that another hypothesis was proposed suggesting the employment of a combination of chemical and cementitious grouting with giving priority to cementitious grouting.

Therefore, one more borehole entitled S4 was drilled near the access gallery 950 and was injected in the proposed way to verify the efficiency of the proposed plan. The records of grouting in test hole S4 are summarized in Table 4.

As shown in Table 4, after two treatments consisting of cement-bentonite grouting followed by sodium silicate chemical grouting, the permeability value was brought down to 1.2 lugeones which was less than the acceptable limit of about 5 Lugeons indicating the convenient performance of the performed process. In Fig.5, the results of water-pressure tests, which were performed at increasing and decreasing pressures, are shown.

The graphs presented in Fig. 5 can be interpreted as below:

Fig. 5 (b) and (c) approximately depicts a straightforward case in which absorption is directly proportional to pressure. Fig. 5 (a) shows an increase in water absorption, which might be due to rupture of the rock. Also it suggests continuing in water absorption after the pressure was dropped.

In phase 1, cement and chemical grouting were done at 5 kg/cm^2 and 4 kg/cm^2 respectively. In addition, the average cement and chemical grout take in the test hole S4 were 10.3 Lit/sec and 11 Lit/sec respectively. For preparing and injecting of chemical grouts, a system including two mixing tanks and one pump was exploited. In this system one tank contains the reactant, i.e. acetate ethyl and the other tank contains all of the other components, i.e. water and sodium silicate (Fig. 6). In addition, before chemical grouting, to ensure the accuracy of mix design throughout the chemical grouting, the grouting line was calibrated using the system shown in Fig. 7.

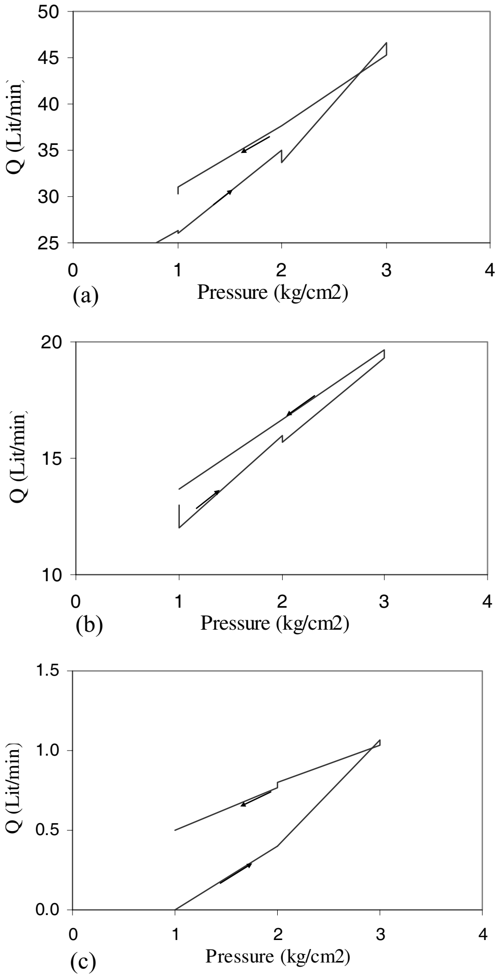

Fig.5 Water- Pressure tests for test hole S4.
(a) Before injection,
(b) After cement injection,
(c) After cement and chemical injection

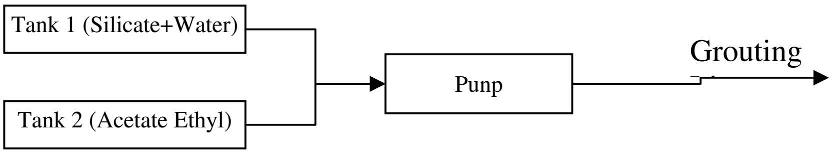

Fig.6 System used for injection of chemical grouts, including two tanks and one pump

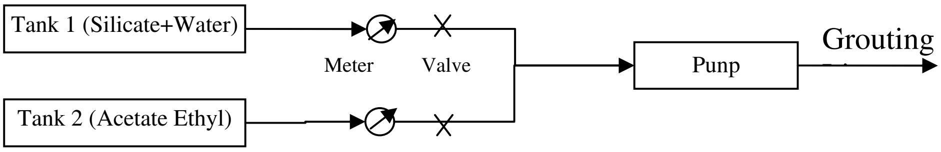

Fig.7 Utilization of two valves and two discharge-meters for calibrating the grouting line

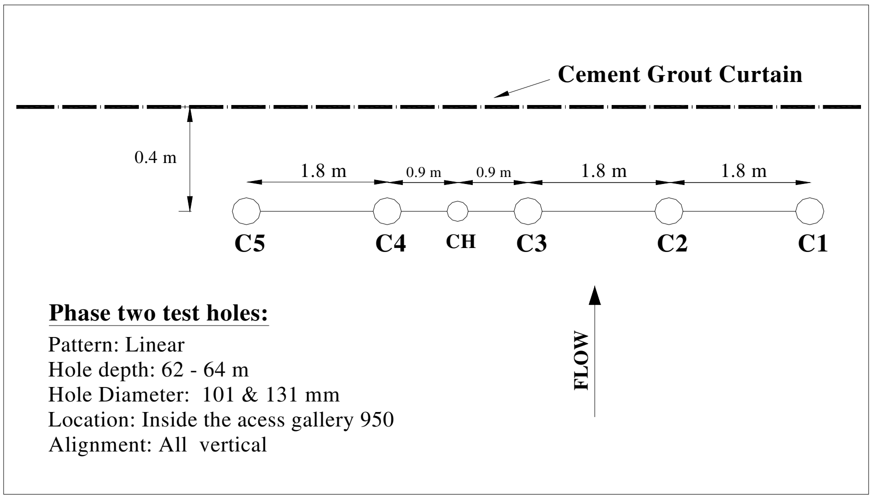

Fig.8 Sketch showing the linear placement of full-scale test holes in phase 2 of test chemical grouting.

At the end of this section, based on the demonstrated experience and associated analyses and measurements performed in phase 1 of test chemical grouting, the two following conclusions can be made:

The use of chemical grouting alone can not yield satisfactory results in treating of formations with both large and small openings like conglomerate formations.

Employment of a combination of chemical and cementitious grouting with giving priority to cementitious grouting is the most efficient method in treating of formations with both large and small openings like conglomerate formations.

6. Second Phase of Test Grouting: Full Scale Test Holes

It is widely accepted that whenever the size and complexity of a project warrant, full-scale test programs can yield information unavailable by any other method. They can provide a number of benefits that will result in an improved, more cost-effective design. These benefits include: confirmation of assumptions for new or innovative design, improved confidence level allowing reduced safety factors, proof of constructability, and confirmation of environmental compliance.

With respect to the above-mentioned rewarding benefits, the decision was made to perform a full-scale test chemical grouting in phase 2. In this way, five test holes named C1, C2, C3, C4, and C5 were drilled inside the access gallery 950, where the main chemical grouting to be performed, to depth of about 64 m, with a center to center spacing of 1.8 meter, and each having 131 mm diameter. Also a control hole (CH), having 101 mm diameter, was drilled between C3 and C4 to depth of 61.5 m.

Similar to phase 1 test holes, all of these test holes were water-flushed rotary-drilled and equipped with tub-a-manchettes. As shown in Fig. 8, they were placed in the upstream side of the existing one-row cement grout curtain which, as mentioned before, was constructed previously. In fact, full-scale test facilities were used to evaluate the performance of chemical grouting under dam hydrostatic pressure and to simulate gelled grout below ground water.

Table 5 Summary of grouting records in the second phase test holes

Test Hole Name	Permeability before Treatment		Permeability after cement grouting		Permeability after cement and Chemical Grouting	
	Cm/s	Lu	Cm/s	Lu	Cm/s	Lu
S4	$9.1*10^{-4}$	70	$3.7*10^{-4}$	29	$1.5*10^{-5}$	**1. 2**

In this phase, with respect to the results obtained from phase 1 which indicated the employment of a combination of chemical and cementitious grouting with giving priority to cementitious grouting, first test holes C1, C3, and C5 were injected with cementitious grouts with a water:cement proportion of 2:1 along with 8 percent by volume of bentonite. The permeability test taken before and after this stage of grouting is summarized in table 5. It should be noted that the relatively low permeability of the area before injection (Table 5) may be due to the presence of the previously constructed one-row cement grout curtain. Anyway, as can be seen in Table 5, with performing cement grouting the permeability was brought down from an average value of 72 Lugeons to about 46 Lugeons.

In the next step, due to the two-treatment grouting procedure consisting of cement-bentonite grouting followed by sodium silicate chemical grouting, test holes C1, C3, and C5 previously injected with cementitious grouts, should be injected with chemical grouts. Due to the considerable lag time between two grouting steps in the test holes C1 and C5 and associated strength gaining of the previously injected cementitious grouts with time, it was very difficult to break it in order to allow chemical grouts to penetrate into the remainder small voids.

Therefore, to continue the process, test hole C3, more recently injected with cement grouts, was injected with chemical grouts using pressures in the range of 30 to 35 kg/cm^2. Furthermore, chemical grouts, based on the grout mix obtained in section 3, were injected into test hole C4, which had experienced no grouting works before, at pressures ranging between 15 to 30 kg/cm^2. As shown in Table 5, despite using a relatively large grout hole spacing and performing just chemical grouting in test hole C4, the permeability test taken in CH was of the order of 6.6 Lugeons indicating the convenient performance of the method.

Although there were some geotechnical problems in the second phase of test chemical grouting, this phase of test program continued to verify the good efficiency of the employment of a combination of chemical and cementitious grouting with giving priority to cementitious grouting.

The typical results of water-pressure test performed at test hole CH is shown in Fig. 9. As can be seen, with increasing depth, there is a sudden increase in water absorption, which might be due to rupture of the rock. Fig. 9 (c) suggests that in lower depths approximately absorption is proportional to pressure.d

At the end of the second phase of test chemical grouting two main findings are as follows:

- This phase of test program continued to verify the good efficiency of the employment of a combination of chemical and cementitious grouting with giving priority to cementitious grouting.

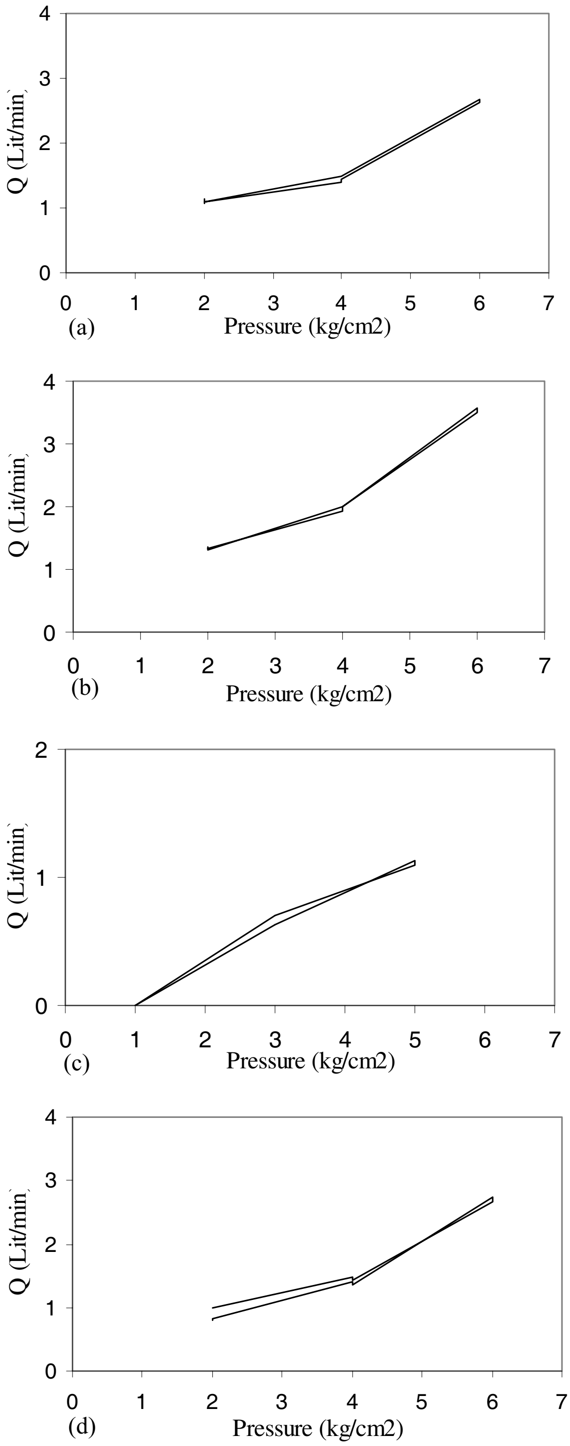

Fig.9 Water- Pressure tests for test hole CH located inside the access gallery 950 performed at different depths of. (a)32-32.5m , (b)34-34.5 , (c)14-14.5 , (d)24-24.5

- Injection of cement-bentonite grouts followed by sodium silicate chemical grouting at the same borehole is not applicable for treating of deep boreholes, due to strength gaining of the previously injected cementitious grouts with time.

In the next section some solution to the encountered problem in phase 2 of test chemical grouting will be discussed.

7. Solutions to the Encountered Problems in the Second Phase

In order to overcome problems discussed in the previous section, a convenient method should be devised which in one hand could maintain the benefits of two-stage grouting; cement-bentonite grouting followed by sodium silicate chemical grouting, and in the other hand lack the problem associated with the breaking of the cement grouts. Regarding this fact, various methods may be considered. Among these methods two more applicable, efficient, and cost-effective methods are proposed as follows:

1-The Sandwich Curtain Method (SCM):

The SCM includes multiple parallel rows of grout injection holes divided to primary and secondary rows. So called primary rows, generally external ones, are those being injected at first with cementitious grouts to block large voids of the formation. In the next stage, the soil remaining between these primary rows will then be treated by the injection of chemical grouts in the secondary rows in order to clog the remaining small voids of the formation. It can be noted that similar to other types of grouting practices, the holes in adjacent rows in a multiple-line arrangement should be staggered with relation to each other.

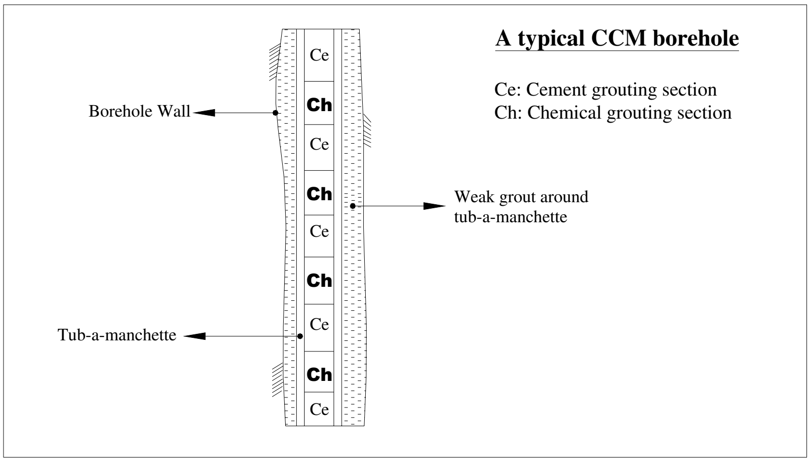

Fig.10 A typical CCM borehole

For example, given a three-row sandwich curtain, two external rows would be counted as the primary ones which should be injected at first with cementitious grouts while the middle row would be considered as the secondary one and should be injected then with chemical grouts.

It is obvious that the SCM requires at least two rows of grout injection holes, one as primary cement row and another secondary chemical one. It is also worth noting that it is better to place the secondary chemical row at the upstream of the primary cement one to be protected by cement grouts against water flow.

2- The Complex Curtain Method (CCM):

CCM, in contrast with SCM which requires at least two rows of grout injection holes, may be made up of a single row of holes, or it may be composed of two or more parallel rows. A typical borehole in a complex curtain consists of a combination of cement grouting sections and chemical grouting ones. In fact the grouting sections in a typical CCM borehole would be alternated between cement and chemical ones (Fig. 10). With regard to the previously discussed concept of two-stage grouting; cement-bentonite grouting followed by sodium silicate chemical grouting, in the CCM at first all cement grouting sections (sections represented by Ce in Fig. 10) would be injected by cementitious grouts. In the next stage, the remaining sections (sections represented by Ch in Fig. 10) will then be treated by the injection of chemical grouts.

Similarly, in a row of grout injection holes consisting of more than one borehole, at first all cement grouting sections in all boreholes would be injected by cementitious grouts. Then the remaining chemical grouting sections will be treated by the injection of chemical grouts in the following stage.

8. Concluding Remarks

Experimental and field investigations were conducted in this study to assess the effectiveness of chemical grouting in water sealing of conglomerate formations and to find the most efficient grouting system in such formations. It was found that the most efficient grouting system is to employ a combination of chemical and cementitious grouting with giving priority to cementitious grouting. Furthermore, based on the results obtained in this study the ideas of SCM and CCM are proposed to overcome the problems associated with the breaking of the stage one cement grouts in a two-stage grouting technique.

In summary, the main findings of this experimental study are as follows:

1. The chemical grouts alone were examined with regard to viscosity-time behavior, gelation time, temperature-influence, stability, and deformability. These laboratory tests, led to the selection of the final chemical grout which was a solution of sodium silicate, water, and ethyl acetate as reactant. This evaluation procedure used in this study is generally valid for any grout selection.

2. The use of chemical grouting alone can not yield satisfactory results in treating of formations with both large and small openings like conglomerate formations.

3. Employment of a combination of chemical and cementitious grouting with giving priority to cementitious grouting is the most efficient method in treating of formations with both large and small openings like conglomerate formations.

4.Injection of cement-bentonite grouts followed by sodium silicate chemical grouting at the same borehole is not applicable for treating of deep boreholes, due to strength gaining of the previously injected cementitious grouts with time.

5. To overcome the problem discussed above, the sandwich curtain method (SCM) and the complex curtain method (CCM) are proposed.

9. Acknowledgments

The authors would like to acknowledge the Iran Water and Power Resources Development Company, IWPC, and C.S.C Company for their assistance. Also sincere thanks are extended to the colleagues in Karkheh dam chemical grouting project in the Mahab Ghodss Consulting Engineers.

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