Economical Grout for Tunnelling through Highly Jointed and Sheared Water-Charged Strata in Himalayan Region

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ABSTRACT

Tunnelling, which was considered as an art, is now full-fledged science. With the advancement in technology, new tunnelling methods including mechanization of various activities involved in tunnelling have been evolved. Due to high degree of unpredictability of rock strata through which tunnel is being bored, especially in Himalayan region of Northern India which are young fold mountains, a number of problems are likely to be encountered while tunnels are being excavated. One of the major problems that affects the progress of a tunnel is the excessive water seepage, when strata through which tunnel is being excavated is soft, sheared/crushed due to which tunnelling progress is halted for years or may lead to abandoning of the existing tunnel alignment. This serious problem experienced in tunnelling by civil engineers is driving civil engineering to look for new techniques at a frequent rate to overcome such excessive seepage and allied problems in tunnelling. The existing techniques to tackle these problems, like freezing the water, using DRESS method, polyurethane grout (PU Grout) etc, are either very expensive or ineffective in case where water seepage is very high. Herein a new grout referred to as 'Cement-based Bituminous Emulsion Suspension Grout' was developed to overcome heavy seepage problems associated with tunnelling. The performance of this grout was examined at laboratory level. This technique was found to be quite cost-effective, with good strength and better adhesion as compared to the existing techniques.

Keywords: Bitumen Emulsion; Grout; Permeability; Flash point

1. INTRODUCTION

In the present day environment, as we have seen, underground structures, especially tunnelling have become a very important aspect of civil construction in vast variety of fields. Tunnelling, which was considered as an art, is now full-fledged science. With the advent of growth in technology and industrialization, new tunnelling methods including mechanisation of various activities involved in tunnelling have been evolved. As rock strata is very unpredictable, especially in Himalayan region of Northern India which are young folded mountains. At the same, tunnel has no fixed design methodology, therefore, the tunnelling method is chosen with maximum flexibility and suitability according to working conditions.

There are many problems encountered while tunnels are being driven, such as ground settlement, ventilation, excessive water seepage, etc. A major problem that affects the progress of a tunnel is the problem of excessive water seepage when strata through which the tunnel is being excavated is soft/ sheared/ crushed due to which tunnelling progress is halted for years or may lead to abandoning of the existing tunnel alignment. As work is halted for months together or even for years, the cost of project increases with time as cost of material increases. If alignment is abandoned, then the initially invested money goes waste and further more money has to be invested to start the work again. This ultimately leads to unexpected problems, disputes with contractors or other agencies, cost overruns and delays in completing the project.

There are many advanced techniques available to tackle this problem of excessive water seepage such as freezing the water, using DRESS method, polyurethane grout (PU Grout), but these techniques are either very expensive or ineffective in case where water seepage is very high. For removing water, drain holes are made which may remove water, but in the longer run they prove to be harmful as tunnel is continuously exposed to water i.e. deterioration of tunnel lining. In some cases like construction of a railway or a metro tunnel, it is not possible to abandon the tunnel as alignment cannot be easily changed. So we should find a method to progress through water borne strata, which is effective, fast, long lasting and economical. Chandrawat et al. (2001), has reported the characteristics of cement based bitumen emulsion, but has not checked its applicability. In this study, a new grout (cement based bitumen emulsion suspension grout), has been prepared and its applicability from field point of view has been checked.

2. RESEARCH SIGNIFICANCE

As mentioned in the preceding section, the various techniques to tackle the problems of excessive water seepage in tunnelling are either very expensive or even ineffective when the water seepage is very high. Hot Bitumen has already been used as a grout material in many cases and has resulted in a reduction in the hydraulic conductivity of the formation surrounding the main tunnel by approximately 95%. But, it required a combination of high pressure and high temperatures and a custom designed grout plant had to be built on short notice, which is normally not available in market. Herein, Bitumen Emulsion Based Cement Grout has been introduced to overcome excessive seepage problems during tunnelling. The grout comprises equal proportions of bitumen emulsion {rapid setting}, cement & crusher sand with turpentine as diluent. The flows can be sealed by injecting the grout into the fracture (seepage) surface. The bitumen initially gives adhesion characteristics and thus restrains the flow of injected material with seepage flow; while as the binder (cement) delivers strength to the grout on hardening and therefore permanently seals the pores. The grout is simple, economical and does not require special equipments to work with.

3. CASE STUDIES

- Many Railway tunnels are being excavated through dolomite in J& K state. Dolomite is highly jointed, fractured and sheared. Besides these weak geological features, rock mass is highly charged with water. Tunnelling through these weak features which are charged with water is difficult, time consuming and costly since while excavating through shear zone material charged with water muck start flowing and covers the entire tunnel face leading to formation of cavity which takes a lot of time to tackle the tunnel zone.

- During excavation in tunnel thick shear zone has been encountered. The shear zone is charged with water. The shear zone material consisted of sheared plastic clay and pulverized sand stone. Due to the presence of sub surface water, shear zone material comes out flowing into the tunnel resulting in formation of cavity at the crown (Table 1).

Table 1 - Delay in progress of railway tunnel due to cavity formation in jointed, fractured and sheared strata charged with water in J&K

Hazard No.	Date of Occurrence	Date when the Cavity was tackled	Time Delayed	Remarks
1.	30 Jan 05	8 Feb 05	9 Days	At Ch-43/021, during heading a cavity was formed due to flow of muck from RHS of the crown.
2.	14 Jun 05	7 Sep 05	86 Days	At Ch-43/143.5, during heading a huge cavity was formed due to flow of muck. The strata was highly jointed sheared crushed fractured dolomite and charged with water about 4 to 5 lit/sec.
3.	19 Jun 05	28 Jul 05	40 Days	At Ch-43/111, cavity was formed due to yielding failure of RHS SPL beam. Under heavy pressure of sheared crushed carbonaceous dolomite charged with water.
4.	16 Jan 06	20 July 06	186 Days	At Ch-43/312 at heading, a huge cavity was formed due to flow of muck charged with heavy seepage from LHS of crown. Tunnelling was done by multi drift method.

4. GROUTING

It is a technique of forcing a material (grout) under pressure (Warner, 2004; Chandrawat et al., 2001), so as to fill joints and other defects in rock, soil, concrete, masonry and similar materials. It is also a means to modify soil through pore space or compaction into a denser state.

Applications of grouting in tunnels

- Block the flow of water and reduce seepage
- Strengthen soil, rocks, or combination thereof
- Fill massive voids and sinkholes in soil or rock
- Form bearing piles
- Support soil and create secant-pile wall
- Install and increase the capacity of anchors and tiebacks
- Immobilize hazardous materials and fluids

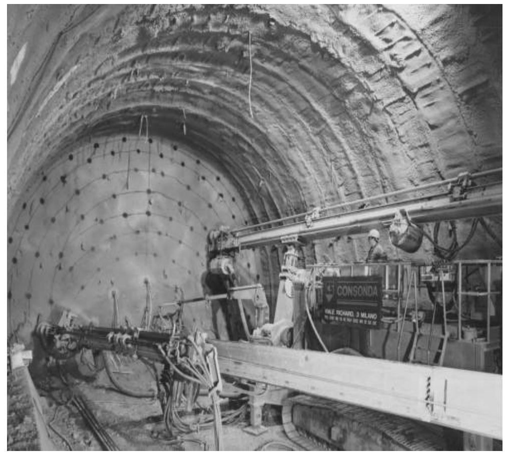

Fig. 1 – Grouted tunnel face

5. PARMETERS THAT A CHEMICAL GROUT SHOULD SATISFY

A grout should essentially satisfy the following requirements.

Dimensional stability: The dimensional stability of a material refers to its propensity to change shape or volume. All materials experience volume change with variation of temperature; many grouts and cementatious mixture shrink as they harden and dry out. This can be prevented by use of chemical additive.

Strength: The strength of a material refers to the magnitude of a stress, or load, the material can withstand without rupture. In some grouting, especially that which is in connection with water control, strength is not of much importance. It is significant in the strengthening of rock or soil to enable it to withstand greater loads.

Modulus of elasticity: It refers to stiffness of a material. Grouts of high modulus do not deform under load as much as those of low modulus. When materials of widely differing moduli are in contact with each other, the lower-modulus material will tend to yield or bulge under load whereas high- modulus component will be unaffected (Singh, 2001).

When load is perpendicular to bond line, a difference in modulus usually does not cause great problems. However, when the load is applied parallel to the bond line, deformation of the lower-modulus material results in transfer of some, or all loads it should support to the higher-modulus material. This can cause an overstress condition and, in extreme cases, failure.

Coefficient of thermal expansion: Virtually all materials expand and contract with changes in temperature. For a given temperature change, the amount of expansion or contraction depends on the coefficient of thermal expansion of the particular material. The coefficient of thermal expansion represents the change in length over a unit length divided by the temperature change. Temperature extremes can affect the performance and durability of many hardened and cured grout.

Thixotropy: Thixotropy is the characteristic of a fluid to behave as an immobile paste or gel when at rest (Tatiya, 2005). This is important when considering allowable injection pressure for a given application and an adequate initial pressure level that must be provided to start the flow.

Flow properties: Fluid flow is described as either Newtonian or Non-Newtonian. In Newtonian flow, the shear stress, which is the force required to move the fluid, is essentially constant, regardless of the rate of movement, which is technically referred to as the shear rate or shear strain.

Non-Newtonian or pseudo plastic flow possesses some thixotropy and requires a measurable force (shear stress), which in grouting is the injection pressure, to become mobile.

Viscosity: Viscosity refers to a fluid's resistance to flow, which is the result of internal molecular friction. It is established by dividing the shear stress (pumping pressure) by the shear rate (pumping rate) at a specific temperature. The slope of the non-Newtonian curve represents viscosity. At a constant shear rate, thixotropic fluids will exhibit a reduction in apparent viscosity or resistance to flow.

Mobility: Mobility denotes the property of a grout material to travel through the delivery system and into the desired voids or intended deposition zone of the formation, being grouted. For proper performance, the grout should be of sufficient mobility to penetrate and fill the desired defects, but sufficiently limited so as to not flow beyond them.

Penetrability: Penetrability defines the ability of a grout to permeate a porous mass, such as sand or soil, or to fill thin fracture or small voids. The penetrability of grout is dependent on a combination of viscosity and wetability. The wetability of a fluid is a function of its interaction or affinity to a solid and is defined by surface tension.

Mixing shear: A given amount of mixing shear; not too much and nor too little, is essential for grouts that contain many common ingredients. Variable shear laboratory mixers are thus widely used, which measure and display the actual value of the viscous shear occurring.

Cohesion: Cohesion is an important grout property, as it has a strong influence on the distance a grout can penetrate. It is desirable to have high grout permeability, which calls for low cohesion. Cohesion is usually divided by the unit weight of the grout to provide a relative cohesion (Cr), which is normally reported value. It is of the order of 0.2-0.4 mm for high and as low as about 0.006mm for very low-cohesion mixes or grout.

Bleed: When at rest, the individual particles of a fluid suspension grout tend to settle out of solution, leaving excess mixing water on top of settled solid and this is referred to as bleeding. To prevent bleeding of the grout prior to injection, it is usually agitated continuously after mixing.

Setting time: Control of the time required for a grout to set or harden can be crucial to proper performance. Depending on the individual conditions, either rapid or delayed setting time may be desirable. Where many holes are to be grouted, grout injected into a given hole must set or become immobile before the adjacent holes are drilled. In such cases, resumption of drilling is delayed until the grout sets. Rapid setting times are also often desirable when injecting into moving water, so that the grout will set before being excessively diluted or washed away. Even where the water is not moving, a rapid set will minimize the opportunity for dilution of the grout. If grout does not dilute and is insoluble in water, then setting should be high so that it gets enough time to penetrate into cracks.

Solubility: When preparing a grout, rapid dilution of all components is beneficial and it decreases the amount of time and energy required for mixing. If the grout is to be placed in a saturated formation or void, however, it is undesirable for the mixed grout to be easily separated or dissolved. Under such prevalent conditions, and especially in placement with moving water, grout with high cohesion and low solubility is required.

Flash & fire point: The values of flash point and fire point of a grout chemical should be high enough so that a grout can be safely pumped without any hazards of fire.

6. EXPERIMENTAL PROGRAM

A three phase experimental program was launched to expedite the performance of proposed grout. Phase one comprised of the preparation of the grout. In second phase the properties of the grout were evaluated at laboratory level and in the last phase the performance of the grout was checked through application on field extracted core samples. Each phase is discussed as follows.

6.1 Preparation of the grout

A number of trial mixes were prepared to arrive at suitable combination of the various constituents of the grout. The quantities per kilogram of the successful trial are shown in the Table 2 below.

Table 2 - Quantity per kg of the proposed grout

Materials	Weight in grams
Cement	400
Crusher Dust	200
Bitumen Emulsion	200
Turpentine	100
Water	100

Fig. 2 – Tunnel in progress

The weighed quantities of cement, crusher dust and water were mixed in a container to form a thin paste. In a separate container the turpentine was mixed with hot bitumen emulsion and then the cement paste was added to it. The composite mix was thoroughly agitated till a homogenous mix was formed. The resultant mix is identified as cement based bitumen emulsion suspension grout. This should be noted that turpentine is highly volatile and therefore the grout should be prepared in desired quantities only and immediately applied over the target, otherwise it will loose flowability and penetrability with time.

6.2 Characteristics of the Grout

A thorough laboratory investigation was carried out over the grout to evaluate its various properties, which are pre-requisite for the grout. The important properties evaluated are described as follows.

Initial and final setting time of the grout sample

* Place- NIT Srinagar-India
* Date-17 November 2006
* Room Temperature-10°C
* Apparatus used- Vicats Apparatus
* Initial Setting Time- 07 hrs
* Final Setting Time- 12 hrs

Fig. 3 – Vicats apparatus

Strength

* Date: 17 January 2007
* Size of Specimen: 15 cm cube
* Apparatus: Universal Testing Machine
* Place- Field Laboratory of J&K Railway
* Project-India
* Room Temperature-25°C
* 28 day compressive strength of specimens:
Cube 1: 13.5 N/mm^2
Cube 2: 16.5 N/mm^2
Cube 3: 14 N/mm^2

The average strength of the grout was determined to be 15 N/mm^2.

Fig. 4 – Samples before testing

Fig. 5 – Samples after testing

Flash point and fire point test of sample

* Place- NIT Srinagar-India
* Date of Test- 19 November 2006
* Mixed in proportion of 1:2:2 (Bitumen Emulsion: Cement: Crusher Dust)
* With 10% Turpentine for dilution to ease injection of grout
* Room Temperature/ Initial Temperature-10°C
* Flash Point-75°C
* Fire Point-90°C

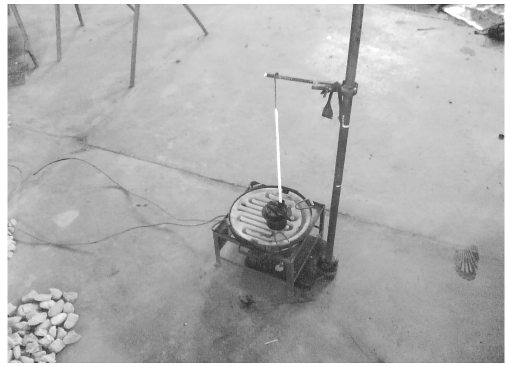

Fig. 6 - Flash and fire point test

Cohesion test

* Date-29 December 2006
* Place- IIT Roorkee-India
* Room Temp. 19.5°C
* Proportion of grout- 1:2:2
* Dimension of plate- 10cm x 10cm
* Weight of Plate before dipping in grout- 370gm
* Weight of Plate after dipping in grout- 652gm
* Weight of grout adhered to plate- 293gm
* Value of Relative Cohesion (Cr) - 1.12
* It is highly cohesive

Fig. 7 – Cohesion test

Viscosity test

* Date-29 December 2006
* Place- IIT Roorkee, India
* Room Temp.- 20°C
* Proportion of grout- 1:2:2
* Apparatus Used- Redwood Viscometer
* Diameter of orifice- 1 cm
* Volume of Grout passed- 50ml
* Time taken for flow- 2min 52sec
* Value of dynamic viscosity- 0.683 poise

Fig. 8 - Viscometer

Table 3 - Summery of test results on the properties of Proposed Grout

Property	Results
Dimensional Stability	Shrinks on drying
Strength	After 28 days, Temperature 20°C, Strength of Sample – 15 KN/mm^2
Thixotropy	High pressure required for injection
Flow Properties	Non-Newtonian Flow
Viscosity	0.0683 kgs/m^3 Highly viscous paste. Can be reduced by adding turpentine upto 10%
Mobility	Immobile. Can be reduced by adding turpentine upto 10%
Penetrability	Can easily penetrate into cracks > 4.75mm May take some time to penetrate to lesser size.
Grain Size of Solids	< 4.75mm (Size of crusher dust particle)
Mixing Shear	High Mixing Shear
Cohesion	Cr (Relative Cohesion)-1.12 Highly Cohesive
Bleed	Does not bleed
Setting Time	Initial Setting Time- 7 hours Final Setting Time- 12 hours
Solubility	Insoluble in water
Fire Point and Flash Point	75° C & 90° C (Respectively)

7. APPLICATION OF THE GROUT ON CORE ROCK SAMPLES

The performance of the grout was checked directly on field samples. Three different core samples were extracted from fractured rocks at three different locations from a tunnel site in J & K Railway Project (India). Permeability tests were performed on the samples before and after the application of the grout. The details of the specimen and permeability results are shown in Table 4(a) through Table 4(d) as follows.

From the experimental results it is clear that the proposed grout satisfies the basic requirements of the grouting material. The proposed grout has got very high flash point to safe guard against fire hazards. The grout has proved to be very effective in preventing the seepage flow. The addition of cement binder adds sufficient strength to the grout to withstand the generated stress up to reasonable limit. It is very cost effective and costs about Rs. 30 per kg in comparison to PU grout, which costs Rs. 3000 per kg. The proposed grout, therefore, is nearly 100 times cheaper than PU grout, besides being more effective. Hence the use of proposed grout would result in saving of hundreds of crores of rupees in tunnelling especially in Himalayas**.**

Table 4(a) - Details of samples

Rock	Length (L cm)	Diameter (cm)	X-Sectional Area (A cm^2)
Schist	5	4	12.56
Dolomite	6.5	5.5	23.75
Dolomite	6	5.5	23.75

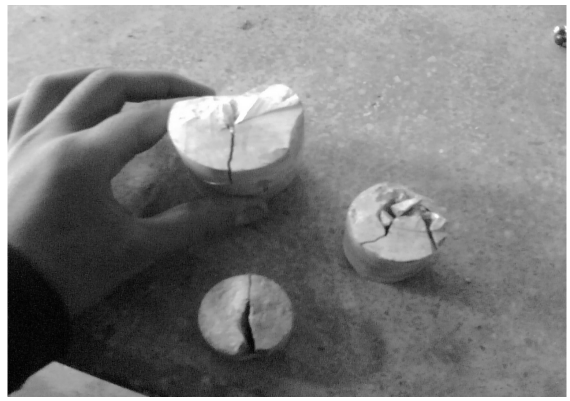

Fig. 9 – Fractured core samples

Table 4(b) - Permeability before grouting using constant head method

Rock	Length (L cm)	X-Sectional Area (A cm^2)	Head (H cm)	Discharge (Q cm^3/sec)	Permeability (k) [k=Q/iA] (cm/s)
Schist	5	12.56	73	2.75×10^{-5}	1.516×10^{-3}
Dolomite	6.5	23.75	107	1.4×10^{-6}	3.5×10^{-5}
Dolomite	6	23.75	117	4.3×10^{-5}	6.47×10^{-4}

Table 4(c) - Permeability before grouting using variable head method

Rock	Length cm L	X-Sectional Area (A cm^2)	Area of Tube (a cm^2)	Time (sec) t	H_1 (cm)	H_2 (cm)	Permeability $k=\frac{2.303aL}{At}\log(H_1/H_2)$
Schist	5	12.56	3.14	4	135	65	2.28×10^{-3}
Dolomite	6.5	23.75	3.14	53.44	135	115	2.578×10^{-5}
Dolomite	6	23.75	3.14	4.3	135	95	6.48×10^{-4}

Table 4(d) **-** Comparison of Permeability before and after the application of grout

Sample	Permeability before grouting	Permeability after grouting
Fractured schist	5.52×10^{-3} cm/sec	No permeability
Fractured dolomite	4.105×10^{-5} cm/sec	No permeability


Fig. 10 - Permeability test of samples, performed in the laboratory

8. CONCLUSIONS

The following conclusions have been drawn from the present study:

- Initially a thick paste was formed after mixing bitumen emulsion, cement and crusher dust. It lacked properties like viscosity; mobility & penetrability, so these were improved by adding 10% turpentine which volatises immediately after injection at high pressure.
- It can easily penetrate into cracks of size greater than 4.75mm and can be mixed both in anionic and cationic form depending on the type of emulsion (both forms are available). It should be opposite to the charge of the surface, so that it is attracted towards the surface.
- The initial setting time was 7 hrs, so it gets enough time to penetrate into deep cracks and sets finally after 12 hours.
- The flash point of the grout was 75°C and fire point was 90°C, so considering safety parameters, it can be safely injected at high pressures.
- It was used for sealing fractured rock core samples obtained from tunnel construction sites and results were found to be successful.
- The value of relative cohesion was found to be 1.12, which is very high, so it adheres to the surface of rock immediately on injection.
- The value of dynamic viscosity was found to be 0.0683 kg/m^3, so it is highly viscous.
- It is very cost effective as compared to other expensive chemical grouts. So it is economical to use.
- It can be injected easily and does not require any special pumps for injection purpose.
- The materials used in this grout are easily available near the construction site and can be easily mixed in a mixer.
- Different size of aggregates can be added depending on fracture/crack or cavity and the equipments available for injection on the construction site
- In addition to sealing cracks it also stabilizes the weak strata, as sandy and silty soils have been grouted successfully using emulsified asphalt. Slow setting emulsions are generally preferred as these can travel a large distance into the stratum.

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