CHAPTER VII

SUMMARY OF FINDINGS

The search to understand the rheological behaviour of coarse and fine grouts amongst investigators have a motive to evolve a unified flow mechanism and strength interaction with natural formation. The present investigation attempts to bridge the gap of knowledge essential for the rheological changes during sol to gel and microscopic events occurring during the gelation. The flow mechanism and strength interaction of grout with formation is mainly dependent on its time-viscosity relationship and strength. It is necessary to balance flow and strength behaviour of an injection mix within ideal framework to suit particular time-viscosity relationship and post gel strength which can resist foundation stresses and wash out forces by proper occupation in spaces of the formations. The microscopic changes associated with time-viscosity relationship of grout are important to correlate the limits of injectability and pumpability with respect to field conditions. It is the time-viscosity relationship of grout which interest the grouting engineer while studying their behaviour during mixing and injecting them into the natural formations.

In gel mechanism, the vacant lattice sites of the sol grout is triggered by admixtures or precipitants or catalysts evolving activation gradient by various physico-chemical processes causing molecular growth and filling vacant lattices with progress of time having primary and/or secondary valance bonds in the gel mass. Conceptual framework formulated from the unit cell of the gel along with ideal framework help developing new grout mixes. Gellation concepts of coarse grout conceived by microscopic
measurements bear out from time-viscosity experimental observations.

Thus, the approach followed for the present investigation is the validification of the experimental time-viscosity relationship and strength of grouts against their gel mechanism. The modified time dependent viscosity equation is suggested to account rheological changes occurring during gelation. Also the efficacy of some of the coarse and fine grout systems are examined for flow and strength interactions.

Following are the summary of findings of present investigations:

A. EXPERIMENTAL DEVELOPMENT AND MEASUREMENT INNOVATIONS

I. Major factors that influence the measurement during the development of grout mix and time-viscosity characteristics are: homogeneity of the system, quality of the ingredients, sequence of mixing of various ingredients, method and time of mixing and ambient temperature. Time-viscosity study needs to maintain a constant temperature.

II. A pitched curved blade with high speed impeller having its diameter to tank diameter ratio of 0.86 found to be efficient for forming vortex along with blending and shearing action during mixing cement based Binghamian grouts with and without sand, bentonite and/or fly ash. In cement-bentonite grout mix, cement is added to fully activated bentonite water system to enhance the stability of the grout.

III. Low initial viscosity of basic components and optimum concentration of catalyst or precipitant reduce
mixing time in Newtonian grouts. Pre-polymerization and quasi-prepolymerization processes help reducing mixing time, minimizing toxicity and handling problems. Molar ratio of 1:1 of urea and resorcinol with formaldehyde in UF and RF systems, isocynate with hydroxyl in polyurethane system and SiO₂/Na₂O ratio of 3.9 in silicate give minimum mixing time of 2 to 3 minutes with low initial viscosity (2 cP to 13 cP).

IV. In developing chemical grout system, conceptual framework approach and equivalent weight approach along with conventional ideal framework found to be suitable for appropriate design of grout mix.

V. Amongst the experimental techniques available to investigate initial viscosity, time dependent viscosity and yield value, gel strength, limiting injection time and gel time of Binghamian and Newtonian grouts, Brookfield viscometer set up satisfies the highest degree of exactitude. Calibrated T-bar spindle with special coupling facilitates high viscosity measurements.

VI. A flow value between 40 cm to 50 cm by Colcrete flow meter and time of afflux using Marsh cone between 30 to 42 seconds for cement based Binghamian grouts endure linear relation with corresponding viscosity measurements employing Brookfield viscometer. Time for 60 ml. and 100 ml. extraction of water through cement and sand-cement grouts respectively subjected to vacuum of 0.96 kg/cm² are standardized as water retentivity. Turbidity and wave velocity measurements through grout under gellation by turbidimeter and pulse transmission technique respectively give clue for rate of reaction and change of shear modulus with time.

VII. Syneresis measurements of gel by mercury
displacement and critical gradient at maximum turbidity along with discharge measurement for given time of washed out water from grouted mass help understand permeance aspect of grouts.

VIII. Innovated micro measurements to grout studies by energy dispersive X-ray analysis along with scanning microscopy and infra-red spectroscopy with optical photometric measurements help explore excellently point to point bonding in cement based and chemical grouts at various stages of gellification.

To help understand flow mechanism and strength interaction of grouts, the exactitude of experimental set up is most essential for exposition of process of gellification and bond formation. A microscopic measurements with experimental observations become the only approach to produce a rational and realistic physical model to understand time-viscosity relationship and post gel strength.

B. TIME-VISCOSITY RELATIONSHIP AND STRENGTH

Time-viscosity relationship of any grout system describes viscosity at initial, limiting injection, zero displacement and gel time; time dependent yield value or resistance of grouts, and gel strength. Post gel strength is time dependent which increases up to 7 days in Newtonian and 28 days in Binghamian, tends to remain constant thereafter.

I. Binghamian Grouts

Binghamian coarse grout system shows distinct time-viscosity relationship from Newtonian fine grout systems. This distinct behaviour is attributed to crystallization, edge to face and edge to edge bondings in coarse grout
while, polymerization leading to chain reaction in fine grouts.

a. Neat Cement Grout

(i) Grout mix having water : Cement ratio 2:1 endures a distinct characteristics, below which in thick grout, it exhibits higher initial viscosity, more initial yield value, greater initial flow value, low bleeding potential along with less time for final bleeding potential, more short term strength (up to 7 days), high initial tangent modulus with low failure axial strain and above which in all thinner mixes reverse is the behaviour. Gel time increases with increase of water : cement ratio up to 2, which tends to remain constant thereafter in thinner grouts.

(ii) Yield value increases with time for a given grout. Grouts which are linear Binghamian during initial time becomes nonlinear Binghamian with progress of time. Increase of viscosity with time appears to be gradual during limiting injection time tends to increase rapidly after zero displacement time.

(iii) Shear stress build up is low during initial stages tends to increase rapidly after zero displacement time leading to maximum at gel time. The variation pattern with time of rheological time factor and shear modulus suggests that the grout transforms to visco-elastic after zero displacement time and may tend to elasto-viscous just after gel time.

(iv) Time dependent linear elastic and time dependent nonlinear elasto-plastic leading to brittle failure of hard mass are identified while evaluating deformation of set mass from stress-strain curve.
Initial Binghamian nature (yield value) of grout is attributed to ionic potential formation due to dissolution of tricalcium silicate and tricalcium aluminate. Van der Waal type of attractive forces so produced tend to nonlinear behaviour because of nucleation and initial growth process in cement water system showing little increase in viscosity and stress buildup up to limiting injection time. The rise in viscosity at and after zero displacement is due to coagulation of hydrated C-S-H gel phase producing visco-elasticity in the grout showing percentage increase in hydrated phases.

b. Cement Grout with Admixtures

(i) Antibleeders, accelerators and air entrainers as an admixture to the cement grout increase the initial viscosity developing more yield value, while retarder and water reducer improve fluidity with reduction in alkalinity of the grout. Aluminium sulfate as an antibleeder and, sodium silicate and calcium chloride as an accelerators along with their characteristic effect, they increase alkalinity of the grout and improve long term and short term strength. Water reducer and air entrainer along with their characteristic effect, they increase gel time while antibleeders reduce the gel time.

(ii) Accelerators and antibleeder give higher yield value showing higher degree of Bingham behaviour at any time since mixing, while retarder and water reducer produce lower yield value at any time compared to neat cement. Sodium silicate amongst the accelerators and aluminium sulfate amongst antibleeders are more effective in causing grout more nonlinear Binghamian.

Antibleeder and accelerator display time-viscosity curve left side showing higher viscosity at any time for
a given water:cement ratio. Retarder and water reducer shift time-viscosity curve right side with consistance difference between limiting injection, zero displacement and gel time exhibiting lower viscosity unlike accelerators and antibleeders.

Water reducers and retarders exhibit linear Binghamian in the low stress range compared to neat cement, while accelerators and antibleeders remain nonlinear Binghamian in the same low stress range.

(iii) Calcium chloride and sodium silicate as an accelerators and aluminium sulfate as antibleeder show early stress build up and visco elasticity than neat cement. Bentonite as an antibleeder and retarder exhibit lower value of stress build up and visco-elasticity at any time compared to neat cement. Though water reducers give consistance delay in stress build up, it reaches to same level of stress build up and visco-elasticity of cement.

(iv) In set mass accelerators and aluminium sulfate as antibleeder remain elastic for higher peak stress while bentonite, retarder and air entrainer show reverse behaviour reaching to elasto plasticity at lower peak stress compared to neat cement.

Accelerator involves a rapid rate of $C_2S$ and $C_3S$ hydration which alters the rate of cement gel formation by catalytic reaction of monochloride. The quicker stiffening increases percentage hydrated phases from 24 to 55 per cent within 15 minutes, changing specular ciggar shaped fibrous morphology to conchoidal fibrous morphology at gel time. Reduction in action of gypsum by consuming sulfate and high adsorptive nature of silica gel on and between hydrated flocs tends to accelerate the hydration process producing more hydrated phases which changes usual morphology to sponge like mass with connected silica gel phase, reflec-
ting increase in the strength. The additional formation of aluminate hexagonal rod with average length of 3.86 micro meter of aluminate sulfate provides good bridging between hydrated flocs and increasing size of hydrated phases by 2.56 times help reducing bleeding and increase in strength with time. A flocculated card house structure of bentonite captures setting flocs of cement producing morphology of average size 4.2 micro meter help reducing bleeding potential increasing degree of Binghamian nature of the grout system and the formation of the linkage gap between hydrated cement flocs lowers the stress buildup and ultimate strength with time. Hampering action of retarder to the nucleation and growth of hydrated crystals in usual cement-water system from 63 per cent to 48 per cent lengthen the rate of reaction forming a weak mass by occupying sheath complexes within and surrounding the lattice of hydrated crystal causing linkage gaps. The micro bubble formation to the interfaces of cement-water hydrated phases in air entrainer increase the viscosity and the volume of hydrated mass. High adsorbing nature of water reducer help reducing attractive forces and inter particle friction in the system improving the workability at any time compared to cement.

c. Cement-Bentonite Grout

(i) For a grout mix having high water:cement ratio of 10:0.25 with high bentonite content of one part, low strength and long gel time are the main features of the grout, while with low water:cement ratio of 5:1 and low bentonite content of 0.4 and 0.7, exhibit short gel time and comparative higher strength. The admixture like sodium silicate and mono sodium phosphate in proportion 1:1 to previous weak grout improve fluidity, gel time, bleeding and progressive strength.
(ii) Magnitude of yield value at any time is dominated by bentonite content exhibiting high degree of Binghamian nature. Higher initial viscosity during early stages and lower viscosity at gel time with comparative more limiting injection, zero displacement and gel time than neat cement are the main characteristics of time-viscosity relationship. Presence of bentonite keep the grout in non linear Binghamian state even at low stress range.

(iii) Higher concentration of bentonite lowers the acquisition of shear stress build up after zero displacement time. Though the rate of acquisition of visco-elasticity in cement bentonite is more than neat cement due to characteristic nature of bentonite gel, the rigidity of gel is of low level compared to neat cement.

(iv) Bentonite detoriates time dependent strength, however low level strength increases with time, showing less increase after 7 days.

The characteristics Binghamian nature of bentonite is attributed to formation of card house structure due to linking of edge to face or edge to edge contacts. This linkage is reversible tending to sol-gel-sol process. The anionic dispersion due to mono sodium phosphate improve the initial fluidity. The presence of sodium silicate forms a bridging action between bentonite and cement particles by silica gel accelerating the rate of hydration of cement.

d. Sand-Cement Grout

(i) Grout mix having water : cement ratio of 0.7 : 1 and 0.78 : 1 with sand : cement ratio of 1.5 : 1 and 2 : 1 gives pumpable flow value without segregation, appropriate water retentivity, gel time and consistent compressive
and flexural strength compared to grout having sand : cement ratio 3 : 1 at water : cement ratio of 0.95 : 1. Increase of sand : cement ratio for given water : cement ratio or decrease of water : cement ratio for a given sand : cement ratio reduce the flow value there by increase of initial viscosity and yield value and lower the bleeding potential. Decrease of water : cement ratio for a given sand : cement ratio decreases the gel time.

(ii) Sand-cement grout needs high value of shear stress for given shear rate to maintain the flow at any time compare to neat cement. Sand-cement grout gives higher viscosity showing more limiting injection, zero displacement and gel time than neat cement grout at same water : cement ratio. The cement grout which is linear Binghamian in a lower stress range, sand-cement grout shows nonlinear Binghamian in the same stress range at a particular time interval.

(iii) Sand : cement ratio 1.5 : 1 gives higher stress build up and early acquirement of visco-elasticity compared to sand : cement ratio of 2 nearer to gel time.

(iv) A pumpable grout having sand : cement ratio 1.5 : 1 shows higher stress at any value of per cent strain in stress-strain curve of set mass. For a given water : cement ratio, a failure axial strain decreases, while E-value increases with decrease of sand content remaining (E-value) less than neat cement grout. Initial elasticity followed by elastoplasticity is the characteristic deformation as identified from stress-strain curve.

A matrix consisting of envelop of cement flocs to rough and angular sand particles in sand-cement-water system help interlocking with one another producing inner
cohesion with progress of time resorting to viscosity increase and stress build up at various stages of time-viscosity relationship forming viscoelastic mass nearer to gel time.

e. Cement-Fly Ash Grout

(i) Fly Ash in grout mixes as an replacer to cement improve the intial fluidity and delay the gel time, while as an additive to cement reverse is the behaviour.

(ii) The reduction of initial and progressive yield value suggest the low degree of Binghamian nature than neat cement grout. Lower viscosity up to limiting injection time and higher viscosity thereafter with more limiting injection, zero displacement and gel time than cement seems to be the characteristic time-viscosity relationship of fly ash as replacer to cement in the grout. Up to limiting injection time grout with fly ash as an replacer remain linear Binghamian than cement at any stress range.

(iii) Rate of stress build up and rate of gain of visco-elasticity is low up to long induction period of about 45 minutes which increases thereafter.

(iv) Fly ash detoriates the short term strength of set grout, while it improves long term strength to some extent than neat cement. Fly ash decreases short term E-value with increase of failure axial strain corresponding to peak stress than neat cement.

Higher initial fluidity with long gel time is attributed to ultrafineness of fly ash and pH reduction due to consumption of bye product of initial hydration reaction of cement respectively. The development of additional
hydration phases (ghelenite) by pozzolanic action of fly ash with waste bye product of cement help increasing viscosity during later stages and rate of acquirement of visco elasticity nearer to gel time. Un reacted pozzolana residue influence the early strength.

In brief time-viscosity relationship of Binghamian cement based grouts reveal that initially linear Binghamian transforms to non linear Binghamian after initial yield value with time which tends to increase viscosity and to some extent rigidity progressively due to precipitation and coagulation of colloidal gelatineous hydrated phases with time leading to visco-elastic mass nearer to gel time converting finally to brittle hard mass. Time dependent linear elasticity and time dependent non linear elastoplastic leading to brittle failure of hard mass are identified while evaluating deformation of set grout.

II. Newtonian Grouts

Time-viscosity relationship of Newtonian grouts exhibits less distinct transition between zero displacement and gel time, while in Binghamian grouts these times are separately noticed. Newtonian grouts have irreversible and controlled gel time, while Binghamian grouts particularly with bentonite have reversible and uncontrolled gel time.

a. Sodium Silicate

(i) Initial minimum viscosity of grout which can produce gel is by $\text{SiO}_2:\text{Na}_2\text{O}$ ratio of 3.9, having pH value 8.5 to 9.2 for a given dilution within ideal frame work of gel time. Rate of reaction (gel time) and gel strength are directly proportional to concentration of acidic or basic catalysts and silicates in grout at constant temperature respectively. Formamide helps increasing rigidity
compared to other precipitants.

(ii) Lower increase of viscosity of silicate-formamide during limiting injection and zero displacement compared to aluminate and phosphoric acid but higher viscosity at gel time are the characteristics features of time-viscosity relationship of silicate grouts. Limiting injection, zero displacement and gel time of aluminate are longer than phosphoric acid but shorter than formamide. It seems that formamide remains Newtonian for longer time for any stress range compared to other precipitants.

(iii) Rate of stress build up is rapid after limiting injection time which was nominal before. Grout with formamide precipitant produces highest stress build up at gel time and also higher order transformation from semi viscous to visco-elastic compared to other precipitants.

(iv) Amongst various precipitants formamide give more post gel strength for any progress of time. Silicate grouts remain elastic for low value of strain with comparative lower E-value exhibiting mainly elasto-plastic deformation.

A randomly dispersed silica microgel in the liquid grout fill the vacant lattice by further nucleation, cross linking and developing primary valance bonds of cured coils of length 4.35 micro meters nearer to gel times explain time-viscosity development of silicate grout. The additional saponification process required by formamide to precipitate gel with formation of additional C = 0 bonding without intrinsic water help lengthening gel time and increasing visco-elasticity having more gel and set strength with no syneresis.
b. Urea Formaldehyde

(i) Molar ratio of 1:1 (urea:formaldehyde) help minimizing initial viscosity of the grout and produce gel when the mix has pH value 3.5 to 4.5 within ideal frame work at constant temperature. Acid concentration in the grout controls the gellification time, while gel strength is directly depend on resin concentration. The additional urea improves both gel time and gel strength, while sodium aluminate and melamine improve the strength but lengthen the gel time. Amongst various acid catalysts oxalic acid is more effective in producing strong gel by chelate complexes.

(ii) The urea formaldehyde grout system transforms non-Newtonian semiviscous earlier than silicate grout system showing more viscosity at any time. Though oxalic acid develops low viscosity at earlier stages compared to other acid catalysts, exhibits high viscosity at gel time. More increase of viscosity at limiting injection, zero displacement and gel time is characteristic feature of urea admixture compared to aluminate and melamine for same acid catalyst.

(iii) Urea formaldehyde system with oxalic acid catalyst along with urea and melamine admixtures develop maximum stress build up with higher rate of acquirement of visco-elasticity at gel time compared to other acid catalysts with sodium aluminate.

(iv) Set strength of urea formaldehyde system with oxalic acid along with urea and melamine show higher long term strength compared to aluminate. E-value and failure axial strain increase with increase of curing time. Gel mass remain elastic up to 2 per cent axial strain thereafter transforms to elasto-plastic leading to failure.
In condensation and hydrolysis of mono, di, or tetra methylol urea forms methylene linkages increasing the density of hexagonal polymer coil having arm length 2.5 micro meter. With increase of molecular concentration, loosing freedom of flow in stepwise manner showing increase in viscosity and visco-elasticity after limiting injection time. Hexamethylol and tetramethylol derivatives of melamine and urea can produce higher coil density leading to more long term strength compared to other admixture.

c. Resorcinol Formaldehyde Grout

(i) Resorcinol formaldehyde grout system needs resorcinol to formaldehyde ratio 1:1 and pH 1.7 to 2 and 8 to 10 for acid and base catalysts respectively for producing rigid gel having gel time within ideal frame work at constant temperature. Concentrations of acid or base in a given resorcinol formaldehyde system increases or decreases the gel time. Strength of raw gel is controlled by resorcinol content. Base catalyst produce comparative rigid gel than acid catalyst.

(ii) Resorcinol formaldehyde system remains Newtonian for longer time compare to silicate and urea formaldehyde grouts. The rapid transition from Newtonian to non-Newtonian (semiviscous) and finally to high viscous with little distinction between zero displacement and gel time is the characteristic feature of time-viscosity relationship of resorcinol formaldehyde grout. The abrupt transition from sol to gel without semiviscous stage is the idealized characteristic for base catalyst.

(iii) Minimum, moderate and maximum stress build up at limiting injection, zero displacement and gel time of resorcinol formaldehyde grout system is recognised. Moderate stage remains absent for resorcinol formaldehyde
base catalyst system. Variation of rheological time factor exhibits transformation of semi-viscous mass to visco-elastic before gelification showing elastic dominance at gel time.

(iv) The set mass remain elastic for a longer strain showing linear delayed elasticity with non linear time dependent elasto-plasticity compared to silicates and urea formaldehyde grouts. In acid catalyst E-value is time independent.

The sudden filling of vacant lattice sites by polymerised spherocolloid molecules of average diameter of 4 micro meter and volume of 1.99 cubic micro meter help explains the characteristic time-viscosity curve. Predominancy of methylene bridges in base catalyst system help evolving more strength and rapid visco-elasticity compared to acid catalyst system.

d. Polyurethane

(i) The molar ratio 1:0.75 of Polyol to tolune-di-isocynate can produce a flexible gel with pH value of 9.4 to achieve a gel time within ideal frame work in quasi prepolymer system. Increase of polyol : tolune diisocynate ratios in the same dilution increase the initial viscosity, decrease the gel time and gel strength. Initial viscosity is higher among silicates, urea formaldehyde and resorcinol formaldehyde grout systems.

(ii) The gradual but high magnitude of viscosity at limiting injection, zero displacement and gel time are the prominent features of time-viscosity relationship. The degree of non-Newtonian behaviour at any time is comparatively more than silicates, urea formaldehyde and resorcinol formaldehyde systems for any stress range.
(iii) Higher visco-elasticity and stress build up are the primary properties of this grout system after limiting injection time compared to other grouts.

(iv) A long duration elastic deformation with increase of compressive or tensile strength reaching to about same peak value at higher rate of strain leading to elastic bulge failure is the typical stress-strain behaviour of this system.

The gradual polymerization with microbubble formation involving nucleation combined with polymerization tends to increase viscosity gradually. The flexibility of the gel is attributed to linking of chain unit with oxygen atom instead carbon atom. The increase in chain length of polymer matrix with progress of time introduces viscoelasticity and sets in configurational elasticity at gel time. The long duration strain softening of elastomer characteristic is due to high degree of internal mobility allowing elements of chain to slip past one another during deformation.

e. Epoxy Resin

(i) Bisphenol-A and epichlorohydrin in 1:1 molar ratio is suited to get desired rate of reaction and minimum viscosity along with controlled heat of reaction. As the ratio of resin to hardner increases, the pot life (gel time) increases for a given constant dilution. The influence of water is limited in reducing heat of reaction and to make grout pumpable owing to highest initial viscosity compared to silicate, urea formaldehyde, resorcinol formaldehyde and polyurethane systems.

(ii) High initial viscosity with only two stages of gellification, viz., liquid and gel stage with no
The higher initial viscosity is attributed to formation of primary microgels of 0.5 micro meter to 1 micro meter which grow secondary microgel interacting each other before the inset of physical gelation immediately after mixing. At critical concentration secondary microgel (10 micro meter) pack together abruptly forming gel mass having high cross linked density explains typical time-viscosity curve. The configurational elasticity gain by high chain length overshadows the viscous flow instantly. Strong methylene and phenyl linkages help giving high compressive strength.

In brief time-viscosity relationship of Newtonian chemical grout reveal that initially watery Newtonian liquid transforms to non-Newtonian semi viscous, which tends to increase viscosity and to some extent rigidity comparatively quick exhibiting less distinct transition between zero displacement and gel time. Nucleation and cross linking of chain unit of coils increasing density and molecular concentration loosing freedom of flow in a stepwise manner showing increase in viscosity and formation of primary and secondary valance linkages exhibit acquirement of visco elasticity and rigidity after limiting injection time. Time dependent linear elastic for silicates and aminoplast
while time independent linear elastic for phenoplast and urethane, and further time dependent nonlinear elastoplastic for all leading to failure of set mass seem to be the stress-strain behaviour.

III. Flow and Strength Interaction

A. Flow Interaction

The flow mechanism of particulate Binghamian grout in sand seems to be different from those of Newtonian chemical grouts.

(i) Consistent injection pressure seems to be essential to overcome characteristic initial yield value of Binghamian grouts for maintaining uniform flow during grouting.

(ii) It seems from the time-viscosity relationship of Binghamian grout that injection should be done before the limiting injection of grout to avoid blockage and achieving desired radius of penetration. In case of Newtonian-grout the lapse of limiting injection time may cause pendular film of set grout only at contact points leaving void spaces blank, as grout can not ingress in it due to high viscosity after limiting injection time, showing some strength but no permeability reduction.

(iii) Gel time is the most important in limiting hapazard flow of a grout through a sand sample. Use of little short gel time may limit dilution in saturated sand. In Binghamian grouts in addition to above, high water retentivity improve cohesiveness and prevent screening effect.

(iv) For achieving uniform grouted mass while injecting from top to bottom or vice a versa the optimum
stage length may be maintained.

Knowledge of time-viscosity relationship helps keep grout in its zone of placement and tends to promote uniformity of penetration.

B. Strength Interaction

a. Binghamian cement-bentonite grout

A grouted sand with grout having bentonite : cement : water (1 : 0.25 : 10) with admixture of sodium silicate to mono sodium phosphate in equal part give adherent strength of 0.9 kg/cm$^2$ and show permeability reduction of 200 times.

b. Newtonian grouts

(i) Stress-strain-time relationship of silicate, urea formaldehyde, resorcinol formaldehyde and polyurethane grouted sand is strongly time dependent.

(ii) For evaluation of deformation of grouted sand two categories of deformation are identified: mainly time dependent linear elastic, and time dependent elastoplastic leading to failure.

(iii) Resorcinol formaldehyde grouted sample show highest unconfined peak strength compared to silicates, urea formaldehyde and flexible urethane systems, while cohesion imparted to sand samples after aging period of 7 days show in the range of 1 to 1.5 kg/cm$^2$ with negligible change in frictional angle.

(iv) In urethane grouted sand failure axial strain remains more or less same for any time of curing at any confining stress unlike silicates, urea formaldehyde and resorcinol formaldehyde grouted sand.
Average adherent strength exhibited by Newtonian grouts are in the range of 1.45 kg/cm\(^2\) to 2.4 kg/cm\(^2\) with permeability reduction in the range of 125 to 200 times.

The additional linking sites provided by C = 0 bond along with high durability of silica grouted mass, methylene linkages with chelate complex produced by oxalic acid in urea formaldehyde grout, and an encapsulation of sand grain by spherocolloid of resorcinol formaldehyde with similar primary valance methylene linkage in resorcinol formaldehyde grouted mass, and elongated elastomer urethane foam accumulated in urethane grouted mass help enhance and evolve the interacting bond at contact points and within the fully occupied voids, which give the time dependant strength of the grouted mass.