BERGINJEKTERING I TUNNLAR I SVÅRA HYDROGEOLOGISKA BERGFÖRHÅLLANDEN
Rock grouting for tunnels in difficult hydrogeological conditions

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Sammanfattning
Användning av kemiska och polymera injekteringsbruk började på allvar femtio år sedan med hjälp av endast ett fåtal typer; silikater, akrylamider, epoxi, vissa fettsyror derivat och på slutet polyuretan och urea-silikat hartser. Sedan dess har vissa typer av injekteringsbruk frodats med några av originalen kvar, andra släpps helt, och ytterligare andra i typ förändras. Vatten reaktiva polyuretan hartser infördes i injekteringsbranchen under de sena nitton sextiotalet av företaget Takenaka i Japan under varumärket TACSS. Det blev möjligt att injektera så kallade "enkomponent" medel som var resistent mot bortspolning och reagerade med grundvatten. Med hänsyn till resultat av miljögranskningar, den första serien av TACCS ersattes av lösningsmedelsfria, hydrofoba, MDI baserade polyuretan pre polymerer. Samtidigt som anmärkningsvärda framgångar nåtts i gruvindustrin och geotekniska projekt, sedan dess används mer och mer dessa produkter för permanent läckage kontroll som tätning av betongkonstruktioner och jorddammar.
Sedan 1980 ersätts mer och mer klassiska injekteringsmedel som natrium/natriumsilikat och cementbaserade bruk med polyuretan hartser (PUR) p.g.a. framgångar i att stoppa stora läckor i tunnlar; tätningar med akrylamiderna begränsades p.g.a. praktiska och miljömässiga överväganden. Av mitten på 1980-talet utvecklades flera nya och förbättrade hydrofoba vatten reaktiva polyuretaner; tillverkarna skapat produkter med slutna celler. Vatten reaktiva hydrofila polyuretaner kom under noggrann kontroll med hänsyn till dess livslängd. Den klassiska tvåkomponent polyuretan och urea-silikat hartser (OMR skum), använda i gruvindustri infördes successivt i geoteknik för permanent läckage kontroll i betongkonstruktioner samt tätning och förstärkning (konsolidering) av berg.
Detta föredrag handlar om den allmänna användningen av polyuretan och urea-silikat hartser som injekteringsbruk för byggande av bergtunnlar, och presenterar en kort diskussion där specifika produkter inom en kategori kan användas. Jämförelser kommer att relateras till injekteringsbruk förmåga att penetrera jordar och sprickor i berg och konkreta och rekommenderade omständigheter att överväga där polyuretan harts bör tillämpas istället för traditionella cementbaserade bruk.

Abstract
Chemical and polymeric grout use began seriously some fifty years ago with the use of only a few types; silicates, acrylamides, epoxy, some fatty acid derivates and on the end polyurethane and urea-silicate resins. Since then, the kinds of grout have proliferated with some of the originals still there, others dropping out entirely, and still others changing in type. Water-reactive polyurethane resins were introduced into the grouting industry

during the late nineteen sixties by the Takenaka company in Japan under the trade name TACSS. It became possible to inject "one component" grout which was resistant against easily wash-out and reacted with the groundwater. Because of environmental scrutiny, the first series of TACCS were replaced by solvent-free, hydrophobic, MDI based polyurethane pre polymers. Whilst remarkable successes were booked in mining and geotechnical engineering projects, more and more these products were used for permanent seepage control for sealing concrete structures and earth dams.
In 1980 replaced more and more classic grouting materials like natrium/sodium silicate and cementitious grouts by polyurethane resins (PUR) thanks the successes in stopping major leaks in tunnels; seepage control grouting using acrylamides restricted because of practical and environmental considerations. By the mid-eighties several new and improved hydrophobic water-reactive urethanes were developed; manufacturers created products with closed cells. Water-reactive hydrophilic polyurethanes came under close scrutiny because of longevity problems. The classic so-called two-component polyurethane and urea-silicate resins (OMR foams), used in mining were gradually introduced in geotechnical engineering for permanent seepage control, in concrete structures and for rock sealing and strengthening (consolidation).
This paper is about the general uses of polyurethane and urea-silicate resins as grouts for rock tunnelling, and presents short a discussion of where specific products within a category can be used. Comparisons will be related to the ability of the grout to penetrate soils and cracks in rock and concrete, and specific and recommended circumstances to consider where polyurethane resins should be applied instead of traditional cementitious grouts.

1.0 General information about polyurethane grouts

Polyurethane grouts (resins) are probably the most popular type of solution grouts today replacing natrium/sodium silicates. The term “solution grouts” pertains to grouts that behave like Newtonian fluids. Contrary to suspensions grouts, which behave like Binghamian fluids, solution grouts do not contain particles. Solution grouts are injectable into very fine apertures, not accessible to (even microfine) suspension grouts.
A so-called true solution grout is characterized by a flat viscosity curve, followed by a sudden increase in viscosity, immediately prior to gelation or curing. Acrylamides, acrylates and most polyurethane based grouts are typical examples of true solution grouts. Applied for grouting in soil and rock water-reactive polyurethanes have one thing in common: they react with the in-situ available (ground) water to create a foam or gel that is either hydrophobic or hydrophilic.
Water reactive polyurethane resins are classified into two sub-categories:

a) Hydrophobic polyurethane resins; they react with water but repel it after the final (cured) product has been formed (Hydrophobic: Latin (hydro) = water and (phobic) = fear),
b) Hydrophilic polyurethane resins react with water but continue to physically absorb it after the chemical reaction has been completed (Hydrophilic: Latin (hydro) = water and (philic) = affinity).

1.1 One (single) component polyurethane resins (PUR)

1-component system consists of the main component in the form of MDI or TDI polyisocyanates pre-polymer with high polymerization grade. To finalize the polymerization only the catalyst is needed. The delivery tank (the little bucket) attached to the membrane pump is filled with the main component. The percentage (2÷5%) of catalyst added straight to the main component and mixed there with a simple handle regulates the gelling time (therefore catalyst is commonly wrongly named as accelerator). In water-reactive polyurethanes isocyanate groups of 1-component polyurethane pre polymer immediately reacts with hydroxy groups from water in the presence of a catalyst so that the molecules link up to form a macromolecular chain (note **Fig. 1**).

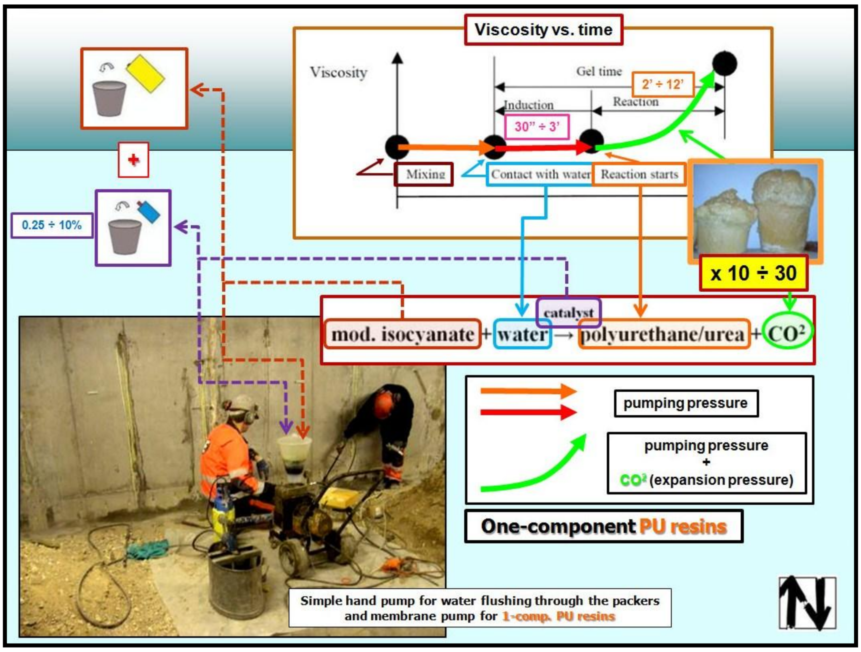


Fig. 1-komponent polyuretanhartset system

***Fig. O**ne-component (single component) polyurethane resin system*

Simply these products react with the in-situ water and expand during the exothermic chemical reaction. The following relates entirely to resins, which contain MDI isocyanate as reaction components. The isocyanate groups, of which every MDI molecule has at least two, react with water under the release of carbon dioxide CO^2. The reaction time can typically be adjusted between ca 45 seconds up to few minutes by adding a tertiary amine-based catalyst. More catalyst only speeds up the gelation process. Surfactants are added to the resin to prevent collapse of the foam and to create small uniform cells.
The setting is simply the result of the reaction with water (water-reactive polyurethane); 5÷6% water in relation to the resin is sufficient for the setting. During the exothermic reaction, polyurethanes expand and penetrate pervious media: fine cracks (as narrow as 0.05 mm) and soils (with a permeability coefficient as low as 10^{-5} m/s).
During grouting, the carbon dioxide, generated during the chemical reaction will generate additional pressure, as the grout flows through the cracks and pore channels, pushing the grout into very fine cracks. The penetration is greatly enhanced by the formation of CO^2, independent from the grouting pressure; from here is coming the name: “active” grouts.
1-component PU resins are available on the market nowadays both hydrophobic and

hydrophilic. These resins as reacted are semi-elastic or semi-rigid.

1.2 Moderate and slow reacting two (dual) component polyurethane resins

Most of the 2-component resins (grouts) almost don't need water to start the reaction and they are hydrophobic. Without water the resins will not foam but form strong and rigid structure. With water the resultant foam has a structure with visually bubbles (**Fig. 2**).

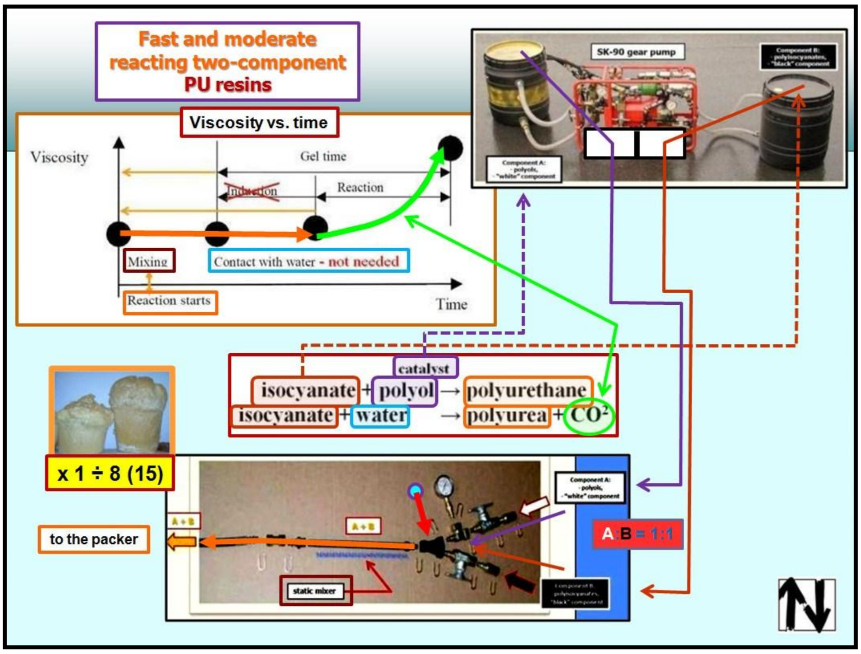
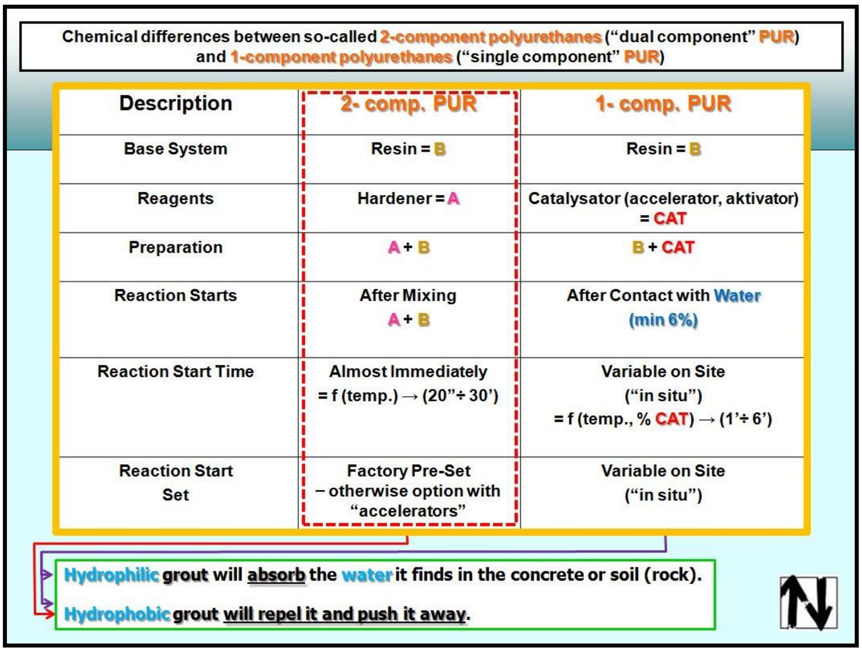


Fig. 2 2-komponent polyuretanhartset system

Fig. 2 *Two-component (dual component) polyurethane resin system*

2-component system consists of separately delivered components to the piston or gear pump (indeed two pistons or two gears with speed coordinated only). The main component is a "blend" of monomers, isomers, co-polymers and MDI or TDI polyisocyanates in the form of pre-polymer with low polymerization grade.
The second component is a mixture of polyols with other additives like catalysts, plasticizers, stabilizers, diluters and surfactants. Both components in proportion 1:1 meet first passing the pump's pistons or gears in so-called static mixer pushed through a mixing tool and are jointed with each other in a long common delivery hose (15÷25 m) to approach the packer inserted deeply with extension (feed) pipe into the drill hole in the rock. 2-component PUR is formatted by reaction of isocyanate with a polyol containing hydroxy groups in the presence of a catalyst. The formulation of a finally proper mixed grout (resin) ensures requirements like start of foaming, reaction and hardening time, final strength, modulus of elasticity and foaming factor. To make the reaction (gelling) time shorter, accelerators or water added to the polyols are the options.
2-component PU resins have higher viscosity comparing with 1-component PUR and when hardened a rather high strength. They are suitable for sealing dry and damp cracks in rock and concrete structures including shotcrete and concrete element linings as well as cracks dripping with water. These resins are relatively hard and semi-rigid. Main differences between 1-component and 2-component PU resins are presented in **Fig. 3**.



Chemical differences between so-called 2-component polyurethanes ("dual component" PUR) and 1-component polyurethanes ("single component" PUR)

Description	2- comp. PUR	1- comp. PUR
Base System	Resin = B	Resin = B
Reagents	Hardener = A	Catalysator (accelerator, aktivator) = CAT
Preparation	A + B	B + CAT
Reaction Starts	After Mixing A + B	After Contact with Water (min 6%)
Reaction Start Time	Almost Immediately = f (temp.) → (20"÷ 30')	Variable on Site ("in situ") = f (temp., % CAT) → (1'÷ 6')
Reaction Start Set	Factory Pre-Set – otherwise option with "accelerators"	Variable on Site ("in situ")

Hydrophilic grout will absorb the water it finds in the concrete or soil (rock).
Hydrophobic grout will repel it and push it away.

Fig. 3 Skillnader mellan 1-komponent och 2-komponent polyuretanhartssystem

***Fig. 3** Differences between 1-component and 2-component polyurethane resin systems*

1.3 Fast setting two-component urea-silicate hybrid foams (Organo-Mineral-Resins) OMR

In the case of very high water flow velocity like more than 10 cm/s 2-component PUR systems with accelerators can be applied. The alternative is so-called 2-component urea-

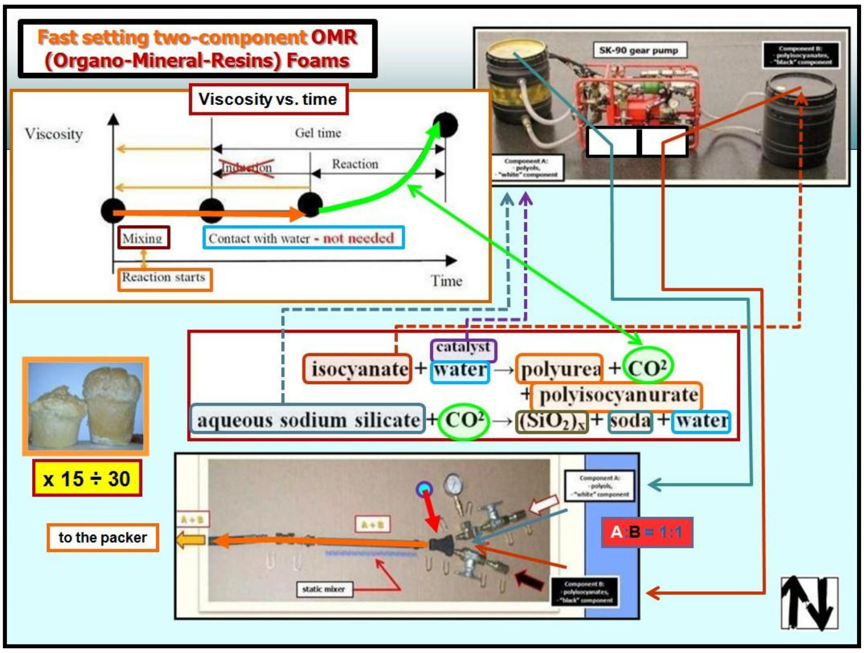


Fig. 4 Snabb reagerande och skummande urea-silikat hybrid harts system

***Fig. 4** Fast setting, strongly foaming 2-component urea-silicate hybrid resin system*

silicate resins (organo-minerals foams OMR). Instead of polyols reacting with isocyanates, watery solutions of sodium silicate (silicate-isocyanate-resins) are applied (**Fig. 4**). These resins are foaming at least 25 times (x 25) or even more and they are excellent for back-filling of wide gaps and large caverns in rock.
These resins, however, while hardened are relatively brittle (“crispy”). To ensure that this sealing remains functional, the re-grouting might be needed with “normal” PUR. The grouting systems (pumps, delivery hoses, accessories and packers) are the same like for 2-component PU resins. The reaction time (start of foaming) of PUR and OMR components are very short, comparing with other grouts, like for example cement based. PUR and OMR are liquids only seconds or minutes. In addition 2-component hydrophobic resins in fact don’t need water to start reaction, like 1-component PU resins absolutely need.

2.0 Comparison between behaviour of PUR (OMR) and other grouts

2.1 Penetration ability of different grouts in rock, cracked concrete and soils

For penetration ability of cementitious, chemical and polymeric grouts please note **Fig. 5**. Classic permeation grouting in soils is possible for PUR and OMR even in fine sands and silts; the last soil type is not available for ultra fine cements (UFC) but by fracturing only.

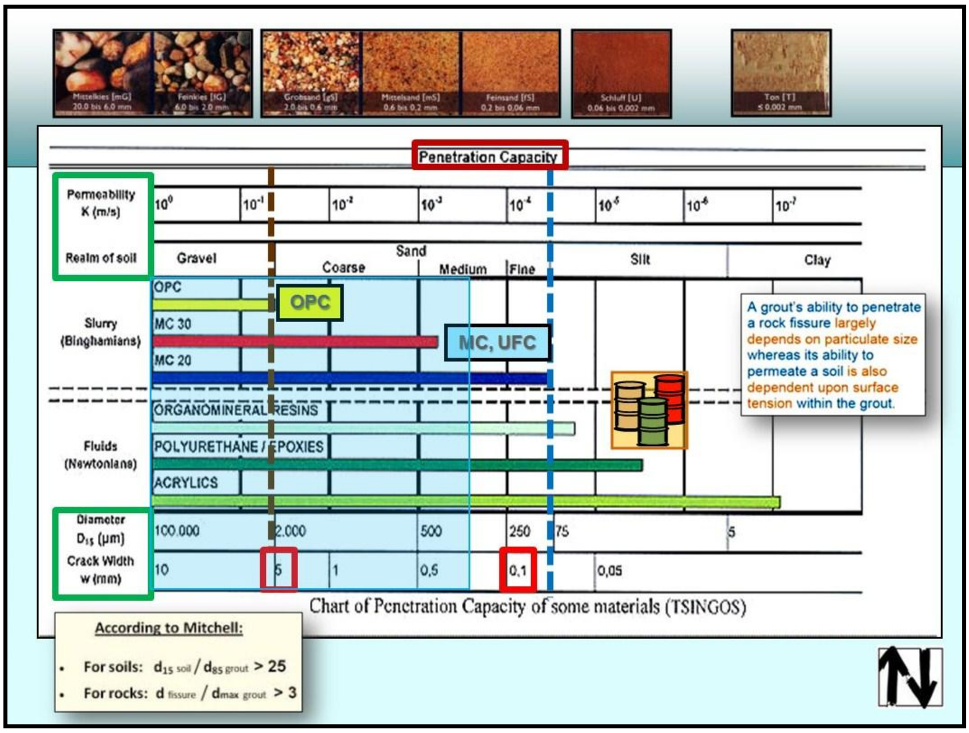


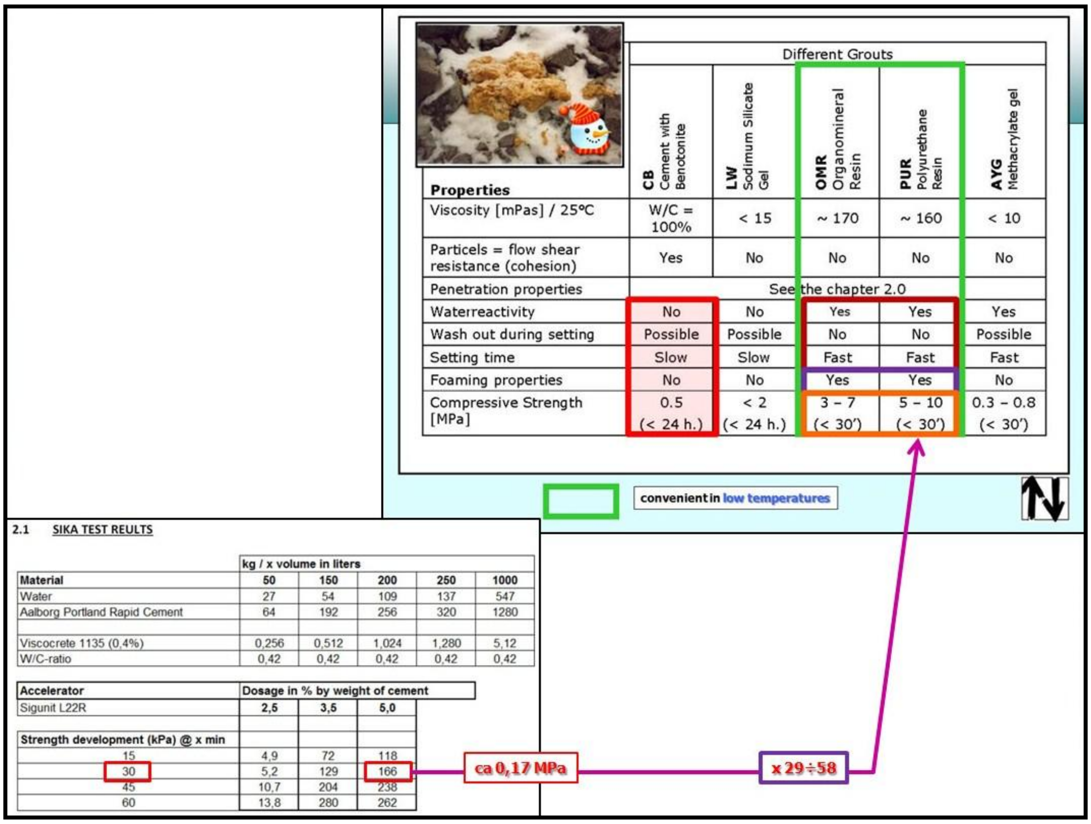
Fig. 5 Penetrationsförmåga av cementbaserade bruk och kemiska (polimeriska) injekteringsmedel

***Fig. 5** Penetration ability of cementitious and chemical (polymeric) grouts*

Classic penetration grouting in rock and concrete (without causing fracturing) can be described by certain minimal crack width but with assumption that pumping rate will not exceed grout-take of crack system. In author’s almost 42 years praxis in grouting, regarding ability of Ordinary Portland cement and other types with higher Blaine like 4÷6 x 1000 cm^2/g (injection cements and MC) range of penetration is respectively 2÷5 mm and 0.1÷0.3 mm. Only ultra fine cements (UFC) can be comparable with PUR and OMR concerning penetration ability in cracked rock and concrete. According to author experiences minimum crack width for free water flow is ca 0.3 mm, for dripping 0.1 mm.

2.2 Resistance of different grouts against wash-out effect caused by groundwater

Fundamental parameters of cementitious suspensions, chemical solutions and polymeric grouts are presented as **Fig. 6**. Only PUR and OMR can manage huge leakages under high hydrostatic pressure thanks extremely short reaction time counting in seconds (minutes), foaming properties and water reactivity (needed for proper foaming).
Based on tests results in author's on-going project in Vadlaheidi tunnel on Iceland even impressive decrease of water/cement content of still pumpable cementitious grout to water/cement ratio = 0.30 and therefore high early strength increase obtained, still even improved grouts cannot compete with PUR and OMR in high groundwater flow conditions. To induce high early strength increase, tested optimal grouts have been based on usage of both accelerator and rapid cement type; these efforts didn't increase significant resistance against wash-out phenomenon.



Properties	CB Cement with Benotonite	LW Sodimum Silicate Gel	OMR Organomineral Resin	PUR Polyurethane Resin	AYG Methacrylate gel
Viscosity [mPas] / 25°C	W/C = 100%	< 15	~ 170	~ 160	< 10
Particels = flow shear resistance (cohesion)	Yes	No	No	No	No
Penetration properties	See the chapter 2.0				
Waterreactivity	No	No	Yes	Yes	Yes
Wash out during setting	Possible	Possible	No	No	Possible
Setting time	Slow	Slow	Fast	Fast	Fast
Foaming properties	No	No	Yes	Yes	No
Compressive Strength [MPa]	0.5 (< 24 h.)	< 2 (< 24 h.)	3 – 7 (< 30')	5 – 10 (< 30')	0.3 – 0.8 (< 30')

2.1 SIKA TEST REULTS

Material	kg / x volume in liters 50	150	200	250	1000
Water	27	54	109	137	547
Aalborg Portland Rapid Cement	64	192	256	320	1280
Viscocrete 1135 (0,4%)	0,256	0,512	1,024	1,280	5,12
W/C-ratio	0,42	0,42	0,42	0,42	0,42

Accelerator	Dosage in % by weight of cement		
Sigunit L22R	2,5	3,5	5,0
Strength development (kPa) @ x min			
15	4,9	72	118
30	5,2	129	166
45	10,7	204	238
60	13,8	280	262

Fig. 6 Grundläggande parametrar av cementbaserade suspensioner, kemiska lösningar och polymera injekteringsmedel

***Fig. 6** Fundamental parameters of cementitious suspensions, chemical solutions and polymeric grouts (OMR, PUR)*

In addition PU and OM resins resistance against wash-out phenomenon, especial in colder conditions, occurs thanks so-called “hockey-stick” reaction. An initially flat viscosity curve is followed by a sudden increase in viscosity, immediately prior to gelation or curing under polymerization and cross-linking stage within few minutes after appearance of such resins in rock mass crack system or other discontinuities. Cementitious grouts such ability are missing (while hardening due to prolonged in time scale hydratation process) – note **Fig. 7**. So-called critical velocity causing wash-out in the case of none water-reactive chemical solutions and cementitious grouts is estimated to approximately 15 mm/s to compare with ca few cm/s regarding PUR and ca 10÷20 cm/s for OMR in ambient temperature like +10 °C÷ +20 °C – note **Fig. 8**.

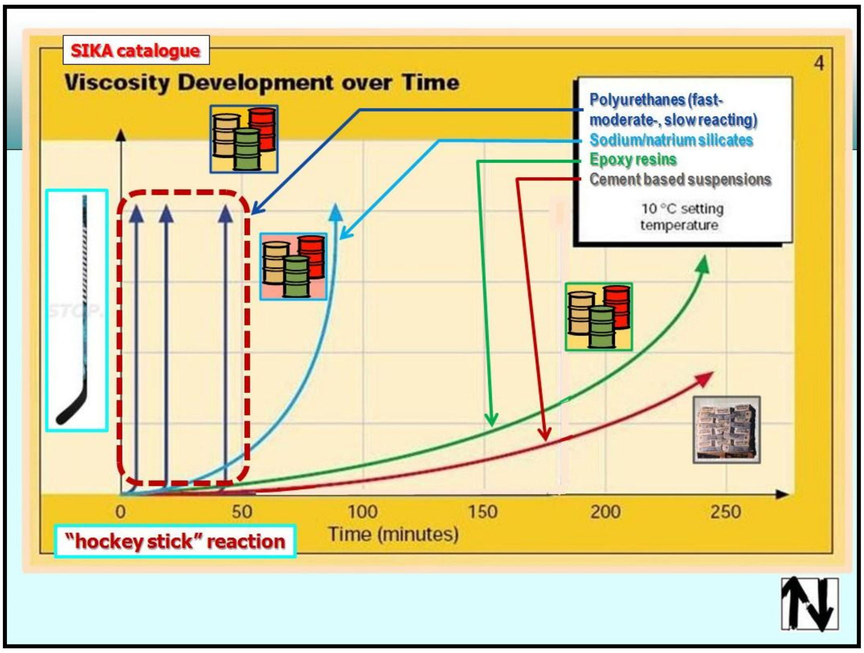


Fig. 7 Viskositet utveckling vs tid av cementbaserade suspensioner, kemiska lösningar och polymera injekteringsmedel

***Fig. 7** Viscosity development vs time of cementitious suspensions, chemical solutions and polymeric grouts*

2.3 Limited hardening of different grout in low rock and groundwater temperatures

One of the factors among others limiting usage of cementitious grouts in Nordic countries like Greenland and Iceland, are too low groundwater and rock temperatures almost never exceeded +5 °C – note **Fig. 9**. In 1993 in tunnel project on Ísafjörður/Iceland (road tunnel 9.2 km long) author started lab and in-situ tests with adding to mixes with extremely low water/cement content accelerators for hastening setting time like salts (NaCl, $CaCl^2$), natrium/sodium silicate and using ready-mix product from Rescon/Mapei containing sodium aluminate. Due to problems with hydratation of cement based grouts in other projects like Kárahnjúkar Hydropower Project (72 km of tunnelling) and Héðinsfjarðargöng (road tunnel 11 km long) several chemicals were tested used as antifreeze and fast-set additives and also alkali and alkali free shotcrete accelerators. All attempts including heating water for mixing or ballast had very limited practical effect to

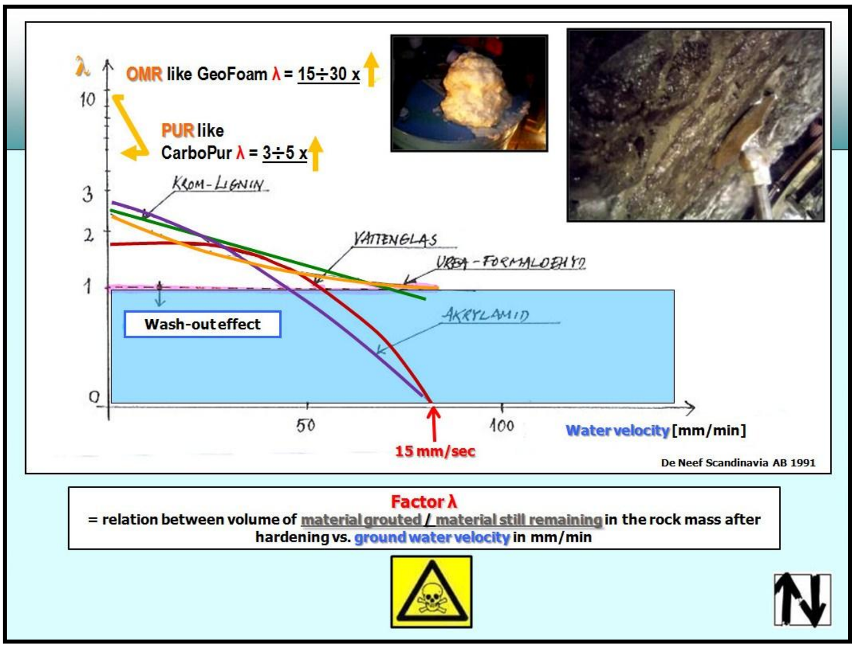


Fig. 8 Kritisk hastighet för bortspolning av cementbaserade suspensioner, kemiska lösningar och polymera injekteringsmedel

Fig. 8 Critical velocity causing wash-out effect in the case of cementitious suspensions, chemical solutions and polymeric grouts

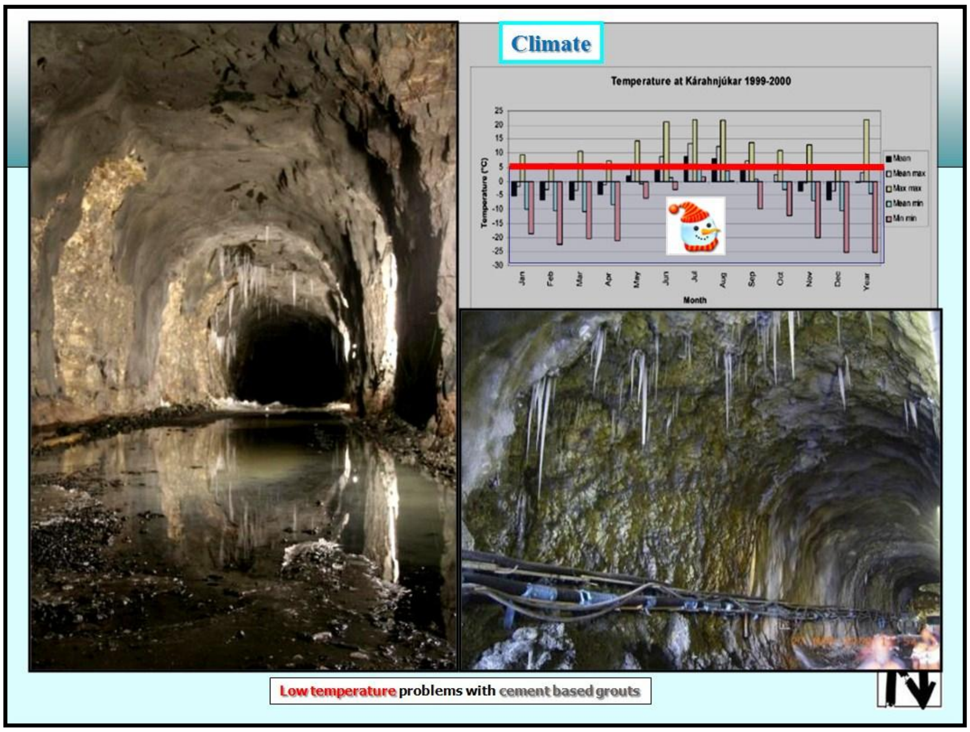


Fig. 9 Grundvatten och rock temperaturer i tunnlar i Kárahnjúkar

Fig. 9 *Groundwater and rock temperatures in tunnels of Kárahnjúkar*

speed up hydratation and to protect grouts against freezing; in the common case of high groundwater velocities usage of cementitious grouts had no any sense. On the contrary PUR and OMR could be used in grouting for crack sealing and rock mass consolidation in the cases of huge water inflows even in the temperatures like -5 °C ÷ -15 °C, but under assumption of course that discontinuities were free from icing.

3.0 Conclusions: recommended circumstances to use PU and OM resins
Based of author's 40 years experiences with different resins for injections in soil, rock and for concrete repairs, whereof since 1984 with PU resins and 1993 in tunnelling, please note 4 indicated in **Fig. 10** circumstances to consider PUR and OMR instead or as completion to traditional cementitious grouts.

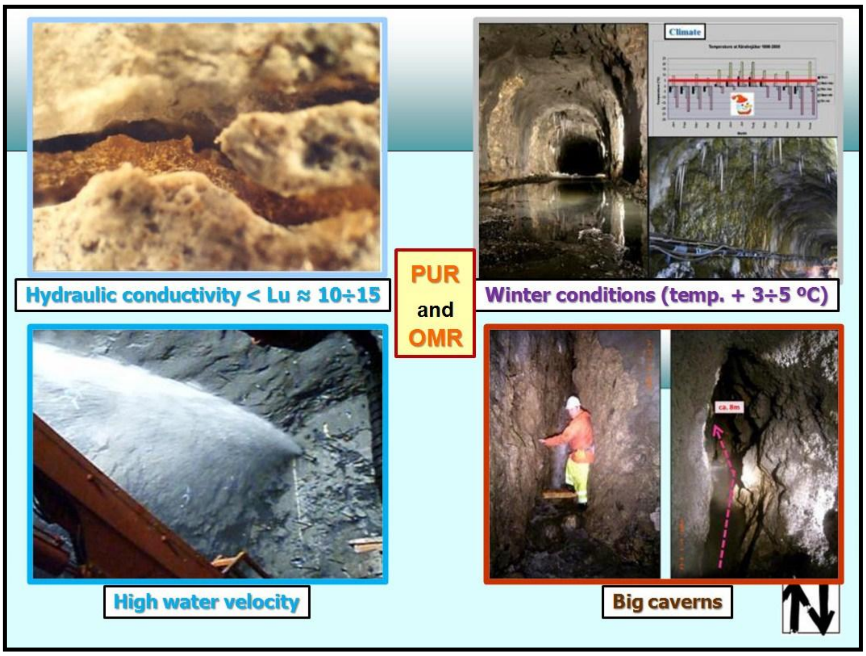


Fig. 10 Rekommenderade omständigheter för användning av PU och OM hartser för injektering i bergtunnlar

Fig. 10 *Recommended circumstances to use PU and OM resins for grouting in rock tunnels*

Polyurethane resins came to Sweden for commercial use in building industry in the beginning of eighties, mainly for sewer and concrete repairs. In the mid-eighties author successfully applied 1-component PU resins in restoring of sealing membranes in earth dams, for tie-backs, underpinning and sealing of sheet-pile walls. With later appearance of 2-component PUR and OMR author has started with usage of last mentioned in rock, among other in D&B and TBM tunnel engineering, unfortunately mainly abroad due to mental and bureaucratic reasons in Sweden. In general, polyurethane and urea-silicate resins should be applied in following cases (enclosed project list refers to tunnels directly consulted by the author, who in addition in most of them personally conducted grouting works):

a) **1-component PUR** in concrete repairs for sealing of cracks, construction and expansion joints. In tunnel engineering this kind of materials is convenient in repairs of concrete segmental lining elements (TBM tunnels like in Hallandsås,

extension of subway A-line in Prague/Czech Republic, The Great Melen Tunnel under Bosporus channel in Istanbul/Turkey), and repairs of shotcrete lining (Torsgatan Access Tunnel, Southern Link and Northern Link/Norrtulls Tunnel – all in Stockholm).
However is absolutely not recommended to use 1-component PUR to copy injections for concrete repairs, especial using small diameter (ø 10÷19 mm) short packers for grouting in rock. The same is not advised single sequential or single sequence rock grouting using 1-component PUR in combinations with cementitious suspensions or fly-ash.
Low viscosity 1-component PU resins are excellent for so-called grouting hoses mounted along construction and expansion joints or soil grouting in earth dams.

b) **2-component PUR** in forming of pre grouting fans (umbrellas) in D&B tunnels, alone or in combination with cementitious grouts but never injected in the same drill holes; suitable both in cold and hot temperatures (Hallandsås, Torsgatan Access Tunnel, Ísafjörður, Kárahnjúkar, Héðinsfjarðargöng and Vaðlaheiðargöng – last four listed in Iceland. This kind of materials is useful for annulus grouting, proof grouting and forming of cut-off membranes in TBM tunnels (The Great Melen Tunnel in Istanbul/Turkey). 2-component resins are as well convenient as alternative to 1-component resins in repairs of concrete segmental lining elements but indirectly at extrados (extension of subway A-line in Prague/Czech Republic), and repairs of shotcrete lining (Southern Link, Northern Link/Norrtulls Tunnel and subway tunnels at Red Line in Stockholm).

c) **OMR (urea-silicate foams)** are most of all useful, thanks strong foaming, in filling of large caverns, but not dry (such must be previously and with the plan moisten before starting grouting (Ísafjörður, Kárahnjúkar, Héðinsfjarðargöng and Vaðlaheiðargöng). Thanks extremely short reaction time and foaming urea-silicate resins might be as alternative 2-component PUR for sealing of huge leakages of groundwater under high pressure causing high water velocity, but not in extremely hot conditions like > ca +45 °C ÷ +50 °C.

Concerning unfortunately often repeated by contractors and consultants in Sweden mistake of usage 1-component PUR in rock grouting for tunneling please find **Fig. 11** with further explanations mentioned there. In addition this none professional approach is used as argument against polyurethane resins as such, as not reacting properly or at all, or as argument against expensive and poisoning material ("Hallandsås syndrome") having negligible penetration in rock. Explanation of this "mystery" of bad reactivity of to be exact 1-component PUR only is known, at least since 1986 and called as "soda water phenomenon" – note **Fig. 12**. Namely in the case of 1-component resin, where water existence is absolutely needed to initiate reaction (in contrary to 2-component resins and OMR) and if in addition, 1-comp. PUR of hydrophobic type is pushing away water in narrow cracks and fissures, resin and water are not exposed for turbulent flow and mixing entirely or at all with each other does not occur. Experiences from grouting practice show in addition that even if 1-component resin is entirely mixed with groundwater but "encapsulated" in crack or cavern under pumping pressure not released under long time (where as well CO^2 cannot be released from the mix either), resin of this type might be dormant plenty of months – note **Fig. 12**. Enclosed pictures there show previously injected silica sol (gel) and "old" unreacted (after almost 1 year after grouting performed)

1-component resin, wash-out through remained not plugged old boreholes by relatively low pressure (ca 6 bars) of water/air flush during drilling of next additional holes for grouting. By the way, this time 2-component PUR was successfully used.

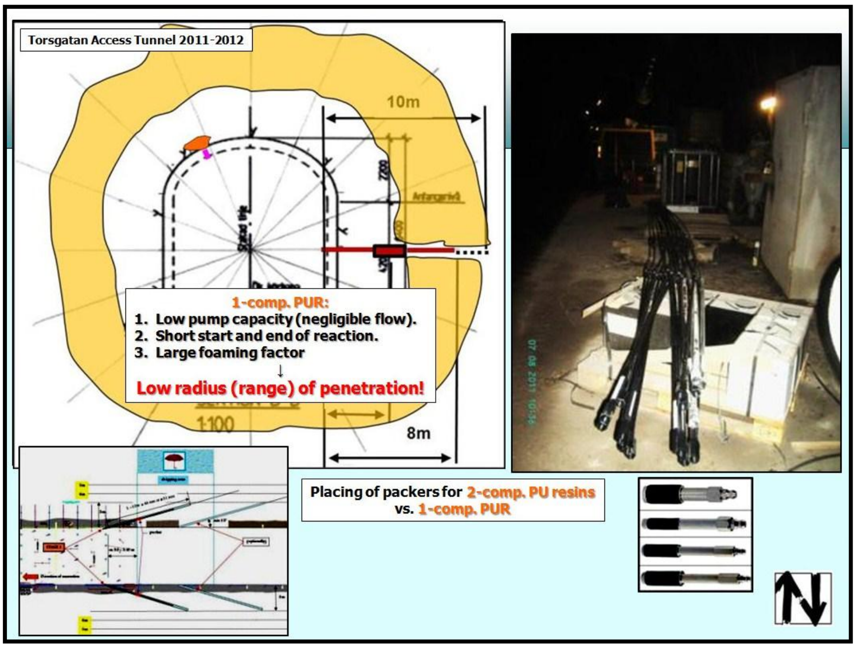


Fig. 11 Ej rekommenderad användning av 1-komponent PU harts för injektering i bergtunnlar

Fig. 11 *Not recommended usage of 1-component PU resins for grouting in rock tunnels*

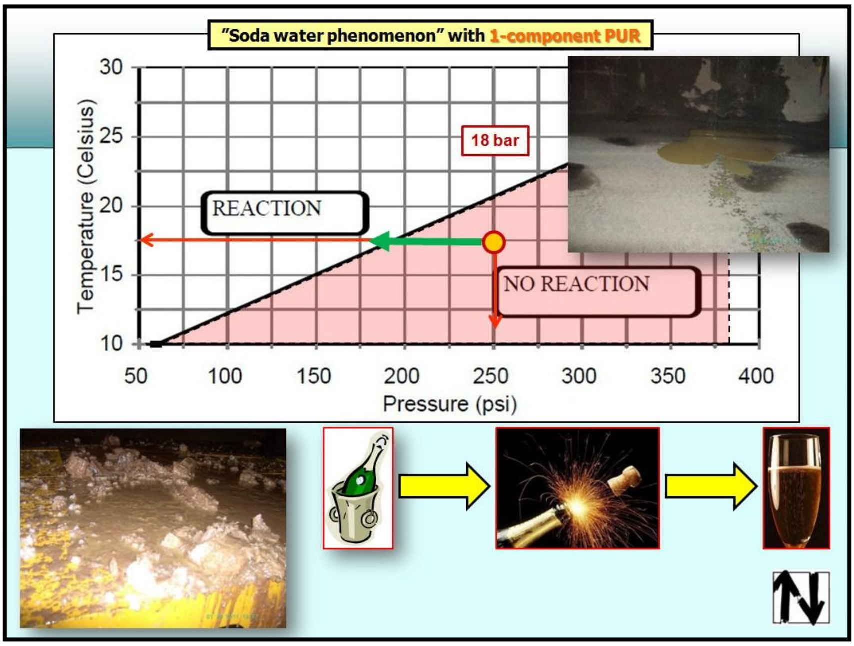


Fig. 12 Begränsning i reaktivitet av 1-komponent PU hartser under injektering i bergtunnlar

Fig. 12 *Limitation in reactivity of 1-component PU resins under grouting in rock tunnels*

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