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Polyurethane Grouting Technologies

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1. Introduction

Grouting with polyurethane [PU] resins represents an effective method of improvement of mechanical and sealing properties of soil and rock environment and constructions. The principle of grouting technologies is injection of liquid grouting material into the rock environment or construction under pressure. During the grouting process, fissures and pores are filled with the grouting material, which subsequently hardens and connects the disintegrated parts of the rock mass or grains of loose material. Polyurethane grouting technologies started to be used in the 80s of the 20th century in the mining industry. In the last recent years, PU grouting technologies spread significantly from the mining applications to civil engineering and geotechnics. The application possibilities have a rising tendency and new possibilities occur. Currently, grouting technologies are used mainly in the following fields:

- **Underground constructions, tunneling**
 - filling of caverns and voids
 - protection when crossing fault zones
 - stabilization of loose material in the foreland of excavation
 - securing of excavation during tunnel construction
 - preventive improvement of mechanical properties of the rock mass in the line of the workings
 - sealing and stopping of water inflows into the construction
 - anchoring of soil and rocks
 - strengthening and stabilization of overburden and etc.
- **Mining**
 - strengthening and stabilization of deposit layers before exploitation
 - crossing of fault zones
 - securing of the overburden
 - stabilization of the surrounding of the mine workings
 - lowering of permeability of the rock mass

- strengthening of coal in areas with rock burst risk
- limitation of the mine wind blowing
- anchoring of soil and rocks
- stabilization and sealing of old mine pits and etc.
- **Geotechnical works**
 - stabilization of slopes, embankments, excavations
 - anchoring of retaining walls
 - construction of underground barriers with low permeability
 - stabilization of unconsolidated soil
 - sealing of dilatation joints
 - micropiling of foundations
 - stabilization of landslides
- **Civil engineering**
 - strengthening of subsoil (also under groundwater level)
 - securing of stability of structures threatened by mining or construction works
 - strengthening of brick or stone masonry
 - restoration of insulation of structures
 - sealing of utility entries into constructions
 - sealing of joints
 - stopping of water inflows into constructions and etc.
- **Foundation of buildings**
 - sealing and anchoring of bottoms and walls of construction pits under groundwater table
 - anchoring of walls of construction pits
 - improvement of subsoil conditions before starting of the construction
 - micropiling in soil with low bearing capacity
 - foundation of buildings in undermined areas
- **Water management works**
 - sealing of joints on dams
 - anchoring and sealing of flood dams, anchoring of bottom of water canals
 - anchoring and strengthening of embankments
 - repair of concrete structures under water
 - limitation of underflowing of dams
- **Bridges and roads**
 - strengthening and sealing of brick and stone masonry on bridges
 - repair of cracks in the constructions
 - improvement of subsoil parameters under pillars (also in rivers)
 - anchoring and micropiling of foundations

This chapter contains brief description of PU grouting technologies and characteristics of basic grouting material types. It further presents practical findings of the authors obtained throughout their long term experimental research, design work and application of PU

grouting technologies. The findings are based also on development of PU grouting systems Geopur, Geocream and Supermin from the production of company GME, s.r.o.

2. PU grouting resin types

PU grouting materials can be divided according to their chemistry to three main groups:

1. two-component (PU) organic resins:

component A – polyol in mixture (polyetherpolyol, catalysts, additives),

component B – isocyanates in mixture (methylene diphenyl diisocyanate [MDI], homologes, isomeres).

After curing they form solid PU resins or foam.

2. one-component organic resins:

react with moisture present in the environment or construction and form an organic resin (material is on the basis of prepolymer MDI)

3. two-component organic-mineral resin (OMR):

component A – polysiliceous acid (natrium water glass, catalyst and additives),

component B - isocyanates (MDI, homologes and isomeres).

The main difference between the above materials is, that **material on the basis of polyol – isocyanate react with moisture present in the environment**, while material on the basis of polysiliceous acid – isocyanate are inert to moisture or water.

In case of OMR material, the mixing of the components plays an important role in the grouting process. The component A is inorganic - formed by water glass and additives. It is very different form the component B, which is of organic character on the basis of MDI. During mixing the water glass disintegrates to small drops in the organic phase of MDI and an inhomogeneous system is formed. Two different components A and B are in contact with each other only at the surface of individual drops. Chemical reaction proceeds better, the smaller the drops of component A are (the contact of the components is more intense). The reaction can be influenced also by additives, which lower the surface tension of water glass (e.g. silicones). The best results are achieved when mixing by ultrasound. Formed product of hardening process is a resin with solid closed pores of polysilicious acid gel.

In case of PU material, the intensity of mixing does not have fundamental impact to the reaction proceeding. A homogenous solution is formed by the mixing, which cures quite well.

The hardening process, following the mixing and injection of the PU mixture into the rock mass, takes from several minutes up to few hours, according to the type of used grouting resin. Currently, a wide variety of PU grouting materials of various producers exist on the market. Physical and mechanical properties of individual systems differ and it is often quite difficult to choose the appropriate system for particular application. In table 1 we present for example technical data of universal PU grouting system Geopur® (Bodi, 2003), produced and used since 1994.

Type	Geopur® 082/1000		Geopur® 082/600		Geopur® 082/350		Geopur® 082/290	
Component	A	B	A	B	A	B	A	B
Volume weight, 20 °C [kg/m³]	1075	1235	1075	1235	1075	1235	1075	1235
Viscosity, 20 °C [mPas]	150-300	170-230	150-300	170-230	150-300	170-230	150-300	170-230
Mixing ratio A/B weight.	100	126	100	126	100	126	100	126
Mixing ratio A/B volume.	100	100	100	100	100	100	100	100
Foaming factor*	1 - 1,2		1,5 - 2		2 - 4		4 - 5	
Volume weight of the foam [kg/m³]	1000 ± 20		600 ± 20		360 ± 20		290 ± 20	
Temperature of the curing reaction max [°C]	do 132		do 132		do 132		do 132	
Beginning of foaming at 20 °C [sec]	120 ± 2		120 ± 2		120 ± 2		120 ± 2	
Type	Geopur® 082/180		Geopur® 082/90		Geopur® 230		Geopur® 240	
Component	A	B	A	B	A	B	A	B
Volume weight, 20 °C [kg/m³]	1075	1235	1075	1235	1090	1235	1075	1235
Viscosity, 20 °C [mPas]	150-300	170-230	150-300	170-230	150-300	170-230	150-300	170-230
Mixing ratio A/B weight.	100	126	100	126	100	126	100	126
Mixing ratio A/B volume.	100	100	100	100	100	100	100	100
Foaming factor	5 - 6		9 - 11		10 - 15		až 40	
Volume weight of the foam [kg/m³]	180 ± 20		90 ± 20		90 ± 30		35 ± 3	
Temperature of the curing reaction max [°C]	do 132		do 132		do 140		do 132	
Beginning of foaming at 20 °C [sec]	120 ± 2		120 ± 2		120 ± 12		120 ± 3	

Table 1. Technical data of the grouting system Geopur® produced by the company GME

3. Grouting equipment

Injection of grouting material into the rock massive is performed by grouting pumps. Usually piston type pumps with electric or pneumatic drive are used. There are one component and two component pumps available. An example of a grouting pump is presented on Fig. 1 below.



Figure 1. Two component electric grouting pump DV 97.

Grouting elements are used during the injection of the grouting material into the rock mass. These are technically designed to transfer the pressure of the grouting material, preventing back flow of the material out from the borehole. They are usually equipped with a back valve. According to the method of fastening in the borehole, we distinguish mechanically fastened once, hydraulically, drilled, pushed in, vibrated or glued. They are called grouting packers, grouting anchors or bolts, grouting tubes and etc.

4. Grouting technology

Mixing of the PU mixture is made in mixing chamber, which is located behind the pump. This is located as close as possible to the borehole. Grouting pump sucks both components of the grouting resin from separate tanks or the components flow in gravitationally. The pump takes the components in appropriate ratio and delivers them separately to the mixing chamber. In the mixing chamber, components are mixed and subsequently injected through the packer into the rock mass. The resin penetrates under the pressure into surrounding fissures and cavities up to the distance of a few meters from the borehole. As a result sealing and strengthening of the rock mass or construction is achieved. After finishing of the grouting, it is necessary to flush the pump, hoses and accessories and clean the equipment. In case of longer regular use, it is possible to leave the components in the pump and hoses.

The work team is usually formed by a couple of trained workers. Parameters of the grouting works are recorded during the work like e.g. location of boreholes, grouted quantities, grouting pressure and temperature.

Injection of material into the rock environment proceeds:

- without reshaping of the grouted rock mass or
- with reshaping of the grouted rock mass.

Grouting without reshaping of the rock mass may be of penetration or filling character. Penetration grouting works are performed in sandy soil or in constructions. Filling grouting is used in fissured rock and coarse grained soil like sand or gravel.

Geopur® type	foaming factor [-]	Volume weight [kg/m ³]	Water intake after 28days [vol. %]	Flexural strength [MPa]	Elasticity modulus [MPa]	Compressive strength [MPa]
82/90	9 - 11	82	2,8	1,6	21	0,5
82/180	5 - 6	185	2,2	2,8	54	2,8
82/290	4 - 5	276	1,7	7,4	192	5,9
82/350	2 - 4	354	1,2	8,3	241	9,5
82/600	1,5 - 2	589	0,9	13,4	443	23,2
82/1000	1 - 1,2	1060	0,4	30,3	985	67,7

Table 2. Physical and mechanical parameters of the grouting system Geopur® produced by the company GME

In case of grouting with reshaping of the rock environment a so called claquage occurs, which is in principle hydraulic fracturing of the rock well known from the oil and gas exploitation. Due to the high hydraulic pressure of the grouting media in the soil a spatial net of fissures is formed, which are subsequently filled with the grouting media. The length and width of fissures depends on the pressure of grouted resin, velocity of penetration and quantity of the grouting resin. Compacting grouting belongs among the grouting methods considered as reshaping the rock mass as well.

5. Behavior of PUR resin in the grouted environment

Grouting PUR resin enters into the borehole as a mixture. The grouting material flows through the rock mass first as a liquid. After curing reaction start, gaseous CO₂ is formed, which causes foaming of the mixture. In case of contact with moisture present in the soil or rock, the foaming is more intense, because the water reacts with the present isocyanate groups. Foaming causes increase of volume of the PUR mixture. The mixture is pushed into open structures of the rock mass and the viscosity of the mixture consecutively increases. The flowing stops, when the viscosity of the material is so high that further pumping is impossible, and the resin becomes hard foam. In case, that the pump is further operated, the pressure increases and the material density increases. In practice, this situation is indicated by significant pressure increase. Increase of the pressure may sometime cause opening of new structures for the grouting and continuing of the grouting. In case of formation of new openings the pressure drops. This may occur repeatedly until full grouting of the surrounding of the borehole.

Volume weight of the grouting material increases from the front of the grouted structure towards the packer. In case of the PUR resins, when the pump is stopped, so called autogrouting continues, which is induced by the reaction of the material and formed CO₂, which induces pressure of 0,1 to 0,3 MPa. In case the grouting process stops before full saturation of the environment by the grouting media, the saturation continues due to the pressure formed by CO₂ until finishing of the chemical reaction. In case, that the fissure had been already filled, the pressure is higher than the pressure of CO₂ and bubbles are not formed - CO₂ remains dissolved in the grouting media and has minimal volume. The texture of the material is in this case compact. Formation of the bubble structure depends therefore on the pressure under which the mixture cures. Usually porous structures are formed with closed or partly closed pores during the grouting.

6. Properties of grouted soil, rock and building material

During pressure grouting of PU grouting resins into soil, rock mass or fissured or defected constructions, new specific materials are formed. These materials have the properties of composite material and, taking into account their components character, are referred to as **geocomposites** (Snuparek & Soucek, 2000).

In rocks or constructions the grouted environment contains discontinuities. The geo-component of the formed geocomposite is formed by blocks of the rock (or masonry), which are defined by combination of bedding surfaces, metamorphic foliation, fissures and etc.

In soil, two basic types of geocomposites are formed by PU grouting: in case of non cohesive soil (sand-gravel), the geo-component of the geocomposite is built by solid grains or their aggregations of various size and shape. These contain grains of minerals and rocks, organic particles (shells of organisms, wood, carboniferous parts of plants and others) or parts of constructions (building material, metals, ash and others). In case of cohesive soil (clay, claystones, or siltstones), the geo-component of the geocomposite is formed by blocks of soil penetrated by a net of so called claquage fissures (fissures caused by hydraulic fracturing during the grouting), which are filled with the binding material.

The binding material is represented in these geocomposites by hardened organic or organic-mineral PU resin with various degree of foaming.

Penetration of the grouting media through the inhomogeneous environment, and thus also the resulting properties of the formed geocomposite, is influenced by many factors. In case of geocomposites of PU resin – rock (soil) and PU resin – building material, the following factors have primary effect (Scucka & Soucek, 2007):

- **properties of the unpolymerized grouting media** –viscosity of the media as a function of temperature and rheology of hardening, velocity of injection (volume per time unit), grouting pressure, the right stoichiometric ratio of input components and sufficient time and intensity of their mixing;
- **properties of the grouted environment** – composition of the rock (building material), shape and size of soil particles and rock blocks, humidity, effective porosity or voids,

type and orientation of discontinuities, temperature of the environment, permeability (plastic+water+gas), adhesion of grouting media to the rock surface, composition of water, pore pressure.

Formed structure and texture of the geocomposite (usually very variable in case of PU geocomposites) is a result of the effect of the above mentioned factors. This variability depends on the bedding conditions of the grouted rock and on the parameters of the grouting process, mainly on the grouting pressure. Grouting pressure together with moisture cause for example significant zonal heterogeneity of the geocomposite in case of grouting of wet or saturated sand (mainly of lower permeability) (Aldorf & Vymazal, 1996).

Structural and textural variability of geocomposites significantly complicate the estimation of physical and mechanical properties of geotechnical constructions formed within the grouting process. Mainly the determination of strength and deformation properties of the geocomposite is problematic, because it is often hard to prepare standard laboratory testing specimens from the samples available and collected in situ by core drilling or excavation. In cases when it is impossible to prepare testing specimens from real in situ samples, model geocomposites are prepared by grouting into pressure tanks in the laboratory (Snuparek & Soucek, 2000). Physical and mechanical properties are subsequently determined on such prepared model samples. Qualitative and quantitative structural-textural parameters of the geocomposite are also analyzed by the methods of image analysis and are subsequently compared with parameters of real samples.

In the following text, basic types of structures and textures of geocomposites (with PU binding material) will be described and examples of determination of mechanical properties on real and laboratory prepared samples will be presented.

6.1. Structure and texture of geocomposites

Table 3 below presents a simple classification system for description of structure and texture of PU geocomposites according to various criteria. Some of the criteria are taken over from the modified system commonly used for analyses of structure and texture of sedimentary rocks in petrography (Pettijohn, 1975). We describe in more detail the categories created by the authors based on their long-term research. These include division of geocomposite textures according to the character of binding material penetration into the grouted soil (rock), division of structures according to quantity of binding material and description of the structure of the binding material in the geocomposite from the point of view of distribution, size and morphology of bubble pores.

6.1.1. Character of penetration of the binder into the grouted rock

According to penetration of the binder into the grouted soil or rock, the following textures or their combination may be distinguished:

- **honeycomb texture I.** - rock particle is surrounded by the binder and this has good adhesion to the rock surface (Fig. 2),

GEOCOMPOSITE TEXTURES		
According to ordering of building units	According to character of penetration of the binder into the rock	
<ul style="list-style-type: none"> - parallel • linear parallel • aerial linear parallel • aerial parallel (bedded) <ul style="list-style-type: none"> • bed type • desk type • laminar - massive 	<ul style="list-style-type: none"> - honeycomb type I. (Fig. 2) - honeycomb type II. (Fig. 3) - honeycomb type III. (Fig. 4) - doughy (Fig. 5) - stringer type (Fig. 6) - claquage (Fig. 7) - diffusive (Fig. 8) - barrier type (Fig. 9) 	
According to distribution of rock particles in the binder	According to the level of filling of the space	According to spatial distribution of particles and pores
<ul style="list-style-type: none"> - with particles evenly distributed in the binder material - with particles unevenly distributed in the binder material 	<ul style="list-style-type: none"> - compact - porous 	<ul style="list-style-type: none"> - isotropic - anisotropic
GEOCOMPOSITE STRUCTURES		
According to rock grain size	According to relative grain size	According to angularity of clastic particles
<ul style="list-style-type: none"> - pelitic - aleuritic - psamitic (fine, medium, coarse) - pseftic (fine, medium, coarse) - stone type - boulder type 	<ul style="list-style-type: none"> - evenly grained - unevenly grained 	<ul style="list-style-type: none"> - breccious - conglomerate - angular psamitic - sub angular psamitic - sub oval psamitic - oval psamitic - perfectly oval psamitic
According to quantity of binder	According to distribution and morphology of bubble pores in the binder	According to size of pores in rock or binder
<ul style="list-style-type: none"> - basal - porous - contact type - coating type 	<ul style="list-style-type: none"> - type PUR 1 (Fig. 10a) - type PUR 2 (Fig. 10b) - type PUR 3 (Fig. 10c) - type PUR 4 (Fig. 10d) - type OMR 1 (Fig. 11a) - type OMR 2 (Fig. 11b) 	<ul style="list-style-type: none"> - with micro pores - with macro pores - with cavities

Table 3. Classification system for description of geocomposite structure and texture.

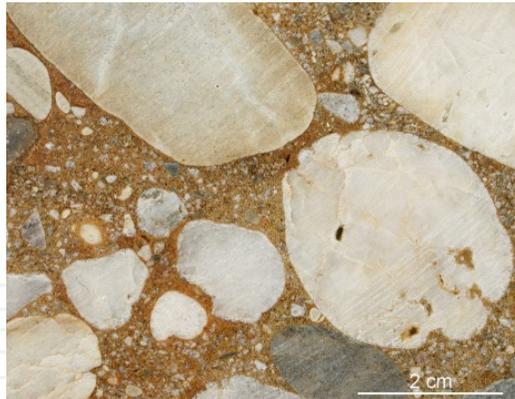


Figure 2. Honeycomb texture I. (PUR is surrounding the rock particle and sticks well to the rock surface).

- **honeycomb texture II.** - rock particle is surrounded by the binder, but the binder sticks only partly to the rock surface (Fig. 3),
- **honeycomb texture III.** - rock particle is surrounded by the binder, but the binder does not stick to the rock surface and is separated from the rock by a gap; free particle may be taken out from the „tissue” of the plastic binder (Fig. 4),
- **doughy texture** - the binder looks like pastry pushed into the gaps between the grains of the aggregate, it does not fill fully the gaps between the grains and does not stick completely to the grains (Fig. 5),



Figure 3. Honeycomb texture II. (PUR is surrounding the rock particles, but sticks only partly to their surface).



Figure 4. Honeycomb texture III. (free rock particle can be taken out of the PUR-binder „tissue”).



Figure 5. Doughy texture - OMR-binder has a character of dough pushed into gaps between the conglomerate grains, it does not fill fully the voids and does not stick fully to the grains.

- **stringer texture** - a net of fissures (usually in all directions), not formed due to the grouting, spreads through the rock (masonry) and is filled with the binder (Fig. 6),
- **claquage texture** - a net of fissures, which was formed due to the grouting, spreads through the rock (masonry) and is filled by the binder (Fig. 7),
- **diffusive texture** - the rock is penetrated by the binder "in diffusive way" in pores (Fig. 8),
- **barrier texture** - binder fills only the interconnected cavities and gaps between the grains, it does not penetrate through the barriers formed by the present fine-grained soil (Fig. 9).

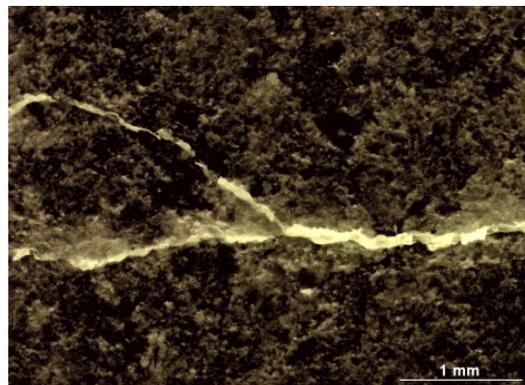


Figure 6. Stringer texture - a net of fissures (usually in all directions), not formed due to the grouting, spreads through the rock (masonry) and is filled with the binder.



Figure 7. Claquage texture – fine-grained soil fractured hydraulically with claquage fissure, which is filled with PUR-binder.



Figure 8. Diffusive porous zonal texture of geocomposite (crushed brick + PUR). A border formed by penetration of the binder into the pores of the brick fragments is visible on the bigger grain edges. Smaller brick fragments are fully penetrated by the binder.



Figure 9. Barrier texture – the binder fills the interconnected cavities between the grains, it does not penetrate through the barriers formed by the basic mass.

6.1.2. Quantity of the binder in the geocomposite

According to the quantity of the binder in comparison with the quantity of rock component in the geocomposite, the following structures can be distinguished:

- **basal structure** – rock particles are distributed in the abundant binder, particles are separated,
- **porous structure** – binding material fills the pores and voids in between the grains, grains are in contact with each other,
- **contact structure** – binding material is present only in places of grain contact,
- **coating structure** – small amount of binder creates coating around the clastic grains.

6.1.3. Distribution, size and morphology of bubble pores in the binder

A specific feature of most grouting media on the basis of PU is increase of their volume by foaming. In order to describe the relative distribution and morphology of bubble pores in the foamed hardened PU binder, we use the following classification for both micro as well as macro evaluation (Scucka & Soucek, 2007).

- **type PUR 1** – binder is compact, vitreous, bubble pores occur only sporadically or are not present at all (Fig. 10a),
- **type PUR 2** – isolated spherical or ellipsoidal bubble pores of similar size are suspended within the vitreous binder, bubbles have smooth walls, no collapsed walls occur (Fig. 10b),
- **type PUR 3** – partly collapsed bubble pores are suspended within isles of vitreous compact binder, bubbles are in contact, walls are of peel or shell character (Fig. 10c),
- **type PUR 4** – collapsed bubble pores with thin walls are in contact with each other and deform themselves, walls are of peel to honeycomb character. Vitreous compact binder is missing or is sporadic (Fig. 10d).

In case of organic-mineral resins, out of which mainly non foaming types are used in the geotechnics, the structure of the hardened resin has different character. The character strongly **depends on the intensity and time of mixing** of the input components. In case of good mixing, isolated or touching, regular spherical, white drops of polysilicious acid gel are densely distributed within the plastic mass. Irregularly distributed spherical or less regular pores of various sizes are also present in the structure (**type OMR 1**, Fig. 11a). In case of insufficient mixing time and intensity, an inhomogeneous mass is formed containing mineral part, which is irregularly distributed within the plastic mass (**type OMR 2**, Fig. 11b).

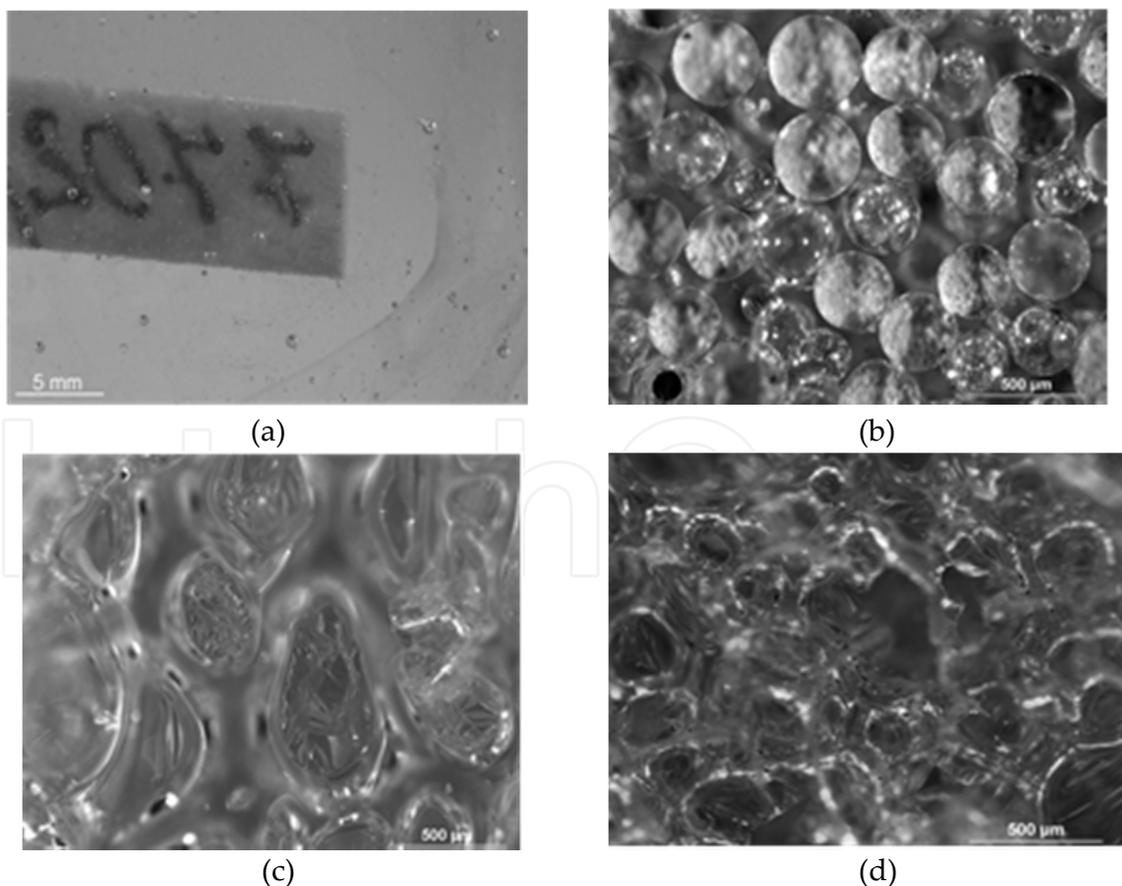


Figure 10. Basic types of plastic binder structure with pores in PUR-geocomposites: (a) type PUR 1, (b) type PUR 2, c) type PUR 3, d) type PUR 4.

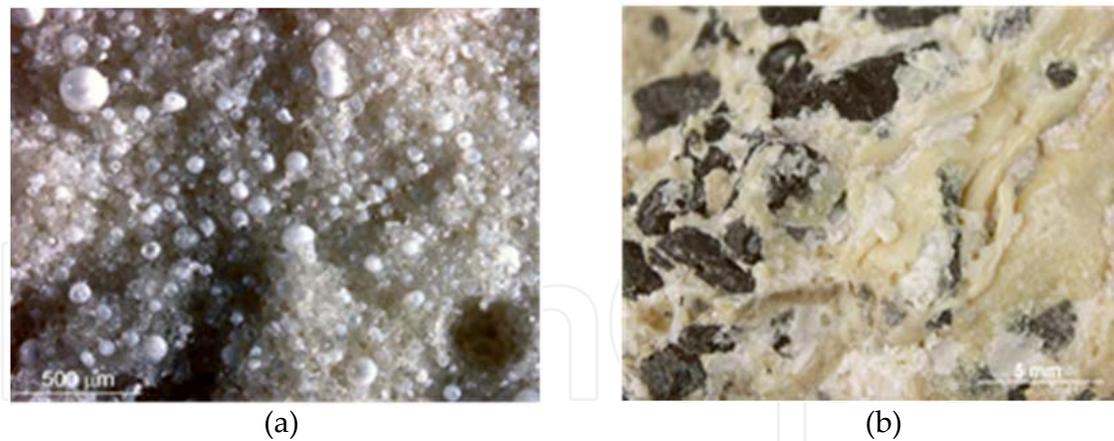


Figure 11. Basic types of plastic binder structure in OMR-geocomposites: (a) type OMR 1, (b) type OMR 2.

6.2. Determination of mechanical properties of PUR-geocomposites

6.2.1. Preparation of samples and testing specimens

Samples and testing specimens of PUR-geocomposites for laboratory testing of physical-mechanical properties are obtained by the following methods:

1. *by pouring and free foaming* – the simplest method, PUR-mixture is hand mixed with grouted material (sand, gravel, rock debris and others) and is poured into forms of required shape, in which it freely foams. Final shape of the testing specimen is adjusted by cutting off of overfoamed part of the sample (over the volume of the form) (Fig. 12a).
2. *by grouting into pressure tank* – testing samples of required dimensions and shape are drilled or cut from the formed geocomposite (Fig. 12b,d).
3. *by in situ test grouting*– PU mixture is grouted into the rock environment in situ, testing samples of required dimensions and shape are drilled or cut from the formed geocomposite, which is excavated after the test grouting (Fig. 12e).
4. *from real geotechnical projects* – during performance of grouting works in practice, test grouting is undertaken with subsequent sample collection of the grouted rock mass or construction, in some cases also control samples are collected in order to judge the quality and effectiveness of the performed works (Fig. 12c).

The choice of shape and size of the testing specimens is determined by the properties of particular geocomposite type. It depends mainly on the dimensions, shape and textural homogeneity of available geocomposite and also on the possibilities of cutting and machining with cutting or drilling tools. A high-speed abrasive water jet can be well used for cutting of large geocomposite samples (Hlavacek et al., 2009). For shaping of test samples, laboratory drilling machine with diamond bit and diamond saw are used.

6.2.2. Laboratory tests of PUR-geocomposites

There are no standard approaches in the field of laboratory testing of mechanical properties of PUR-geocomposites up to date. Corresponding methods and norms, used in rock

mechanics and building material mechanics, are applied for the testing (e.g. ISRM Commission, 1978), and these are adjusted to specific properties of the geocomposites.



Figure 12. Testing specimens of geocomposites prepared by various methods: a) hand mixed mixture of sand + PUR poured into cylinder form with subsequent adjustment of frontal surfaces, b) sand grouted with PUR in pressure tank – cut out specimen of a prism shape of 50mm×50mm×100mm dimensions after uniaxial compressive strength test, c) cylinder shape specimen made from control core drilling, originating from grouted concrete foundation of high voltage pole, d) cube-shaped specimen – coal parts grouted with PU in pressure tank, e) beam type specimen of 40mm×40mm×160mm dimensions during flexural strength test (specimen made of real sample of sand grouted with PUR)

An example of PUR-geocomposite testing is an analysis of sample prepared by grouting in situ with Geopur® 082/90 PU grouting system into saturated sand and shale sandy breccia. Grouting works were performed during construction and excavation of an underground utility tunnel. The underground construction crossed non-coherent strongly saturated sand, where increased water inflows into the construction occurred with subsequent bursting of sand from the working face. Safety of the excavation works at this critical section was secured by creation of a protective “umbrella” above the excavation. This protective “umbrella” was made by the method of PU pressure grouting via perforated steel tubes. During the excavation one of the monolithic geocomposite bodies

was dug out for laboratory testing purposes (Fig. 13a). Cross cutting of the geocomposite body showed macroscopically visible zonal heterogeneity of the material (Fig. 13b). Using the methods of image analysis, it was found out, that the degree of foaming of PUR binder increases with the increasing distance from the grouting tube, and that the volume ratio of PUR binder in the geocomposite ranges from 40 to 45% in the various parts of the geocomposite body. Various consistencies of the binder and variable portion of coarse grained breccia grains were identified in the body of the geocomposite. Due to this heterogeneity, the compressive strength values tested on cube-shaped specimens cut from the geocomposite material ranged in relatively wide interval from 5 to 30 MPa (average 12 MPa) and the deformation modulus ranged in interval from 100 to 2000 MPa (average 700 MPa).



Figure 13. Monolithic geocomposite body formed by GEOPUR grouting into saturated sand and shale sandy breccia (a) and a cross through the geocomposite – zonal heterogeneity of the material is visible (b).

An example of testing of model PUR-geocomposites, prepared in laboratory conditions by grouting into pressure tanks, is an analysis of the effect of grouted environment moisture to the resulting properties of the geocomposite (Scucka & Soucek, 2007). A geocomposite sample, laboratory prepared by grouting into pressure tank filled with loose rock material, is presented in Fig. 14. Grouting was performed into crushed basalt of defined grain size. The material was grouted by the Geopur[®] 082/1000 resin, which reacts during the curing process with water. Grouting was performed both into dry material and saturated material. Fig. 15 shows macroscopically visible differences in the texture of formed geocomposites. While during the grouting of dry material honeycomb type I texture is formed (good adhesion of binder to the rock particles) with slightly foamed binder PUR 2 (see sec. 6.1.), in case of saturated grouted material, honeycomb type II texture is formed (only partial sticking of the binder to the rock particles) with strongly foamed binder PUR 3. The difference in moisture of the grouted material causes, that the compressive strength of saturated samples is in average lower by approx. 80% and the deformation modulus is lower by approx. 90% compared to the values of samples prepared by grouting into dry material.



Figure 14. Sample of model geocomposite (PUR+basalt aggregate) prepared in laboratory by grouting into pressure tank.

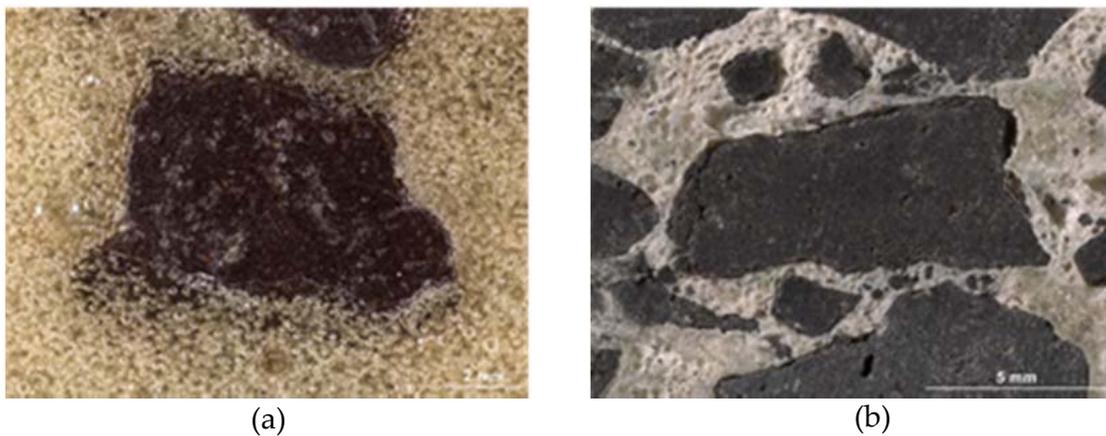


Figure 15. Different types of textures of laboratory prepared model geocomposite formed due to different moisture level of the grouted material (PUR+basalt aggregate): a) dry aggregate, b) saturated aggregate.

6.2.3. Current knowledge about the mechanical properties of PUR-geocomposites

Data about stress and strain properties of geocomposites with PU binder have not been yet evaluated in summary or statistically. Technical literature or company brochures offer information connected with particular applications under particular geotechnical conditions or from testing and comparison of individual grouting materials. A little bit more complex data and unified interpretation of observed parameters are presented by (Aldorf & Vymazal, 1996), where the properties of laboratory prepared and in situ prepared geocomposites are compared (sand grouted with PU and acrylate resin). Further, we present some conclusions deduced from the results of the above mentioned experiments and from the knowledge of the authors in the field:

- PUR-geocomposites behave in comparison with common rock types extraordinarily, mainly in terms of considerable elasticity and plastic deformations. This feature is observed mainly behind the ultimate strength, when along with the relatively high values of longitudinal deformation (approx. 10 - 20% in case of grouted sand) residual strength of the material remains significantly high.

- The ratio of rock grains to the PU binder, distribution of grains, grain size and the possibility of formation of porous foamed material have significant influence to the values of parameters of physical-mechanical properties of the geocomposite. These factors are always very variable at in situ conditions and depend on the bedding conditions of the rock (local porosity, structure, permeability, moisture and etc.). It is therefore necessary to take into consideration during the laboratory testing mainly the parameters of samples of lower volume weight.
- Samples of lower volume weight contain greater portion of foamed plastic binder. This results in decrease of velocity of longitudinal ultrasound waves spreading through the material and decrease of deformation modulus (higher plasticity).
- Greater portion of rock grains (higher volume weight) positively influences the strength of the geocomposite. Compressive and tensile strengths increase with increasing volume weight.
- Geocomposite deforms within the elastic phase mainly in longitudinal direction, transverse deformations are small. This is indicated also by small values of Poisson's ratio. It is caused probably by high porosity of the binder, which is predominantly elastically deformed in the direction of loading force. High values of tensile strength are probably also result of this.

7. Examples of practical applications of PU grouting

7.1. Reconstruction of Retaining Wall (Prague - Horni Pocernice, Czech Republic)

Task:

The retaining wall (Figs 16-19) is located at the D11 highway at Prague, Horni Pocernice. The highway runs here in a deep trench with walls reaching to 10 m height. The works during the reconstruction of the retaining wall included:

1. stabilization of the fill material behind the current wall by grouting technology from static and safety reasons in order to enable performance of the follow up reconstruction works.
2. anchoring of steel concrete pole prefabricates of the newly built retaining wall.

Solution:

Technology of pressure grouting was used in order to stabilize soil and fill potential cavities behind the retaining wall. Double component PU resin Geopur[®] 082/90 was used as a grouting medium. Grouting works were performed through drilled or hammered in perforated steel grouting tubes of 16/22 mm diameter. Drillings were drilled approximately perpendicularly to the wall, to the depth of 2 to 3 m in a periodic grid. In total, an area of the wall of approx. 1500 m² was stabilized, total of approx. 10 000 m of grouting rods were drilled, and a total of approx. 46900 kg of Geopur[®] grouting resin was consumed.



Figure 16. Original state of the retaining wall



Figure 17. Anchoring works



Figure 18. Situation before final completion of the works



Figure 19. Detail of finalized anchor

Drilling of the anchors was made in places of openings of the anchored concrete poles (Figs 17, 19). Self drilling R type rock bolts were used. The length of the anchors was 8 to 10 m, according to the particular geological conditions at the place of the installed anchor (always to reach at least 2 m of stiff rock environment). After drilling in of the anchor rods, pressure grouting was performed through the installed anchor (AR32N) using two component PU resin Geopur® 082/600. The length of the grouted anchor root was approx. 3 to 6 m and approx. 50-60 kg of grouting resin was applied into each anchor.

In total 276 anchors were installed of total length of 1896 m. The consumption of grouting resins Geopur® reached approx. 13 200 kg.

7.2. Hatarmenti water-gate (Zagyva River, Hungary)

Task:

During the time of catastrophic floods on the Tisza River, which occurred from February to March 2001, intensive water seepages occurred around the Hatarmenti water-gate on the Zagyva River by the town of Szolnok (Fig. 20). The dam contains two concrete units with openings of 120cm×120cm. Intensive seepages threatened the stability of the dam. Insulation by PU pressure grouting, using pushed-in grouting tubes at the water-side of the dam, was proposed.



Figure 20. View of the Hatarmenti water-gate

Solution:

Grouting works were launched at 7.00 AM. After preparation of the technical equipment, grouting tubes were pushed in. Pushing in of the 1st tube was followed by immediate start of the grouting works. In total, 9 grouting tubes were made. Grouting was done stepwise. Complete stopping of water seepages was reached at 5 PM. In total, 600 kg of Geopur® 082/350 PU resin material was used.



Figure 21. Grouting material in the surrounding of the water-gate (photo from the control excavation after 10 years)

After 10 years (in February 2011) the river basin authority decided to check the lifetime of the grouting material and its sealing function. An excavation was made down to the concrete construction of the dam. Grouting material was observed on the contact with the concrete structure and in the surrounding (Fig. 21). The material looked undamaged and fulfilled the sealing purpose. It was solid and dry. The efficiency of the performed PU pressure grouting was proved.

7.3. Elimination of contaminated water outflows from the uranium deposit (Rozna, Czech Republic)

Task:

After stopping of mining at the uranium deposit Rozna in 1996, the mine was flooded. The groundwater from the old exploited areas, rich in uranium, infiltrated into the old investigation boreholes, even though the boreholes were sealed in the past (Fig. 22). Contaminated water threatened a drinking water reservoir, and therefore it was necessary to stop the dangerous outflows from these boreholes.

Solution:

The problem was successfully eliminated by application of PU grouting using Geopur® grouting system (Fig. 23). The boreholes were sealed with grouting and the outflows of contaminated water stopped. It was proved that using PU resin of Geopur® type with foaming factor of 12 it is possible to efficiently stop seepages through porous geological environment or boreholes.



Figure 22. Borehole with contaminated water seepages



Figure 23. Sealing of the borehole with PU grouting

7.4. Sealing grouting of sewage collector (Pilsen, Czech Republic)

Task:

During exploitation of a sewage collector in Pilsen – Cernice, drainage in the surrounding area occurred due to drainage effect of the collector. Groundwater disappeared from the wells in the surrounding and drops of the surface occurred, causing even damages to some buildings. In section 4255 – 4350 m of the collector the excavation works ran in close proximity of a residential house. There was a risk of damage to the house and surface drop due to the fast drainage of the groundwater. In order to eliminate inflows into the collector, a hydrogeological survey was performed and a technology of sealing of the environment was proposed.

Solution:

During the exploitation works in the critical section (approx. 100 m), the rock mass was stabilized by PU grouting. Grouting PU materials Geopur® was used. The grouting works were performed always in advance before the exploitation to the distance of 3 m ahead of the face and were followed by exploitation of 2,5 m. Used technology enabled stopping of strong inflows of groundwater and secured higher stability of the rock mass during the exploitation works. Drainage of the surrounding area was eliminated and buildings were not threatened further by the excavation works. Total of 9516 kg of PU grouting material

Geopur[®] was used. Grouting was performed in total of 275 boreholes. The efficiency of the grouting works was proved by monitoring of the groundwater table level.

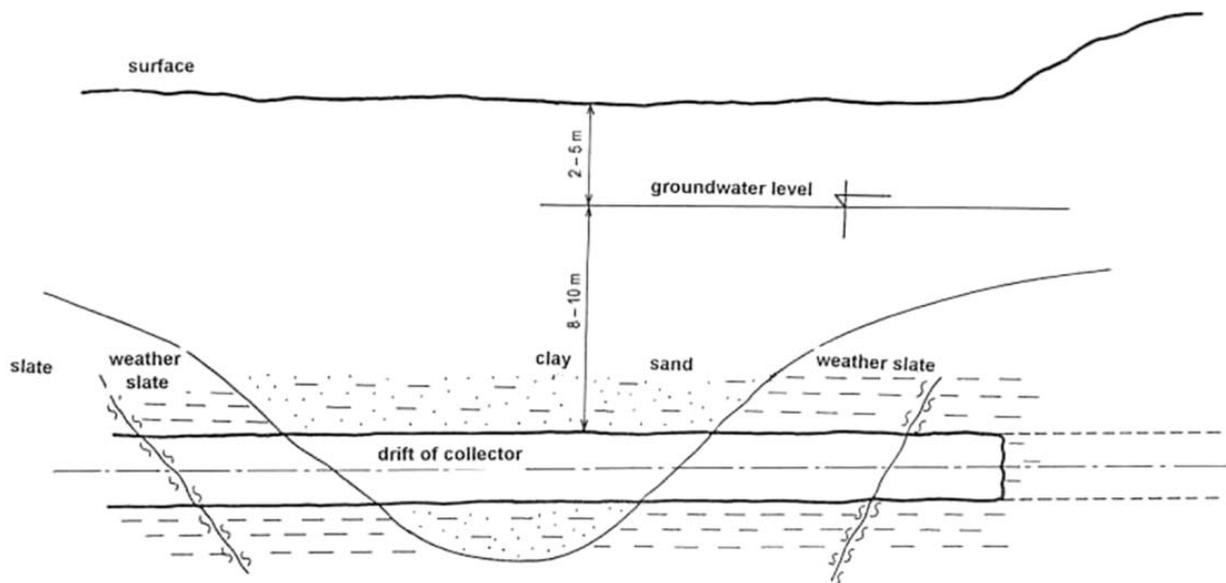


Figure 24. Geological situation of sewage collector construction in Pilsen.

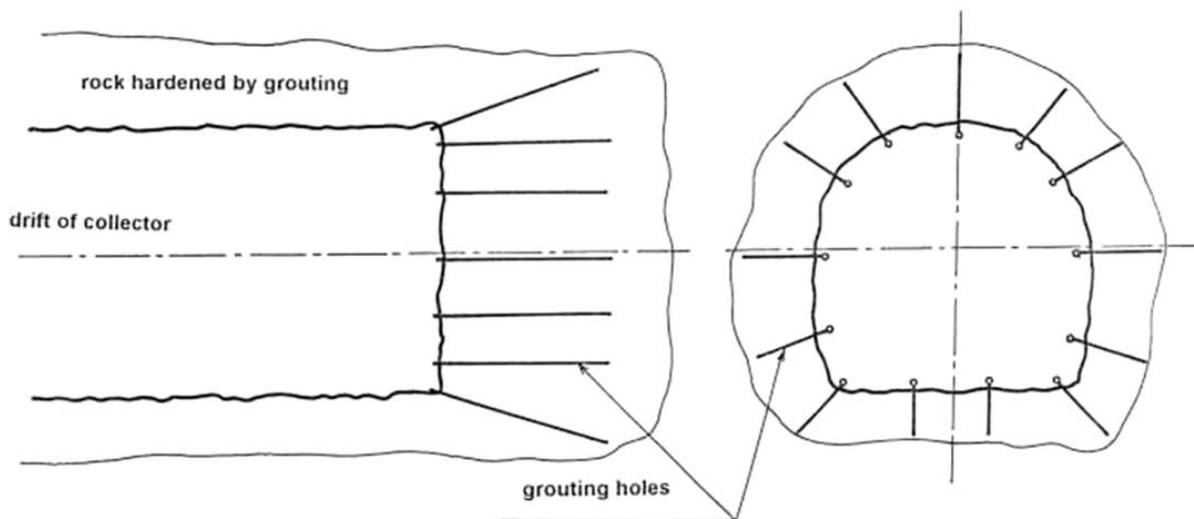


Figure 25. Drift of sewage collector in Pilsen - scheme of grouting works.

7.5. Securing of excavation of underground utility tunnel (Ostrava, Czech Republic)

Task:

In the centre of Ostrava town an underground gallery was exploited (Fig. 26). According to the design of the construction, it was required that the compressive strength of the overburden soil (gravels of the River Ostravice terrace) was minimally 2 MPa.

Solution:

The proposed technology was based on grouting of overlaying rocks ahead of the working-face by PU grouting system Geopur® to the distance of 3 m. In the given geological conditions the technology proved to be a safe and economic solution. The use of PU grouting resin system Geopur® enabled to perform the whole cycle of grouting works in 4 hours. Proposed technology did not require equipment of great size. Borings for grouting were drilled using a light hand drilling equipment; grouting works were performed using transportable pumps. 9-12 grouting tubes were used per one section (3 m), in accordance with local geological conditions. Distance between the grouting tubes was 0,3 m at the face and 0,4 m at the sides of the tunnel. Minimal compressive strength of the formed geo-composite reached in the upper part of the profile 4-6 MPa and 2-4 MPa on the sides. The strength of the rock was reached in 20 min after grouting works.



Figure 26. Grouted gravel in the face of the tunnel

7.6. Repair of cracks in the concrete of highway bridge (Belotin, Czech Republic)

Task:

During the construction of the highway near Belotin, bridge beams were damaged probably due to the frosty weather. Cracks of up to 11 m length formed at the construction. It was necessary to reconnect the cracks using a reinforced grouting technology.

Solution:

Boreholes of 14 mm diameter were drilled into the concrete beam along the cracks, diagonally across the crack. Steel bars of 10 mm diameter were inserted into the drillings and subsequently the drillings were grouted with Geopur® PU resin (Figs 27,28)



Figure 27. Reinforced PU grouting of the crack in the concrete construction



Figure 28. Overall view of the repaired crack

7.7. Lock at the Danube River (Gabcikovo, Slovakia)

Task:

During operation of the lock on the Danube River cavities had been formed on the outer side of the lock in the soil, caused by insufficiently sealed dilatation joints (Fig. 29). Water flowed through the soil embankment, washed out the fine grained particles and cavities were formed. Additional sealing of the dilatation joints was therefore proposed.

Solution:

In 2005 additional sealing of dilatation joints and sealing of cracks in the concrete was performed using PU grouting system Geopur®. In total an area of 42 m² of concrete was repaired, 210 m of dilatation joints was resealed and 207 m of cracks in the concrete was sealed. Total of 7 dilatation joints was successfully repaired using total of 700 kg of Geopur® (Fig. 30).



Figure 29. Dilatation joint before the grouting



Figure 30. Dilatation joint after the grouting

7.8. Repair of metro railway (Budapest, Hungary)

Task:

Metro line East-West in Budapest has been operated since 1970. During the operation the railway must withstand a great load. Daily operation represent passing over of 7000 wheels

with axis pressure of 7,9 tons. Despite everyday maintenance, signs of damage occurred and repair works were launched.

Solution:

A new method of repair of the concrete sleepers was proposed based on anchoring and use of PU resin. The performance of the works concurrently led also to stopping of water inflows from the subsoil of the railway. Concrete sleepers were stabilized and anchored without the necessity to replace them (Figs 31,32).

Grouting works were performed between 2005 and 2006, mainly during night time and without necessity of putting the metro out of operation. Total of 2842 anchors were made of the following parameters: length of the anchor 500 mm, diameter of the anchor 18 mm, diameter of borehole 25 mm, grouting material Supermin[®] with reaction start of 2 minutes. Further, total of 2430 grouting boreholes were drilled of the following parameters: borehole diameter 14 mm, length up to 1 m, length of inserted steel bars up to 600 mm, diameter of the bars 8 mm, grouting material Geopur[®] 082/1000 with reaction time 2 minutes.



Figure 31. Detail of the grouting works



Figure 32. View of the railway after repair works

In addition, water infiltration from below of the railway was stopped in a total length of 58 m of the metro tunnel using material Geopur[®] 082/350.

Applied methods proved to be very effective and did not disturb the regular operation of the metro line.

8. Conclusion

PU grouting is performed in order to achieve improvement of physical and mechanical properties of the rock, soil, or building material in the construction. It requires experience and complex knowledge from various fields like geology, hydrogeology, structural geology, rock and soil mechanics, geotechnics, mining, underground constructions, construction of foundations, structural stability, defects of constructions and their repair, chemistry of the grouting material, grouting technique (pumps, packers) and etc. Grouting technologies represent an effective technology of solving of various kinds of problems in mining, building industry and geotechnics practice.

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