Geosynthetics, J. Kuwano & J. Koseki (eds)
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Energy geocomposites for tunnels

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Keywords: Geocomposites, energy geotextiles, geothermal energy, thermo-active tunnels

ABSTRACT: Thermo-active tunnel linings enable heat extraction from the ground via geocomposites fitted with absorber pipes that carry a heat carrier fluid. This geothermal energy can be used for heating buildings near the tunnel portal. Moreover, seasonal operation makes cooling during summer possible by using the ground for heat storage via the energy geocomposites. The paper describes theoretical aspects, installation details, large scale tests, and site experience.

1 INTRODUCTION: ENERGY TUNNELS

"Energy tunnels" are infrastructure tunnels that are used simultaneously for heating and/or cooling buildings, road pavements, or bridge decks. Until recently geothermal heating from tunnels was used only in connection with hot waters, mostly without heat pumps. But the heat potential along a tunnel can also be utilized by using the tunnel support and lining as energy absorbers. These may be anchors, rock/soil nails, geosynthetics and secondary concrete lining. Anchors or nails reaching deeply into the surrounding ground can activate a relatively large mass for geothermal utilization. "Energytunnel" may be excavated as closed systems, e.g. by the NATM (Fig. 1) or by the cut and cover method.

Near the portals of transportation tunnels with geothermal equipment the following groups may take the available energy:

- The owner or operator of the tunnel;
- Private users (especially large residential blocks, but also one-family houses);
- Commercial, industrial users;
- Public users (municipal, federal).

An example from a railway tunnel in Vienna underlines these advantages: About 1200 private flats could be supplied with geothermal energy, but also large public buildings.

Energy tunnels are an exciting challenge to geotechnical engineering whereby the optimization of energy extraction or feed/storage, of transfer and distribution requires a multi-disciplinary cooperation. Ground investigation and geotechnical design should incorporate geothermal aspects already at an early stage. The main advantages of this innovative technology are:

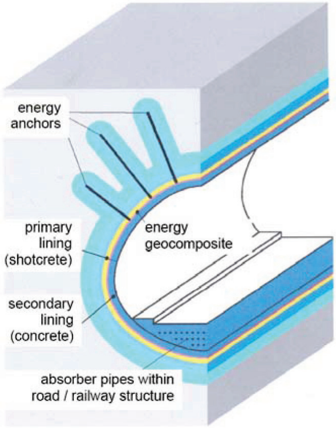


Figure 1. Absorber elements for energy tunnels.

- Commonly, tunnels are situated in a depth, where the seasonal ground temperature is widely constant.
- Tunnels exhibit large interfaces between structure and ground, thus favouring the extraction and/or feed, hence storage of geothermal energy.
- Very deep-seated mountain tunnels can make use of great geothermal gradients.
- In long tunnels significant inner heat is available, mainly due to the waste heat of transportation. In metro-tunnels, for instance, temperatures of more than +20°C are possible even during the winter months.

- Utilizing clean and self-renewable energy from tunnels is environmentally friendly and economical. Therefore energy tunnels have a high public acceptance and political support which makes the approval procedures easier.

Until now only cut-and-cover tunnels and open face tunnels (excavated after the NATM) have been equipped with thermo-active geosynthetics or anchors/nails. But bored tunnels with segmental lining can also be used as energy tunnels as they exhibit earth-contact structural elements. Furthermore, optimized energy tunnels may use not only the ground temperature from their large underground contact area but also inner heat sources from traffic, lighting etc.

2 ENERGY GEOSYNTHETICS (GEOCOMPOSITES)

Since the year 2000 several geosynthetics have been tested at the Institute for Soil Mechanics and Geotechnical Engineering of the Vienna University of Technology for utilisation as geothermal absorber elements in shotcrete supported open face tunnelling ("New Austrian Tunnelling Method"). According to the present state of the art non-woven geotextiles serving simultaneously for mechanical protection and drainage have proved most suitable. Non-woven geotextiles are required in tunnelling for watertight geomembrane protection, and they improve roof and sidewall drainage. Fixing plastic pipes between two geotextiles provides a thermo-active absorber system with a closed circuit for energy extraction (or storage).

A supply pipe (e.g. along the side walls) feeds those cellular geocomposites where the absorber fluid takes the energy from the surrounding ground. The warmed up fluid is then transported from the absorber pipes via collector line (HDPE pipe) to a heat pump. Prefabricated geocomposites with integrated absorber pipes make the installation of independent thermo-active cells possible, which can be easily monitored and separated from the overall circuit for repair. The geocomposites should be prefabricated in plant and transported in rolls to the construction site. The rolls should have the standard width (typically about 2.5 m – Fig. 2) and a length adapted to the cross section of the tunnel. The installation procedure in the tunnel is similar to the placement of conventional non-woven geotextiles. The energy geocomposite exhibits adaptors on both ends and they have to be overlapped in the longitudinal direction of the tunnel. Additional works are only the fixing of absorber pipes when casting the concrete and checking the watertightness of the pipe system.

Three absorber pipe patterns were investigated with respect to fluid flow behaviour required pump power, thermical behaviour, air-free feasibility, assembling, technique and prefabrication costs (Fig. 3). Numerical simulations and field tests showed that a longitudinal distribution with a series circuit design proved to be the best option (Fig. 4).

Figure 2. Unrolling of an energy geotextile.

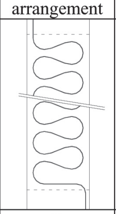
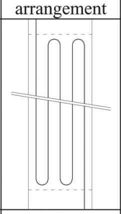
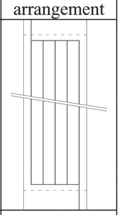
	series circuit		**parallel circuit**
	cross arrangement	lengthwise arrangement	lengthwise arrangement
			
requ. pump capcity	2 (high)	2 (high)	1 (low)
exhausting	1 (very good)	2 (good)	3 (satisfying)
manufactur e	3 (difficult)	2 (good)	1 (easy)
production costs	2 (middle)	1 (cheap)	3 (expansive)
average	*2*	*1,75*	*2*

Figure 3. Evaluation of different types of energy geotextiles.

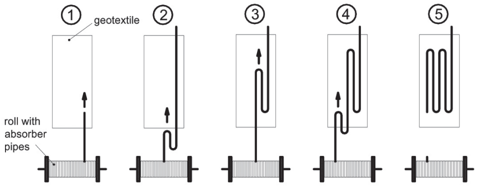


Figure 4. Steps for automatically manufacturing of an energy geotextile.

3 DEGASSING OF ABSORBER PIPE SYSTEM

Absorber pipe systems have to be air-free. Usually, bleeding of pipe systems should start at the point of the lowest pressure and highest temperature, because at that point water can keep only minimal air in solution

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(i.e. highest point in common heating systems). But in the case of energy geocomposites this technique is not possible. Therefore two measures were developed to fill and operate the pipe system without air bubbles:

- "Shouting through" of the absorber fluid by filling it with high pressure and velocity into one pipe end. This technique has proved suitable also for debubbling of heating systems below the turf of soccer fields to enable matches in winter. For making thermo-active earth collectors air-free, similar methods are used.
- Installation of a central vacuum-degassing equipment in the pipe system. Such a device enables the removal of solved gas, thus avoiding later and repeated degassing, circulation disturbances, erosion and corrosion within the pipes.

In order to develop a prototype of an energy geocomposite and optimise the degassing technique 1:1 large-scale tests were performed in a prefabrication hall. The following problems had to be solved:

- Air-free filling of the absorber pipes of the energy geocomposites and the entire pipe systems (including collectors).
- Degassing techniques.
- Air-free re-filling of the entire pipe system after maintenance works.

The required pressure to fill the pipes varies between two borders (Fig. 5):

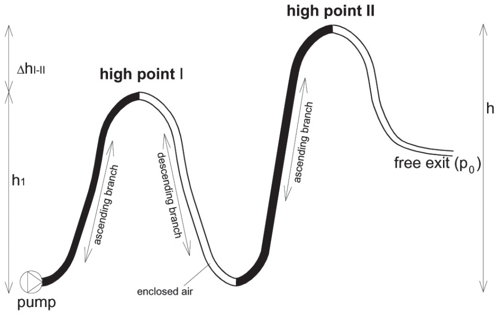

Figure 5. Enclosed air in a pipe system.

Degassing at highpoint I would allow the enclosed air in the following descending line to escape, and the fluid head h_3 would decrease according to the principle of communicating vessels. In this case, a pump has to overcome only the frictional losses h_{fr} in the pipes and the head h_2 including the fluid head difference between points I and II ($\Delta h_{\text{I-II}}$). This yields the minimum lifting height for calculating the required filling pressure.

$$H_{P,\min} = h_{fr} + \Delta h_{P-\max HP} \tag{1}$$

where $\Delta h_{\text{p-maxHP}}$ = level difference between pump and maximum highpoint (= h_2).

If no degassing occurs at the highpoint *I*, a pump has to overcome the pipe frictional losses h_{fr} and the fluid heads h_1 and h_2. This leads to the maximum lifting height

$$H_{p,\max} = h_{fr} + \sum_{i=1}^{n} \Delta h_i \tag{2}$$

with $\sum \Delta h$ = sum of ascending line sections.

Conventional pipe systems, e.g. for energy foundations or secondary circuits in buildings require only $H_{\min}$ due to degassing valves at the highpoints. $H_{\max}$, however, is the theoretical maximum if energy geocomposites are not degassed. This could be verified during the tests when the absorber pipes were filled slowly and bubbles developed at the highpoints.

The large scale tests revealed that the filling pressure for the pipe system has to exceed 2.0 bar in the case of slow filling. Rapid filling at higher pressure ($p_{\max}$ = 3.6 bar) avoided bubbling completely, but if the pressure was subsequently lowered below 2.0 bar, bubbles developed again due to the leaks. If bubbles already existed, a higher pressure was required to drive them out than for bubble-free filling from the beginning.

These observations and values should be considered also on construction sites. Furthermore, for operating the entire system a lower pressure is sufficient than during filing depending on the optimum flow velocity of the fluid.

4 INSTALLATION OF THERMO-ACTIVE GEOCOMPOSITES ON SITE: FULL SCALE TESTS

In principle, energy geocomposites are installed in a tunnel like non-woven geotextiles. But special attention must be given to the connecting pipes leading from the individual heat exchanges (absorber pipes) within the geocomposites through the secondary tunnel lining to the main collector. This detail varies in dependence of the tunnel structure being mainly influenced by the waterproofing system: umbrella (Fig. 6) or full circumference waterproofing, waterproofing with geomembrane, watertight secondary lining (Fig. 7). In the case of groundwater under high pressure special pipe passage elements are required.

In order to optimise the production and installation of thermo-active geocomposites ("energy geotextiles") full scale tests have performed. The tunnel was excavated in fractured to intact rock (flysch), the overburden in the test section varied between 15.6 and 17.3 m. Figure 8 shows the cross section of this single tube railway tunnel close to the test fields. The niche allowed the placement of a heat pump, whereas the test fields extended along the standard tunnel cross section without niche. Figure 7 illustrates the scheme with watertight secondary lining. Hence, no

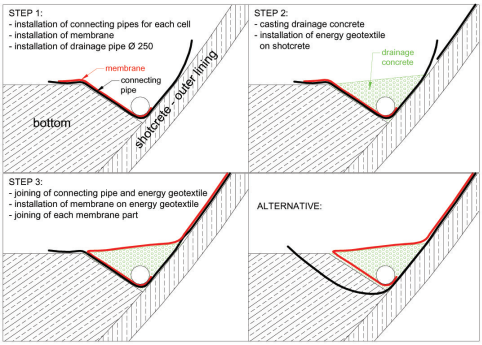

Figure 6. Scheme for installation of connecting pipe in case of an umbrella for drainage.

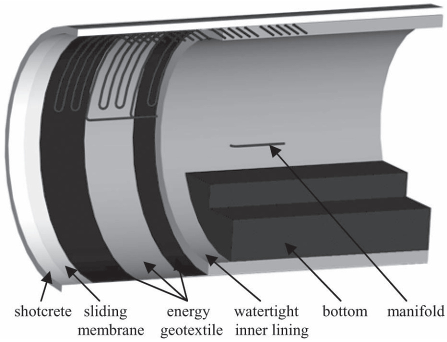

Figure 7. Scheme for installation of energy geotextiles in case of a watertight inner lining.

waterproofing geomembrane is needed, only a sliding geomembrane between thermo-active geotextile and watertight concrete.

The following structural elements were used:

- Non-woven polypropylene geotextile with the following technical data:
  - Mass per unit area: 285 g/m^2
  - Tensile strength: 21.5 kN/m
  - Elongation at maximum load: 100% (MD); 40% (CD)
  - Static puncture resistance (CBR-Test): 3300 N
  - Cone drop test (hole-ϕ): 17 mm
  - Permeability vertical: 70 l /m^{2}s
  - Opening size O_{90}: 95
  - Thickness (2 kPa): 2.5 mm
- Strips of 2.5 × 16.0 m whereby 1.0 m end zones and 0.5 m wide longitudinal zones were not fitted with absorber pipes. The longitudinal strip parts served for fixing the absorber pipes and for overlapping the geotextiles.
- Absorber pipes of linear polyethylene with copolymere octane, outer diameter 25 mm, wall thickness 3.5 mm, exhibiting
  - high flexibility and stability;

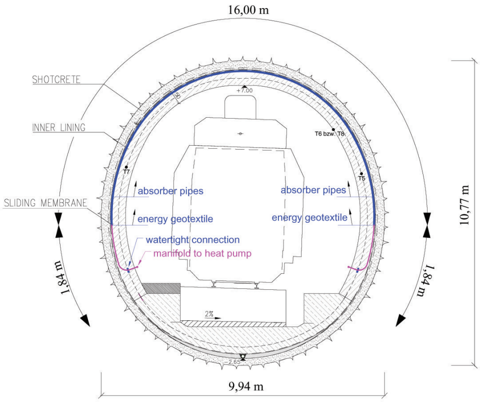

Figure 8. Cross section of the test field.

  - suitability for bending with small radius but small rebound forces;
  - proper long-term behaviour.

The geotextiles were fixed to the primary tunnel lining (shotcrete) with common nails and, additionally, the absorber pipes were fixed with pipe champs to avoid deformations during concreting of the secondary lining (Fig. 9). Four strips of energy geocomposites were connected to one thermo-active unit with one manifold

Figure 9. Installation of energy geotextiles at the testing plant "LT22 – Bierhäuselberg".

for absorber entry and another one for absorber return. Therefore, main attention during filling the absorber system with antifreeze must be paid to a complete filling and degassing of all absorber pipes. Preliminary tests had been conducted to find a suitable technique for filling the absorber system, as there is no possibility for degassing at the top(s) of the absorber system. The passage of the collecting absorber pipes require special measures as illustrated in the examples of Fig. 10. In principle, there are four options: plastic screws, flexible hose, niches, reinforcement cross. The pipes have to withstand the outer pressure of casting the concrete. Therefore, they must be kept under inner pressure (compressed pair, $p_i \geq 2.0$ bar) during concreting. The formwork transport equipment for the secondary tunnel lining needs special openings for the pipe passages. The tightness of the pipe system must be checked after each constructing phase, i.e. before placing the reinforcement, after welding the bars etc.

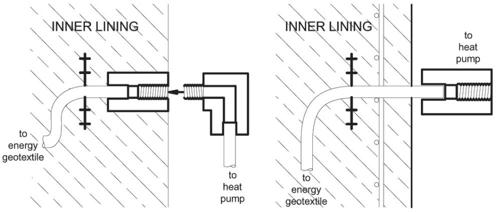

Figure 10. Watertight passage of the collecting absorber pipes through inner lining with screws (left) or flexible hose (right).

5 TEST RESULTS

The energy extracted from the ground was transferred to a heat pump and then to a radiator that emitted the produced heat to the air in the tunnel. Thus, the efficiency of the thermo-active system could be measured. For parametric studies different operating features were investigated. The measurements comprised:

- Temperature of brine solution fluid in the absorbers (entrance, exit);
- Temperature of ground/groundwater and tunnel (air, lining);
- Heat production of the radiator;
- Flow velocities in the heating circuit and absorber fluid circuit;
- Electric current consumption of heat pump and circulating pumps;
- Photographical documentation of the surface of secondary tunnel lining with heat picture cameras to check the operational serviceability of the individual strips of the energy geocomposite.

Immediately after the thermo-active operation started the temperatures of the secondary lining changed. This proved an excellent contact between energy geotextile and waterproof concrete.

In the first operating phase the entrance temperature of the absorber fluid circuit dropped to –1°C due to an over-capacity of the heat pump. The temperature difference between entrance and exit was 3,5°C, and the entrance temperature of the heating circuit went up to 21°C. Therefore, a heat capacity of only 31,4 W/m^2 could be achieved corresponding to a performance factor of $\beta = 4.5$. In order to avoid the formation of ice lenses in the ground the capacity of the heat pump was reduced then.

The measurements have disclosed that a heat capacity of 15 to 20 W/m^2 can be gained from the thermo-active geocomposites, whereby a significant portion of heat comes from the tunnel air. Function tests with a thermal imaging camera showed that two rings of the energy tunnel have a reduced capacity (Fig. 11). This was caused by a not proper degassing of an absorber pipe section.

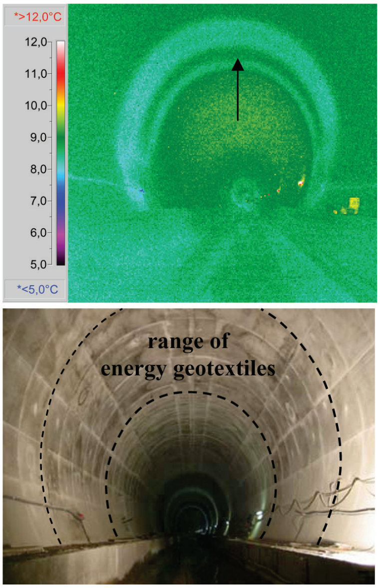

Figure 11. Picture of the test field taken with a thermal imaging camera and a normal camera. The brighter zones of the thermal photo indicate spots of lower thermal capacity.

6 RECOMMENDATIONS FOR PRACTICE AND FURTHER INNOVATIONS

Energy composites consisting of non-woven geotextiles fitted with absorber pipes can be installed like conventional geotextiles. It is not necessary to use absorber pipes of such a high flexibility as at the large-scale test. Conventional plastic pipes are sufficient if the allowable minimum bending radius is considered.

- Fusion-welding of the absorber pipes may cause the formation of bulges inside the pipe seam, thus reducing the fluid discharge area and eventually the efficiency. Therefore, pipe sockets (e.g. electric welding sockets) should be preferred.
- Conventional attachment of thermo-active geocomposite to the primary tunnel lining (shotcrete) is sufficient. Additional fixing of the absorber pipes by means of pipe champs is not necessary.
- The number of pipe passages though the secondary lining (waterproof concrete) should be minimised. The collecting pipes should not be placed along the sidewalls of the tunnel but rather in the base concrete of the invert. At a central point (e.g. emergency exit) they can be led outside then.

Commonly the tunnel structure with waterproof concrete consists of the following elements: Primary lining (shotcrete) – sliding membrane (to minimize transfer of shear forces) – secondary lining (= waterproof structural concrete). With regard to thermo-active geocomposites the following innovative structure was designed: Primary lining – energy geocomposite – secondary lining. This geocomposite consists of three elements: non woven geotextile – absorber pipes – sliding membrane. The geotextile can take the drainage function of the structured geomembrane, if only moderate water ingress is expected.

As sliding membranes these products of 0.2 mm thickness have proved suitable commonly used on construction sites, and possible small leaks don't affect their serviceability, because they serve not for waterproofing but for separation with a smooth interface between geocomposite and waterproof concrete. This reduces stress constraints within the tunnel lining and minimizes the transfer of shear forces on the waterproof concrete (according to the "white tank" technology).

7 CONCLUSIONS

Thermo-active ground structures (energy foundations, retaining walls, tunnels, etc.), but also energy wells are a promising innovation regarding sustainable and clean energy consumption. A significant advantage of such systems is that they are installed within elements that are already needed for statical/structural or geotechnical reasons. Hence, no separate/additional structural or hydraulic measures are required. Foundations, walls (below and above ground) or tunnel linings can be used directly for the installation of absorber pipes for heat exchange.

Energy tunnels using geosynthetics fitted with absorber pipes are a key improvement over the conventional geothermal methods like (deep) borehole heat exchangers or near-surface earth collector systems. Comparative large scale tests and site experience have shown that composites, consisting of non woven geotextiles fitted with absorber pipes provide the best results. Usually, a temperature difference of only $\Delta T = 2°C$ between absorber fluid inflow and returnflow from the primary circuit is sufficient for an economical operation of the energy system. Consequently, such geothermal systems represent low temperature systems. Experience has shown, that the electricity required for operating the entire system commonly varies between 20 to 30% of the total energy output. If no heat pump is necessary (e.g. for free cooling) this value drops to 1 to 3% for merely operating a circulation pump.

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