New yielding elements made of high-strength expanded polystyrene (HS-EPS)

Manuel Entfellner
Implenia Austria GmbH, Salzburg, Austria

Helmut Wannenmacher
Implenia Austria GmbH, Salzburg, Austria

ABSTRACT: Yielding elements as a part of the shotcrete lining represent state-of-the-art tunnelling in overstressed weak ground conditions. These elements avoid overstressing of the shotcrete lining during the early curing process, where the displacement rates are highest and the shotcrete strength/stiffness lowest. A novel yielding element of *High-Strength Expanded Polystyrene (HS-EPS)* is introduced, which overcomes existing systems' drawbacks. This innovative system is lightweight and allows for rapid installation. Furthermore, the modular setup of the element permits an easy on-site adaption to react to in-situ deformation patterns and changing ground conditions. Recent experiences from applications in alpine base tunnels in overstressed weak ground conditions are presented.

Keywords: Tunnelling, Yielding Principle, Overstressed Weak Ground, Squeezing Ground, Yielding Elements, HS-EPS.

1 INTRODUCTION

Tunnelling in weak/fault rocks under high in-situ stress is related to significant and long-term deformations of the primary lining. The range of displacements highly depends on the applied excavation- and support concept (Radončić 2011), but typically reaches several tens of centimetres in weak ground conditions. The direct relation between rock pressure and deformation, represented by the ground reaction curve (GRC) of Fenner (1938) and Pacher (1964), illustrates the two design principles to deal with overstressed weak ground conditions in tunnelling: (i) the resistance and (ii) the yielding principle. The resistance principle with a rigid support system at minimized displacements is limited to low/medium stressed, weak ground conditions and often accompanied by an uneconomic increase in support requirement. On the other hand, the yielding principle allows a certain amount of displacements, enabling tunnelling with reasonable support requirements. The yielding principle is therefore the most suitable construction method in such ground conditions (Anagnostou & Cantieni 2007).

The yielding principle relies on the fundamental relationship of decreasing support pressure with increasing tunnel deformation. The economic optimum between acceptable displacements (over-excavation) and required support resistance depends on the project-specific conditions. Compared to ductile steel sets (e.g. TH-sets with sliding connections), a shotcrete lining with yielding elements generates a high support resistance and allows for controlled ground deformations. This system enabled successful tunnelling in many challenging geotechnical projects (Schubert 1996 and Wittke et al. 2005 and Kovari 2009 and Barla et al. 2011).

Radial displacements caused by the rock pressure are transformed into a tangential closure of the ductile lining by compression of the yielding elements (Figure 1). To avoid overstressing the shotcrete, the load-dependent stiffness of the yielding elements must be less at any time than the time-dependent stiffness of the shotcrete. As the displacement development – affecting the load-dependent stiffness of the yielding elements – is face-distance and time-dependent, a highly flexible excavation- and support concept during tunnelling is necessary.

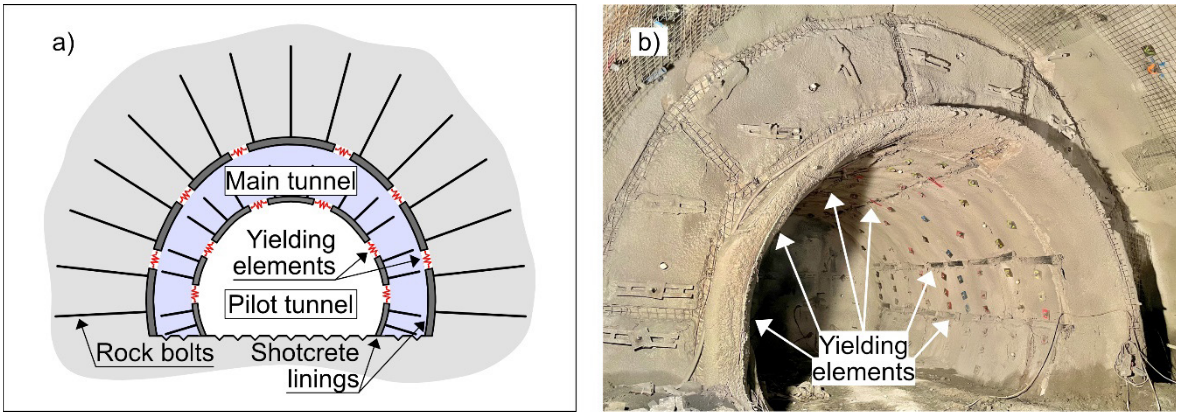

Figure 1. a) Schematic illustration of a pilot- and main tunnel with ductile shotcrete linings with yielding elements; b) Example of a pilot tunnel with 6 rows HS-EPS yielding elements; (Photo: Entfellner, 2023).

Various types of yielding elements have been developed over the past three decades, with a mainly project-specific layout (Moritz 2011 and Schubert & Brunnegger 2017). The elements are either composed of steel, compressible concrete materials or a combined variation. Their heavy weight requires a considerable time for installation. Furthermore, the elements' layout does not allow on-site optimisation in case of changing geological-geotechnical conditions. The experienced disadvantages indicated the following optimisation potentials: (a) reduction of the weight for rapid and simple installation, (b) increase in the flexibility of the stress-strain behaviour, and (c) increase in the stability against tilting in case of anisotropic displacements. Based on these premises, a novel yielding element was developed.

2 YIELDING ELEMENTS MADE OF HIGH-STRENGTH EXPANDED POLYSTYRENE

Expanded polystyrene (EPS) is a polymeric foam, which is produced through physical foaming with steam of the pre-expanded polystyrene beads. The closed-foam cellular structure builds a rigid, tough material with adjustable density/stiffness and holds a high strength-to-weight ratio. The material's inherent mechanical properties are ideal for tunnelling applications, as the strength and stiffness of EPS directly depend on its specific weight, allowing it to control the stress-strain behaviour under axial loading. A novel EPS material with a density ranging from approximately 100 kg/m^3 up to 410 kg/m^3 is implemented for tunnel application. This material is called *High-Strength Expanded Polystyrene (HS-EPS)*. Polystyrene is durable as it is non-biodegradable and chemically inert in soil and water (Horvath 1994). Polymeric flame retardants are added to prevent ignition.

2.1 Layout of the HS-EPS Yielding Elements

The novel HS-EPS yielding element (Figure 2) consists of an assembly of horizontal layered panels with a defined height of 50 mm and a customisable base area (length/width). The total element height typically ranges between 150 mm to a maximum of 300 mm (three to six staggered panels). The modular set-up of distinct density panels affects the mechanical properties of the entire element, being the most vital technical benefit of enforcing various stress-strain behaviour. With modular sandwich construction, configurations for practically all geotechnical conditions can be achieved within a short time. A project-specific configuration/adaption is even possible instantly at the construction site.

The cuboid shape enables a full-surface load transfer between the segmented shotcrete lining. Differential deformations, either in longitudinal or radial directions, are counterbalanced by the materials' elastic flexibility and the shifting of single panels. Therefore, the yielding element is less vulnerable to tilting in case of anisotropic displacements. Depending on the panel configuration and size, the HS-EPS yielding elements weigh only 10-20 kg.

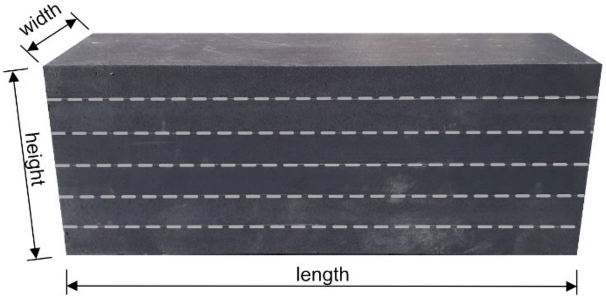

Figure 2. Layout of a HS-EPS yielding element with the dimension 800x250x300 mm (LxWxH) and a total weight of 10-20 kg.

2.2 Mechanical Behaviour of the HS-EPS Yielding Elements

HS-EPS shows a non-linear, hyper-elasto-plastic stress-strain behaviour under uniaxial compressive loading. The stress-strain behaviour can be divided into a (i) linear-elastic phase, (ii) yielding phase and (iii) densification phase, as shown in Figure 3a (Chen et al. 2015). Small-scale and large-scale laboratory tests have been performed to determine the specific material behaviour (Implenia & RWTH Aachen 2020 and Entfellner et al. 2023). The tests display the development of a horizontal compaction band in the centre of the samples as they are compressed (Figure 3b). The lateral strain during compressive loading remains very low, suggesting pronounced axial compaction. This allows for absorbing stresses even at high strains and a reasonable utilization of the material as a yielding element.

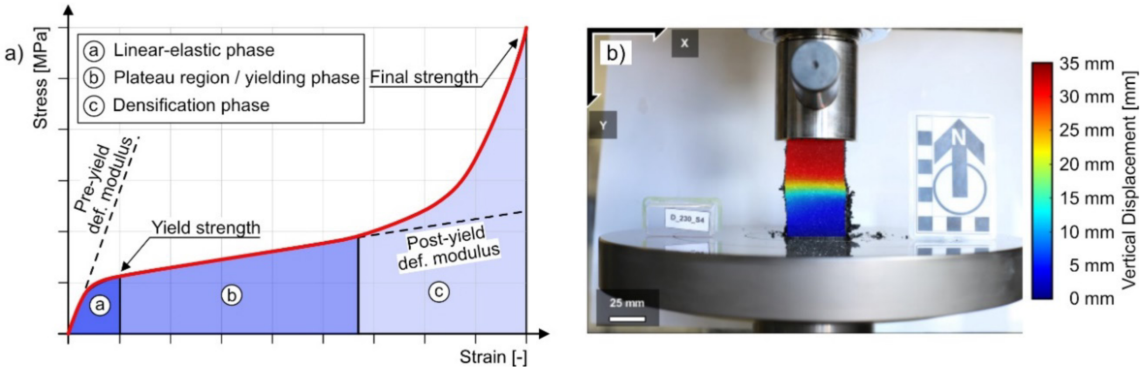

Figure 3. a) Typical stress-strain curve of HS-EPS showing linear-elastic, yielding and densification phase; b) Small-scale unconfined compressive strength test showing contour plot of vertical displacements.

The inherent stress-strain behaviour of HS-EPS ideally fits the desired requirements for yielding elements. The density of the HS-EPS material is the governing parameter for the stress-strain response. In combination with the modular sandwich construction of the element, an individual arrangement of the panels enables one to account for the desired stiffness requirements.

Panels with the lowest density initially start to deform until their stiffness reaches the stiffness of the next stiffer panels, and so on. The panels' density can be chosen in such a way, that the load-dependent stiffness of the yielding element never exceeds the time-dependent strength/stiffness of the shotcrete lining. The stiffness increase of the HS-EPS material, especially during the yielding phase, leads to a good utilisation of the shotcrete and subsequently to reduced displacements.

3 ANALYSIS OF THE SYSTEM BEHAVIOUR WITH HS-EPS YIELDING ELEMENTS

The HS-EPS yielding elements have been first applied to field application in a test section at the Semmering Base Tunnel, Lot 1.1. The section is situated in a fault zone, composed of highly tectonically disturbed cataclastic mica schists at a moderate overburden of 160 m. The unfavourable geological conditions demanded a mechanical sequential excavation with top-heading, bench and invert. The foliation strikes almost orthogonal to the tunnel axis and dips steeply against the heading direction. These conditions required a pocket excavation with up to 21 pockets (Figures 4a and b).

The lining comprises a 300 mm shotcrete layer, four rows of HS-EPS yielding elements and systematically arranged fully-grouted rock bolts. The yielding elements with dimension 800x250x300 mm (LxWxH) are composed of a layered panel configuration ranging from 230 kg/m³ up to 410 kg/m³ to fulfil the stress-strain requirements according to the contract. They are situated symmetrically at the shoulders and upper sidewalls. The elements were installed between two lattice girders, fixed to the first layer of wire mesh, covered by a plate and finally integrated into the shotcrete lining.

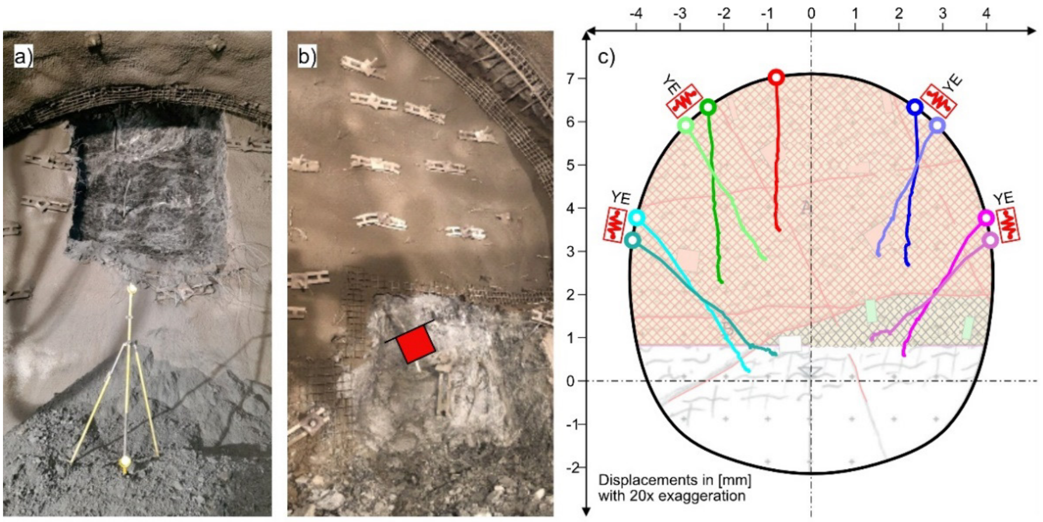

Figure 4. Top-heading advance, showing a) mechanical excavation of first pocket; b) pocket with steeply dipping foliation; and c) displacement vector plot with four rows HS-EPS yielding elements.

Monitoring included daily 3D absolute displacement monitoring with nine targets per section and pressure cells mounted directly on the yielding elements for long-term analyses. Figure 4c shows the vertical-horizontal (V-H) displacement vector plot with 20 times exaggeration and maximum displacements of 210 mm. The monitoring targets are located close above and below each yielding element (YE).

The relative isotropic displacement pattern can be linked to the encountered geological conditions, since the rock mass is more or less structureless due to the governing proportion of cataclasite. The three displacement vectors in the crown show a pronounced vertical settlement, causing a preferential compression of the yielding elements in the shoulders. The neighbouring targets' deviating V-H vector orientation above and below the elements indicates compression. After ring closure (kink at readings of lowest targets), the yielding elements in the sidewalls also experienced an additional increase in compression. The long-term monitoring of the test section shows a stable system behaviour since ring closure.

4 CONCLUSION

The yielding principle promotes controlled and economic tunnel excavation under challenging geotechnical conditions in overstressed weak ground. The application of yielding elements allows a reasonable utilisation of the support capacity and thus reduces the magnitude of displacements, demanding less over-excavation compared to other ductile systems.

The key to success lies in a high level of geotechnical understanding and a flexible excavation- and support concept during tunnelling. In addition, changing geological conditions demand frequent optimising the yielding elements' stress-strain behaviour and spatial positioning in cross-section. However, alternative products of yielding elements are inflexible in terms of rapid adjustment of the stress-strain behaviour and heavy to handle on-site, making them time-consuming for installation. Therefore, the novel HS-EPS yielding element was developed to compensate for these disadvantages.

The lightweight HS-EPS yielding element (~10-20 kg) significantly reduces the time-critical installation process during tunnelling, positively impacting costs and time. Furthermore, the modular sandwich configuration enables a flexible, project-specific adjustment of the stress-strain behaviour even on-site. The tested configurations cover the whole stress-strain range of available yielding elements on the market. The element size can be chosen flexibly and, if necessary, adjusted directly on-site.

The cuboid shape of the element allows for full-surface load transfer between the segmented shotcrete lining. Differential displacements are counterbalanced by the elastic flexibility of the material and shifting of single panels, making the HS-EPS yielding element less vulnerable to tilting.

Figure 5 shows the successful application of the novel HS-EPS yielding elements in the geotechnically challenging Semmering Base Tunnel and Brenner Base Tunnel in Austria.

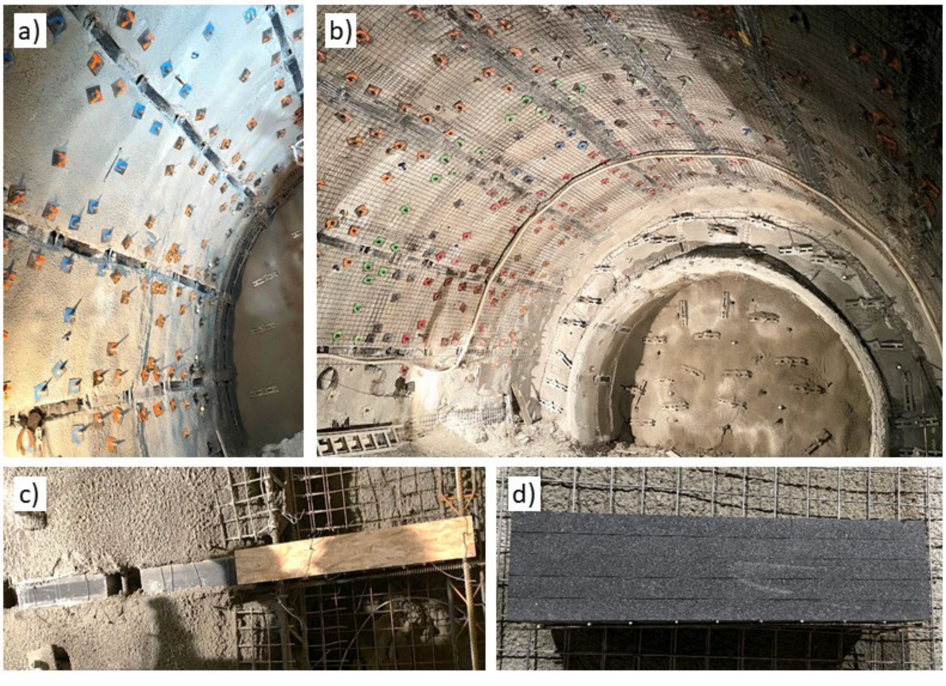

Figure 5. HS-EPS yielding elements, showing a) sidewall with installed elements; b) tunnel with 8 rows yielding elements in the top-heading; and c) & d) installation process; (Photos: Entfellner, 2022/23).

REFERENCES

Anagnostou, G. and Cantieni, L. 2007. Design and analysis of yielding support in squeezing ground. In: *Proceedings of the 11th ISRM Congress*, Lisbon, Portugal.

Barla, G., Bonini, M., Semeraro, M. 2011. Analysis of the behaviour of a yield-control support system in squeezing rock. *Tunnelling and Underground Space Technology* 26 (1), pp. 146–154.

Chen, W., Hao, H., Hughes, D., Shi, Y., Cui, J., and Li, Z.-X. 2015. Static and dynamic mechanical properties of expanded polystyrene. *Materials and Design* 69, pp. 170–180.

Entfellner, M., Hamdi, P., Wang, X., Wannenmacher, H., Amann, F., 2023. Investigating High-Strength Expanded Polystyrene (HS-EPS) as Yielding Support Elements for Tunnelling in Squeezing Ground Conditions. *Tunnelling and Underground Space Technology* 140.

Fenner, R. 1938. Untersuchungen zur Erkenntnis des Gebirgsdrucks. *Glückauf* 74 (32), pp. 681-695.

Horvath, J. S. 1994. Expanded Polystyrene (EPS) Geofoam: An Introduction to Material Behavior. *Geotextiles and Geomembranes* 13, pp. 263–280.

Implenia Austria GmbH and RWTH Aachen University. 2020. Technical report: Uniaxial compressive strength testing of HS-EPS Yielding Elements. (unpublished).

Kovari, K. 2009. Design Methods with Yielding Support in Squeezing and Swelling Rocks. *World Tunnel Congress 2009*, Budapest, Hungary.

Moritz, B. 2011. Yielding elements - requirements, overview and comparison. *Geomechanics and Tunnelling* 4 (3), pp. 221-236.

Pacher, F. 1964. Deformationsmessungen im Versuchsstollen als Mittel zur Erforschung des Gebirgsverhaltens und zur Bemessung des Ausbaues, pp. 149-161. Springer-Verlag Berlin Heidelberg.

Radončić, N. 2011. Tunnel design and prediction of system behaviour in weak ground. Doctoral thesis. Graz University of Technology.

Schubert, W. 1996. Dealing with squeezing conditions in Alpine tunnels. *Rock Mechanics and Rock Engineering* 29 (3), pp. 145–153.

Schubert, W. and Brunnegger, S. 2017. New ductile tunnel lining system. In: *Proceedings of the ITA-AITES World Tunnel Congress 2017*, Bergen, Norway.

Wittke, W., Wittke-Schmitt, B., Schmitt, D. 2005. The 9 km long Kallidromo tunnel of the new highspeed railway line Athens- Thessaloniki, Greece, tunnel sections in squeezing ground. In: Erdem and Solak (Eds), *Underground Space Use: Analysis of the Past and Lessons for the Future*: pp. 321–326.