Testing of TBM excavation material in sandstone and marl for reuse in embankments or as fill

Examination de matériaux d'une machine tunnelière TBM dans grès et marne

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ABSTRACT: Several tunnels in geological formations of molasse, marl or sandstone are planned or are presently under construction in Switzerland. The excavation of these tunnels is very often carried out by tunnel boring machines (TBM). This kind of excavation tends to produce lamellar excavation materials (chips). For the reuse of these materials in road embankments etc., there are certain disadvantages concerning the compression properties. Limiting deformation will be the main restriction on design in the reuse of this material and this is manifested also in terms of the possible changes of volume as a function of time. On the one hand, volume may increase due to instability in relation to water and possibly frost, whereby swelling occurs. On the other hand, volume may decrease due to repeated dynamic loading. Inevitably these volume changes will not occur to the same degree and within the same timeframe. The material can be stabilised by using a variety of cementing agents to improve the key properties. A range of laboratory experiments were performed to find the optimal mixture to be used as a base to the reinforced concrete slabs, which formed the railbed to the major railway line passing through this tunnel. An experimental field test was carried out using this specific mixture to confirm the suitability in relation to the construction method proposed and the properties measured at full scale.

RÉSUMÉ: Plusieurs tunnels dans des formations géologiques de molasse, (Mergel ou Sandstone) sont actuellement en construction. en Suisse. La construction de ces tunnel est souvent fait par des machines à tunnelière TBM. Plusieurs tunnels dans des formations géologiques de molasse, de marne ou de grès sont projetés ou actuellement en construction en Suisse. L'excavation de ces tunnels est très souvent effectuée par les aléseuses de tunnel (TBM). Ce genre d'excavation produit des matériaux lamellaires habituels d'excavation (puces). Pour la réutilisation de ces matériaux dans les remblais etc. de route, il y a certains désavantages au sujet des propriétés de compactage. La déformation limite sera la restriction principale à la conception dans la réutilisation de ce matériel et ceci est manifesté également en termes de changements possibles de volume en fonction du temps. D'une part, le volume peut augmenter en raison de l'instabilité par rapport à l'eau et probablement se givrer, par lequel le gonflement se produise. D' autre part, le volume peut diminuer en raison du chargement dynamique répété. Inévitablement ces changements de volume ne se produiront pas au même degré et dans le même timeframe. Le matériel peut être stabilisé en employant une variété d'agents de cimentage pour améliorer les propriétés principales. Un intervalle des expériences de laboratoire ont été exécutés pour trouver le mélange optimal à utiliser comme base aux dalles en de béton renforcées, qui ont formé railbed à une ligne ferroviaire importante. Un essai sur le terrain expérimental a été effectué en utilisant ce mélange spécifique pour confirmer la convenance par rapport à la méthode de construction proposée et aux propriétés mesurées à complet.

1 INTRODUCTION

The Swiss Federal Railways 'Zimmerberg' Project Team plans to reuse the outbreak material from the tunnel linking Zurich with Thalwil for the foundation layer beneath the concrete running course instead of processed sandy gravel. This project is part of the Swisswide "Bahn 2000".

The outbreak material, a molasse-marl, can not be used as a building material without a further treatment because it is not stable when soaked in water or exposed to frost. Due to this lack of stability, the material is, as a rule, deposited and not used for recycling. Various tests have been carried out using different cementing materials and stabilisation techniques. In addition, a large-scale test field has been carried out (Steiger 1999).

The outbreak material from the first route excavated using a Tunnel Boring Machine in the region of Zurich (Gubrist tunnel) was used to fill nearby gravel pits. However this option was not available for this project and so higher costs and greater feed distances were to be expected. Furthermore, a very sophisticated system and logistic of railroad transport would have had to be organised.

Considerable economies would be achieved by replacing the sandy gravel with stabilised tunnel excavation material. These economies are multiple in reducing the ecological effect – by diminution of considerable emissions in terms of processing, transport and disposal of supplied/unwanted material – and also the cost.

1.1 *Geological and mineralogical details*

The site area is located South of Zurich in the Zimmerberg ridge, which formed one of the restraining boundaries to the glacier, which dominated the Limmat valley during the Wuerm Glaciation. A cut through the tunnel liner is given in Figure 1. A typical geological cross section through is given in Figure 2.

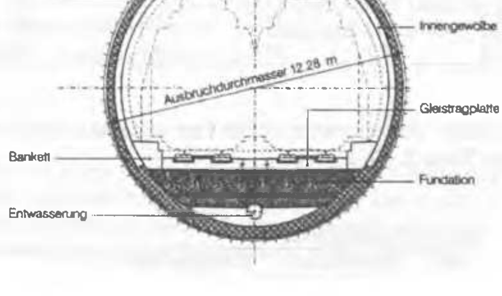

Figure 1 System of the tunnel.

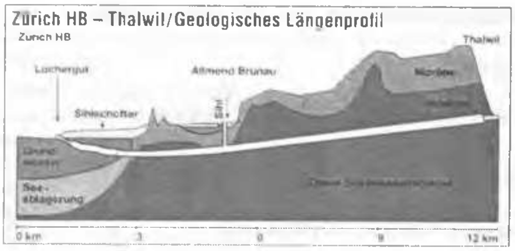

Figure 2. Geological section

The Zimmerberg tunnel is excavated mainly in the Molasse (Obere Suesswassermolasse in Figure 2), which is primarily marl. A tunnel drilling machine (TBM) has been selected for driving the tunnel through this rock. This type of propulsion produces typically lamellar particles of the outbreak material, so-called "chips". Since this marl is known not to be very stable if it comes into contact with water and/or air, various stabilising procedures (with lime and hydraulic bonding agents) were examined. The marl chips also have very weak grain strength.

Neither crushing tests such as those from the Federal Materials Testing Agency (EMPA) nor Los Angeles abrasion tests were carried out on the material. The findings of such tests would undoubtedly have confirmed the existence of weak grain strength. The particle size distribution of three samples taken from storage heaps is not very homogeneous and is shown together with the calcium carbonate content in Table 1.

The marl has a natural lime content ($Ca(OH)_2$) of about 4%. Marls with a carbonate content of 50% have a tendency to exhibit significant swelling (Madsen & Kahr 1985) but this material contains about 15 – 20 % Ca – Smectite, which corresponds to a limited swelling potential. An extensive programme was undertaken by Steiger (1999) to establish the best possible combination of cementing agents (type and percentage) to ensure optimum workability, strength and stiffness gain with time and cost.

First attempts showed that using lime alone as a bonding agent did not deliver the desired results based on Standard AASHTO compaction energy. The addition of lime and a hydraulic binding agent (Dorodur H70 an oilshaletcement) were found both to provide the best improvement in properties and to prevent any tendency towards swelling by coating the particles with the lime-binder-water solution and cementing them together. The Dorodur content was varied between 3 and 9 % of the dry mass, dependent on the maximum particle size.

Not only the chips, but also the cement type, cement content, the age, as well as the compaction and the curing methods have a major influence on the mechanical characteristics of the stabilised layer. This includes the strength and elastic properties as well as the swelling characteristics of the soil-cement mixtures.

Table 1. Grain size distribution and calcium carbonate content

63 mm – 2 mm	2 mm – 63 μm	63 – 2 μm	<2 μm	Calcium carbonate
%	%	%	%	%
65.4	18.3	13.3	3.0	51
59.3	21	16.2	3.5	46
45.8	27.9	21.6	4.7	52

The plasticity characteristics of the fine material (< 63 μm) are shown in Table 2.

Table 2. Plasticity characteristics

Liquid Limit LL	Plastic Limit PL	Plasticity Index IP	Classification
%	%	%	[-]
25.6	12.8	12.8	CL

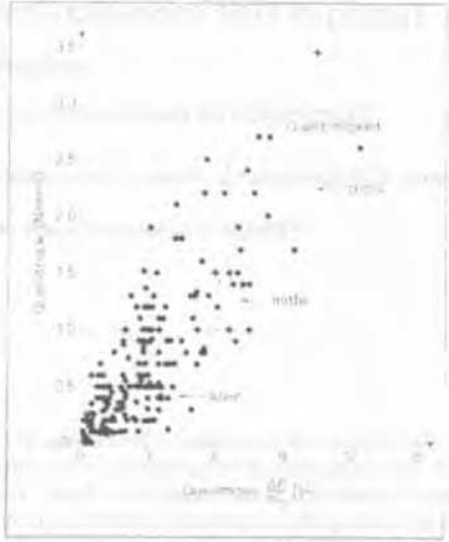

Figure 3. Swelling pressure (Quelldruck) vs. heave (Quellhebung) of marl specimens (Madsen & Kahr, 1985)

1.2 *Project requirements*

It has been specified that the rails (tracks) are to be bedded onto a concrete slab, which is to be founded on a granular base course. This base course was planned initially to consist of well-compacted sandy gravel. The total thickness of the base layer would be up to a maximum of 1.0 m. In the alternative project, the base should be stabilised hydraulically using recycled material from the tunnel excavation.

The following characteristics must be fulfilled, in any case, for an effective foundation layer (or base course):

- inherent stability under all applied loads,
- sufficient load-carrying capacity also under dynamic loads.

These aims can only be achieved when the following requirements are defined and satisfied to within specific tolerances:

- effective/efficient compactibility
- appropriate strength characteristics
- minimal swelling
- sufficient fatigue strength under repeated dynamic loads.

1.3 *Geotechnical Properties*

Various free swelling tests as well as pressure swelling tests on untreated marl have been carried out in the past on material from different origins, as shown in Figure 3. Heave (Quellhebung) of up to 12% or a swelling pressure (Quelldruck) of up to 3.5 N/mm^2 has been measured for samples with large (gross) swelling potential (Quellfaehigkeit).

2 LABORATORY AND FIELD TESTS

Additional field and laboratory tests were carried out to investigate the behaviour and response of the stabilised material. The deformation response was evaluated at specific time intervals at full-scale in the field using a Benkelman beam. The basic strength characteristics were obtained from triaxial tests as well as from CBR tests in the laboratory.

The potential volume change characteristics of the compacted cement-stabilised material seemed to be the most important fac-

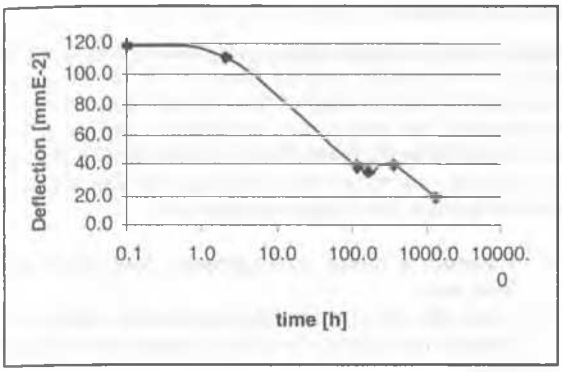

Figure 3. Elastic deflection vs. log time

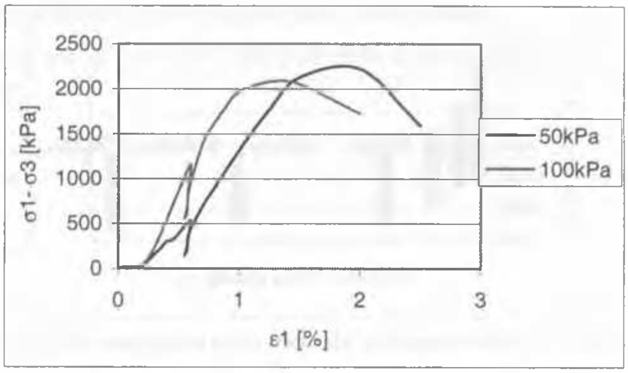

Figure 4. Stress-strain response of the stabilised marl

Table 3. Results from CBR tests

	CBR 1 After compaction 8 h curing	CBR2 After compaction and immersion
Marl with 3 % binder	125 %	151 %
Marl with 6 % binder	187 %	272 %
Marl with 9 % binder	211 %	350 %

tor for the evaluation of this option. The potential increase of volume was investigated by free swelling tests in a temperature-controlled laboratory, without prevention of axial deformation (and volume change). The volume loss associated with cyclic loading was examined via dynamic triaxial testing.

2.1 *Field test*

The filed test was carried out to trial the construction method and the chosen mixture. In maximum 2 layers of 500mm have been compacted by a standard compaction roller. They were covered at the top with a bitumineus layer. Deformation response have been measured with the Benkelman beam and samples have been taken out at two locations for mineralogical investigations and swelling tests. The latter were not possible because the core samples were not stable. Nonetheless, the sides of the boreholes remain stable despite being filled with rain water.

2.2 *Deformation response measured with Benkelman beam*

The measurement of the load-deformation response by means of Benkelman beam showed a decreasing deflection with an increasing period of curing time. This means that the bearing capacity of the stabilised base layer will rise with advancing months. The „SBB“ (Swiss Federal Railways) specification permits 0.50/1.0 mm elastic deflection below the 10 ton axle load. Figure 3 shows the improvement in deformation response, and hence the decrease of the deflection vs. time, and that this is achieved after less than 10 hours. This was achieved although considerable rain fell throughout several days just before the Benkelman measurement was made. However, it was not known whether the water penetrated through to soak the stabilised layer, due to the limited permeability of the material.

2.3 *Bearing capacity measured with CBR laboratory tests*

The CBR-test, in particular also the CBR2-test (after immersion for 4 days), is considered to be a suitable means for measuring the effect on bearing capacity due to soaking/wetting. Although the CBR test results show a positive response for this material (Table 3), the homogeneity of the material, and hence an acceptable bearing capacity with depth, can not be guaranteed.

Table 4. Results of the triaxial shear tests

Test	σ_3	$(\sigma_1-\sigma_3)_f$	u_f	w	ρ_d	ϕ'	c'
	kPa	kPa	kPa	%	g/cm^3	°	kPa
1	50	2131.9	3.9	10.6	2.00	43	430
2	100	2081.9	7.6	10.5	1.96	43	370

Table 5. Results of the swelling tests

w	BM	Dichte ρ	Qh max	Qh max
%	%	g/cm^3	mm	%
9.0	4.3	2.05	0.08	0.06
9.0	4.3	2.09	0.02	0.02
10.0	4.3	2.06	0.03	0.02
11.0	6.0	2.03	0.04	0.03
12.0	6.0	2.03	0.03	0.02
11.0	6.0	2.04	0.63	0.49
8.0	0	2.13	3.57	2.82
11.0	0	2.06	1.37	1.08

Legend:
W initial water content
BM binder content (Dorodur 70)
Qh max maximum swelling during the test time of 30 days

2.4 *Triaxial shear tests*

Two triaxial tests were executed on samples of material stabilised with Dorodur after 24 h curing time. Figure 4 shows the stress strain curves for the mixed material with 6% Dorodur. These tests have been conducted with a material of maximum grain size of 16mm and two different levels of σ_3 (50 kPa, 100kPa). The results show a peak internal friction angle of 43 degree and 'cohesion' of 370-430 kPa (Table 4), while no critical state could be reached.

2.5 *Swelling*

Swelling tests were performed on samples compacted with Standard AASHTO energy in a CBR compaction mould for a period of 30 days. The diameter of the samples was 152 mm. Stabilised material, with a maximum grain size of 32 mm as well as 16 mm, was used but no significant differences in swelling response were determined. However the untreated chips were more susceptible to swelling (Table 5).

2.6 *Cyclic response*

There was some concern that repeated cyclic loads might damage the stabilised material, in that volume loss could occur due to particle abrasion and crushing as bonds were progressively destroyed. This loss of cementation might then also cause abrasion of the particle coating, leaving the chips susceptible to swelling in the future. If almost undetectable breakdown of these bonds was observed, it would be more possible to state that like-

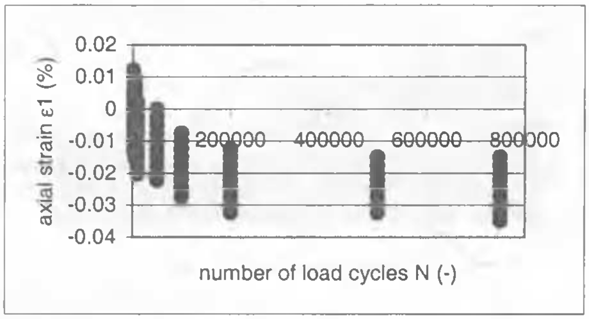

Figure 5. Cyclic response of the specimen with a curing time of 10 days

Table 4. Results of dynamic triaxial tests

Curing time (wet)	Vertical strain ε_1 after 10E6 cycles	Maximum (deviator) stress* σ_1-σ_3
days	%	MN/m²
4	0.105	2.5
7	0.0253	3.0
10	0.0285	3.15
4	0.035	2.35

*for a static compression test after cyclic loading

lihood of extensive long-term swelling would be remote.

The cyclic response of the stabilised marl was obtained from dynamic triaxial tests. Several samples were prepared according to the specification and were subjected, (after 4, 7 and 10 days curing), to 10E6 cycles of a dynamic axial load (at 5 Hz) with a lower value of 65 kPa and an upper value of 300 kPa. This was intended to represent the most likely load conditions in service in the tunnel. Subsequently the sample was loaded axially to failure at a strain rate of 10mm/h. The development of the deformation is measured at specified cycles to obtain the change in dynamic properties (Figure 5). Deformations at 10E6 cycles and the maximum vertical strength after applying this number of cycles are given in Table 4.

The results show that the axial strain tends to be lower as the curing period increases from 4 to 7 or 10 days. The magnitude of axial strain after 10E6 cycles lies well within any serviceability limits and perhaps this is to be expected given that the maximum axial stress applied is between 10 - 13% of the equivalent deviator stress at failure, which is also greater as the curing time increases. The mean vertical strain is the average value of strain in between one load cycle.

3 FINDINGS AND RECOMMENDATIONS

3.1 *Stability*

Long-term stability of the foundation material can be achieved by using cement-stabilised marl, provided that the swelling potential (i.e. the mineral content) of the marl chips does not change significantly as the excavation progresses.

The soil-mechanics investigations and the measurements from the experimental field test have demonstrated good performance relative to:

- material preparation
- miscibility with the bonding agent
- compactibility
- bearing capacity and deformation response.

Nonetheless, the compaction procedures will require special attention immediately after laying the cement-stabilised material. The layer thickness should be limited to 250 to 330 mm and the water content should be slightly higher than the Proctor optimum water content, w_{op}. In any case, the usual compaction requirements should be observed including continuous control of the compaction procedures to ensure a uniform dense layer with low air voids and permeability has been achieved.

3.2 *Risk assessment*

The binder content (dosage) must be selected so that, apart from economic considerations, neither fluctuations in the quality (mineral content, particle size) of the outbreak material nor minor deviations in the construction conditions will lead to damage. In the event that the natural particle size exceeds 32 mm, it will be necessary to review the percentage of Dorodur to be added to the mixture. The long-term target is to:

- construct a robust, homogeneous, low maintenance base layer,
- ensure the deformation response remains within specification throughout the service period of the tunnel, also
- limit the volume change with time.

To reduce the risk of poor performance, the use of the stabilized outbreak material is recommended, for the time being, to dry zones within the tunnelled routes, remote from the portals where detrimental effects due to frost could arise. Only after positive experiences from this project, together with good results from further field tests under appropriate conditions, should this stabilised material be considered for placement in damp and wet zones.

4 CONCLUSIONS

The extensive laboratory and field tests showed that the addition of the binder Dorodur H70 modified the marl chips from the TBM so that the negative characteristics, relating to placement in the base layer, could be eliminated. The tendency for excessive swelling to occur could be avoided and the strength and stiffness were also improved.

This series of tests led to the recommendation to the Project team of the Swiss Federal Railways to use the stabilised tunnel outbreak material in substitution for the commercial supplies of sandy gravel.

5 ACKNOWLEDGEMENTS

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