AFTES

RECOMMENDATIONS FOR THE

DESIGN OF SPRAYED CONCRETE FOR UNDERGROUND SUPPORT

AFTES welcomes comments on this paper

Version 1 - Approved by Technical Committee 9 november 2000

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PREFACE

This document presents the recommendations prepared by AFTES Work Group #20 for the design of sprayed concrete used in tunnels and underground openings. The proposed approach accounts for the different categories of sprayed concrete used in tunneling and underground works. The document presents the state-of-the-art and practice at the moment of its publication. It shall be revised in time to reflect the evolution of technologies and design concepts.

The following three types of sprayed concrete support are considered in this recommendation: protective layer, structural layer, and structural ring. Cases where a structural layer is used in association with other support elements (mesh, ribs, bolts,…) are also addressed, but solely from a sprayed concrete design perspective; design procedures for support systems primarily consisting of bolts, whether these are associated with a protective layer of shotcrete or not, will be dealt with in a forthcoming specific recommendation.

This document is based, amongst other things, on material published in literature or derived from experimental works on the characterization of the mechanical properties of concrete, as well as in situ monitoring and design case histories. This material is documented in articles published in the present issue of the AFTES magazine, "Tunnels et Ouvrages Souterrains".

CONTENTS

CONTENTS

1 - INTRODUCTION

The use of sprayed concrete as a support element in tunnels became popular in Europe in the early 1960s. Meanwhile, calculation methods aimed at a better representation of the ground - structure interaction were being developed (the idea of using a combination of sprayed concrete and rock bolts was introduced in 1956 by the Austrian engineer L. von Rabcewicz during the construction of highway tunnels near Caracas). These approaches, which aim at making the best use of the ability of the ground to "support itself", assume that the primary role of the support system is to provide ground confinement immediately after excavation, thus helping the ground to stabilize itself around the opening.

1.1 - THE THREE PRINCIPAL ACTION MODES OF SPRAYED CONCRETE

Depending on the mechanical properties of the ground, and on the dimension and depth of the opening, sprayed concrete can serve one of the following purposes (Heuer, 1974):

• (1) For lightly fractured grounds, of high strength in comparison to the natural stresses they are subject to before excavation, the role will be that of a simple **"protective skin"**, thus preventing physical, hydrological, or chemical alteration phenomena to occur within the exposed ground;

• (2) For relatively less resistant grounds, an additional level of reinforcement will be required to support the ground around the opening, with this being generally achieved through systematic bolting of the opening walls: this will result in a **"structural layer";**

• (3) Finally, in some cases (e.g. shallow tunnels), sprayed concrete, more often reinforced, will be required to play a more significant supporting role, and will in such case need to be designed as a true **"structural ring".**

Each of these roles corresponds to a different mode of action. This leads to the consideration of three types of sprayed concrete support systems for use in underground construction:

• **Type 1: sprayed concrete as a protective layer;** in this case, sprayed concrete acts as a cement, thus ensuring cohesion to develop between ground particles and/or rock fragments and preventing the ground destructuring to occur. This support system is limited to surficial action, a few millimeters to a decimeter in depth, and is not meant to carry any load.

• **Type 2: sprayed concrete as a structural layer;** this second type of support must be designed as a composite structure, using the combined action of a ring of reinforced ground and a layer of sprayed concrete. In these conditions, the sprayed concrete supports the ground, maintains its cohesion over a limited depth (ranging from a few decimeters to a meter), and acts as a "bridge" between successive support elements (such as rock bolts). It is mainly subjected to shear and has to be reinforced with welded wire mesh, fibers or steel girders.

• **Type 3: sprayed concrete as a structural ring;** in this last case, sprayed concrete has to be designed as a structure per say, and has to be able to resist normal forces and bending moments. As with the sprayed concrete of Type 2, reinforcement is necessary.

These three modes of action are not exclusives nor fully delimited: in particular, sprayed concrete which is meant to serve as "structural layer" always starts to act as a "protective layer". Likewise, a "structural layer" can act locally as a "structural ring", and provide some confining pressure, although the ground is not in a post failure state over the entire periphery of the excavation. At shallow depth, one cannot fully rely on the designer's ability to predict if and where localized failure will take place. One fundamental benefit of sprayed concrete is precisely that it is uniformly applied to the entire tunnel surface, and therefore able to resist at an early stage to defects, heterogeneities or failures within the ground, which are randomly distributed and can play a determinant role in the overall stability of the opening.

1.2- PRESENTATION OF THE RECOMMENDATIONS

The objective of the present document is to put forward some elements of design for each of the three types of sprayed concrete used in underground support systems. It follows three recommendations of AFTES Work Group #6 which contain background information on technological and construction aspects: "Mise en oeuvre du béton projeté dans les travaux souterrains" (Tunnels et Ouvrages Souterrains no1, 1974), "Présentation de la méthode de construction des tunnels avec soutènement immédiat par béton projeté" (Tunnels et Ouvrages Souterrains no31, 1979), and "Technologie et mise en oeuvre du béton projeté renforcé de fibres" (Tunnels et Ouvrages Souterrains no126, 1994). Additional material can also be found in two more recent publications in the UK by the Institution of Civil Engineers (1996) and the Health and Safety Executive (1996), which provide a description of sprayed concrete applications as a support element in tunnels and recommendations on the design and construction of these structures, with focus on shallow tunnels.

This document covers all uses of sprayed concrete in underground works: support of gallery or shaft walls, temporary support at the tunnel face during excavation, either alone or in conjunction with wiremesh, bolts or fibers. However, the design of steel ribs and bolts – which represents, in some applications, an essential element of support – will not be addressed in this document. On the other hand, information will be provided on the use of sprayed concrete as final tunnel liner.

Besides the present introduction, these recommendations consist of five chapters. The three modes of action of sprayed concrete presented in §1.1 are described in Chapter 2. Chapter 3 reviews the principal aspects of sprayed concrete behavior; elements of concrete composition and required mechanical characteristics for each type of sprayed concrete are also considered. The recommendations for the design of sprayed concrete support systems are developed in Chapter 4, with due consideration of all three usage types described above. Aspects related to the inclusion of sprayed concrete into the design of final liners are also treated. Given the role played by instrumentation (especially convergence monitoring) in the design of sprayed concrete support systems, it was felt necessary to review the principles of monitoring; this is discussed in Chapter 5. Finally, Chapter 6 covers the situations where sprayed concrete is used as final liner.

2- THE THREE TYPES OF SPRAYED CONCRETE SUPPORT

This Chapter describes in detail the three types of spayed concrete support introduced in §1.1. It is primarily intended to clarify the field of application of each of the three types of support previously identified, as well as their acting mechanisms.

2.1- TYPE 1: SPRAYED CONCRETE AS A PROTECTIVE LAYER

The first layer of shotcrete placed immediately after excavation, with a thickness of 2 to 5 cm, is essentially meant to protect the ground against any surface alteration. Indeed, this weathering can have detrimental effects on the geotechnical properties of the ground:

• *Dessication* as initially saturated grounds become exposed to ambient air, thus producing a loss of cohesion (e.g. of capillary type) within the first centimeters of ground;

• *Washout* of finer materials at discontinuities which presence controls the shear resistance of joints;

• *Degradation* of the hydromechanical properties of the ground at the opening;

• *Initiation* of swelling phenomena associated with the migration of pore water.

This first layer of sprayed concrete also has a very local (centimeter scale) mechanical effect. This role is vital because it restrains micro displacements, which may in turn to lead to micro failures and subsequent in-depth degradation of the rock characteristics (loss of cohesion) through some "chain reaction" type of mechanism: sand particles left free to move will free the stones that lock the block, and so on (cf. figure 2.1).

Obviously, this weathering mechanism will start developing as soon as the ground is exposed to air and/or water, with more mechanical degradation occurring as the volume of excavated material increases. For this reason, spraying of concrete must start as early as possible, particularly in grounds

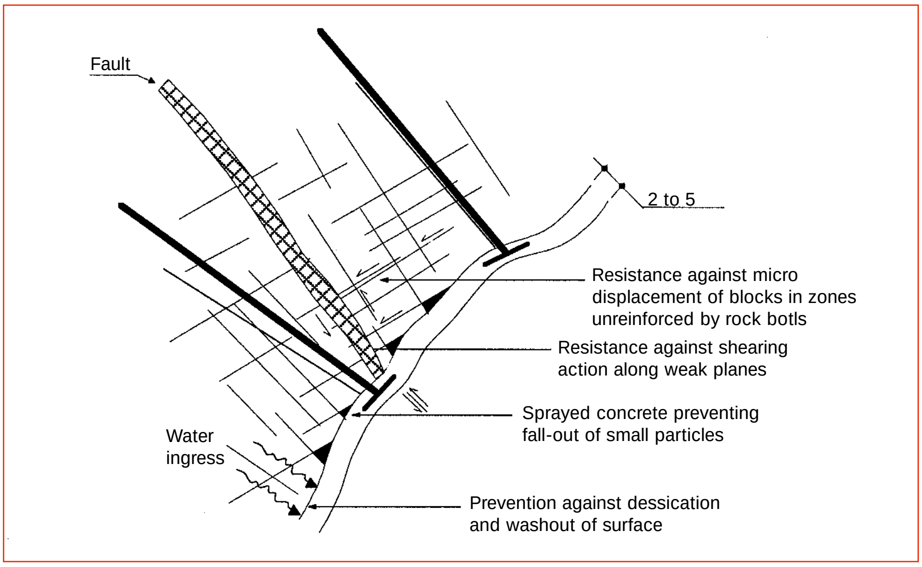

Figure 2.1 - Wheathering mecanisms at excavation faces

sensitive to such weathering: heterogeneous and non cohesive grounds, clays and shales, highly fractured rocks, and swelling grounds. It is often recommended to start the spraying before the completion of the excavation cycle, including over the face that will experience similar weathering effects as the tunnel walls once it is exposed. It must be noted that the mechanical effect expected from the shotcrete layer is not structural resistance but surface cementation.

2.2- TYPE 2: SPRAYED CONCRETE AS A STRUCTURAL LAYER ASSOCIATED WITH REINFORCEMENT

In reality, the ground has already experienced some degree of stress release when the concrete is sprayed: as the ground starts loosening at the opening, stresses are transferred to the underlying grounds, thus creating an area of loosened material that requires support. Even in the absence of surface weathering, grounds such as fractured or stratified hard rocks may lead to similar mechanisms due to unfavorably oriented cracks allowing blocks or wedges of unsupported material to separate from the ground mass.

Similarly to the first case (Type 1), the structural layer of sprayed concrete has the effect of cementing opened cracks and locking unstable blocks. This role is similar to that played by mortar in a masonry arch: it is essential for stability, unless the basic building blocks fit perfectly, which is rarely the case in practice. Besides this stabilizing effect, sprayed concrete acts locally as a structural layer to prevent differential movements of the blocks from occurring:

• Either as a protection net, for large spans (which requires the sprayed concrete to be reinforced). This is the case of the vaults of large underground openings supported with massive rock bolting;

• Or as a compressive shell, when the curvature of the opening is small enough for the concrete to work in compression. This is the case of small arches of sprayed concrete that are placed between closely spaced lattice girders to transfer stresses to the steel elements (using a principle similar to that of soldier piles).

Thus, the main role of a structural layer of sprayed concrete is to resist local failures and small displacements of blocks that could propagate to the surrounding ground. This type of support starts acting on the ground located between the face and the last row of installed rock bolts, then between two consecutive rows of rock bolts and, when necessary on the excavation face.

The second type of sprayed concrete support must therefore offer shear strength and even tensile strength when the excavation profile is irregular or flat (e.g. at the face), or even locally convex. This justifies the use of fibers or wire mesh. The same applies when the shell of sprayed concrete is designed to act as a small arch between lattice girders. The area of influence of the shotcrete layer (at the surface and in depth) ranges between a few decimeters to a meter, i.e. a fraction of the distance between bolts or lattice girders.

Beyond such depth, ground support is primarily achieved by the effect of bolts which prevent plastic deformations to develop within the ground mass as a result of excavation induced stress release. Such deformations, if permitted, could result into progressive failure along weak planes present within the ground mass. Rock bolts can however not act on the area of loosened material that is left unsupported at the surface of the opening, as a result of arching effects developing between the bolts. The role of Type 2 sprayed concrete is exactly to support this area. Because of its creep characteristics, this concrete is flexible enough at the early age to allow the ground to homogeneously deform, without creating any permanent damage in weaker areas.

However, given its limited thickness and irregular distribution Type 2 sprayed concrete cannot be relied upon for transferring stresses over a larger area of the opening. Higher stresses will result in the formation of hinges in the fresh concrete layer. In fact, despite its apparent continuity, the “structural layer” of sprayed concrete can be expected to act as a set of shell elements, bound by hinges, and held by rock bolts. In this respect, it is often compared to the coating plates used with reinforced earth, to contain the ground in the immediate vicinity of the vertical face.

Structural layer types of usage can also be found in the form of grooved shotcrete liners, in which longitudinal recesses, 20 to 30 cm wide, are cut along the shotcrete shell, with the wire mesh being left uncovered at the recesses (figure 2.2). This technique has been used in Austrian deep tunnels in order to allow large conver-

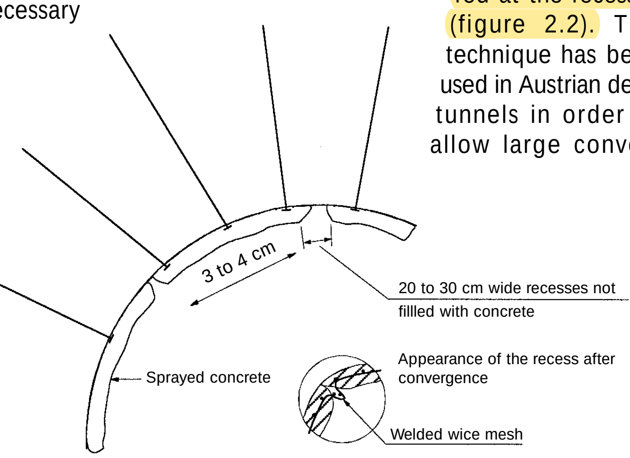

Figure 2.2 - Longitudinal recesses

gences of the tunnel walls to occur (several tens of centimeters) without incurring any damage to the elementary shells of sprayed concrete.

2.3- TYPE 3: SPRAYED CONCRETE AS A STRUCTURAL RING

The layer of sprayed concrete used as a structural ring must be continuous and concave, which is not necessarily the case with Type 2 supports. The layer's curvature must also be as regular as possible: it should be designed as an arch with sufficient resistance to sustain all applied loads. This ring may be closed or opened at the invert, depending on the level of in situ stresses. Its ability to maintain the stability of the whole opening of course relies on the tunnel being stabilized, if required, by appropriate means of support.

Sprayed concrete as a structural ring is primarily used in four situations which are summarized in the following sections.

2.3.1- Limitation of the ground's elastic-plastic deformations

In some heterogeneous grounds and highly fractured rocks, the stability of the opening after excavation cannot be reached without the rapid placement of confinement that will prevent excessive deformations to occur. The main objective of the structural ring of sprayed concrete is to contribute to the required confinement level through its continuous contact with the ground.

The required level of confining pressure can be reduced if a certain degree of convergence is tolerated, provided the corresponding deformations will not damage the ground's characteristics. Due to the high level of creep that develops in young sprayed concrete, these deformations can take place without damaging the concrete, while maintaining the integrity of the surrounding ground and preventing failure to occur in the weaker areas.

The structural ring of sprayed concrete can, in this case, be compared to a structural layer of Type 2, but of higher and more regular thickness, and the ability to resist higher thrusts. It can be considered, in some ways, as a thin shell element acting over the entire vault, or the entire section in the case of a circular tunnel. It should be noted that the larger the radius of the tunnel, the larger the shotcrete thickness required to achieve the desired level of confinement.

A particular case of a structural ring application is that of shallow tunnels in weak grounds where it is imperative to limit ground deformations. The role of the shotcrete ring in that case is to block the ground, even if it means resisting to higher stresses.

The longitudinal stiffness brought by the sprayed concrete shell – especially when it is reinforced by wire mesh, or associated to girders (lattice girder, light or heavy ribs) or rock bolts - can also contribute to control ground deformations in cases where staged excavation is used or where weak grounds are encountered.

2.3.2- CONFINEMENT IN GROUNDS THAT CANNOT BE BOLTED

Most of the time, sprayed concrete rings are associated with rock bolts that limit the convergence, so that ring thrusts are not higher than the level that can be withstood by the structure. However, the ground can in some cases not be bolted, either because of geometrical reasons or of the nature of the ground. In those cases, the concrete ring is left alone to support the ground, and one must ensure that the loads carried by the structure do not exceed its capacity, particularly if the ground pressure tends, in the long run, to reach the initial geostatic pressure, therefore limiting the use of this type of support to shallower tunnels.

2.3.3- CONFINEMENT OF SWELLING GROUNDS (CLAYS, ANHYDRITES)

Due to its continuous contact with the ground, spayed concrete allows to limit water seepage towards the tunnel walls, which is one of the main factors in the development of swelling phenomena.

2.3.4- REPAIR OF OLDER TUNNELS

A continuous ring of reinforced sprayed concrete, placed against a regular masonry vault, can in some cases present a viable economical refurbishment solution even with a small thickness, due to the regularity of its profile (provided the reinforcing wire mesh is anchored).

3- RHEOLOGY OF SPRAYED CONCRETE

Depending on the expected effect and job site conditions, sprayed concrete will play different roles (cf. §1.1).

Some characteristics will require specific attention in order to ensure that the expected effect is achieved. Particular compositions (choice of cement…) should be used in cases where sprayed concrete is taken into account in the final liner design, or if it is used as a long term support element. The different concrete constituents should respect a number of precise guidelines in order to achieve mechanical characteristics that are sufficiently reliable to be taken into account in the design.

3.1- SPRAYED CONCRETE: REQUIRED COMPOSITION

The most recent guidelines concerning sprayed concrete composition are described in the recommendations on the technology and the application of fiber reinforced sprayed concrete – prepared by the AFTES Work Group #6 (Tunnels et Ouvrages Souterrains no 126, 1994) – which should be referred to for more information. The following sections review the main requirements for achieving the minimal characteristics required for sprayed concrete in underground works.

3.1.1- AGGREGATES

The aggregates must comply with current standards. The aggregate distribution must lie within an accepted grading range (cf. Recommendations of the AFTES Work Group #6, 1974 & 1994). This requirement must absolutely be respected (no tolerance) to ensure the characteristics introduced in the design calculations will be as accurate as possible.

The flatness coefficient of the aggregates, measured using the NF P 18-561 standard, must be smaller than 0.25 for aggregates ranging from 5 to 16 mm. This size range is limited to 10 mm in the case of fiber reinforced concrete.

The aggregates must be non-sensitive to alkali reaction.

3.1.2- CEMENT

The cements must comply with current standards, and must be part of the C.E.N. list. The quality and quantity of cement will also be selected based on the aggressiveness of the environment (documentation P 18-011 – June 1992).

3.1.3- WATER

The water used for concrete hydration must meet current standards.

3.1.4- FIBERS

There is no current standard for fibers that are mostly of metallic type. The other categories of fibers (synthetic, glass, carbon) can be used, but they must be tested to prove their efficiency.

The fiber length must not exceed 0.7 times the diameter of the nozzle or else tests should be conducted to assess the risk of pipe blockage.

3.1.5- ADMIXTURES

It is useful to differentiate between two categories of admixtures:

• admixtures included in the concrete composition before spraying (superplastisizer, plastisizer, air entraining admixture, setting delayer and hydration controller);

• Setting and/or hardening accelerators.

The admixtures included in the concrete composition must comply with current standards.

Setting accelerators must be adapted to the type of cement used. One must be careful with some admixtures that can lead to reduced strengths in the medium or long term.

3.1.6- ADDITIVES

Additives (silica fume, fly ash and fillers), when used in the concrete composition, shall conform to the current relevant standards.

3.2- REQUIRED MECHANICAL CHARACTERISTICS FOR THE DIFFERENT TYPES OF SPRAYED CONCRETE

Sprayed concrete will be required to serve different purposes in different situations; its characteristics will need to be defined accordingly.

3.2.1- TYPE 1 SPRAYED CONCRETE (PROTECTIVE LAYER)

This thin protective layer (≤ 50mm) is not intended to play a structural role, and as a result the mechanical characteristics requirements for the concrete are relatively limited. Nonetheless, the concrete will need to (1) adhere to the support, (2) sustain its own weight, and (3) offer immediate protection of the ground.

The spraying method (wet or dry-mix process) will have to be carefully selected in order to ensure that these requirements are met. Concrete bonding to the support can be enhanced through the introduction of additives, such as silica fume (Beaupré). The addition of fibers increases concrete ductility. The mechanical strength of young concrete can be relatively small if the layer only acts as a protective layer. In the specific case where only a protective skin effect is required, a dry-mix sprayed mortar may be used.

3.2.2- TYPE 2 SPRAYED CONCRETE (STRUCTURAL LAYER)

In this case, the objective is to obtain a minimum level of strength in the young concrete. Contrary to Type 1 sprayed concrete, it is also required that this concrete be reinforced with welded wire mesh or fibers in order to meet minimal safety criteria with respect to shear failure (including bending failure) or spalling due to strong convergences (sprayed concrete alone is not capable of playing this role). This reinforcement allows limiting cracking due to restrained shrinkage of concrete (Abdul-Wahads, 1992; Ong & Paramasivam, 1989).

High early strength will be obtained with the addition of setting accelerators during the spraying process. Compressive strengths could in that case reach values around 10 MPa after 24 hours, and even 3 MPa after 3 hours (see recommendations by the AFTES Work Group #6, 1994). When using wet spraying process, concrete composition should be optimized in order to achieve an as low as possible W/C ratio. Pumping can be achieved using a small amount of water provided appropriate admixtures are used.

3.2.3- TYPE 3 SPRAYED CONCRETE (STRUCTURAL RING)

The main concrete parameters for this type of support element are:

• The mechanical strength (short and long term);

• The deformation capacity.

It should be reminded that displacement based calculation methods require the determination of a modulus value to characterize the sprayed concrete behavior. The difficulty, in this case, is to define a simple design approach allowing to account for the simultaneous evolution of the concrete characteristics and the loads transferred by the surrounding grounds during construction. For example, the approach proposed by Pöttler (1990) is based on an overall modulus value of 7,000 MPa which is used to evaluate the short-term state of equilibrium reached by the surrounding ground and its concrete support (cf. § 3.4). Typical modulus values of 10,000 to 15,000 MPa are often used for the evaluation of the support characteristics. It must however be kept in mind that requirements for high early strength values may result in higher modulus values.

Figure 3.1 (after Laplante, 1993) shows the evolution of the elastic modulus E_b of normal concrete (NC) and high performance concrete (HPC) as a function of the compressive strength, σ_b.

This relationship was derived from a model developed by de Larrard and Leroy (1992), using an approach inspired by Hashin's works (1962). It shows a quasi-linear relationship between σ_b and E_b in the short term, with an E_b/σ_b ratio of the order of 2,500 for σ_b < 10 MPa.

Recent tests on sprayed concrete used for railway tunnel structural refurbishment works tend to support the relationship shown in Figure 3.1, both in qualitative and quantitative terms, although some precautions are required for its application to spayed concretes.

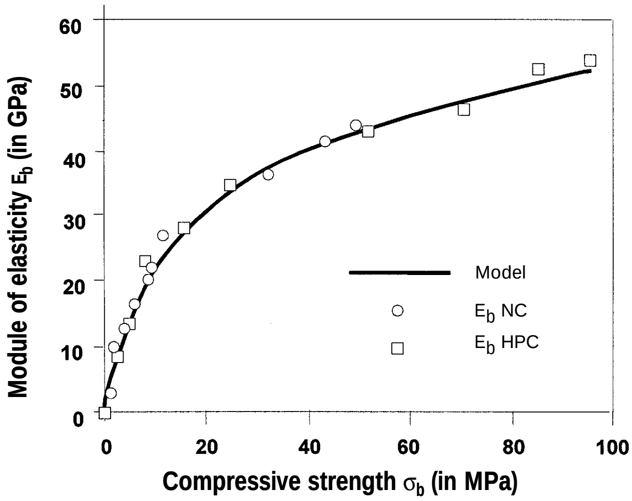

Figure 3.1 - Modulus of elasticity against compressive strength of concrete (from Laplante, 1993)

3.3- LABORATORY TESTS - METHODOLOGY

It is necessary to perform a number of control tests on the sprayed concretes depending on the objectives that are pursued.

The test methods to adopt, for pre-construction trials or for control purposes, are described in the recommendations of the AFTES Work Group #6 "Mise en œuvre du béton projeté dans les travaux souterrains" (Tunnels et Ouvrages Souterrains n° 1, 1974) and "Technologie et mise en œuvre du béton projeté renforcé de fibres" (Tunnels et Ouvrages Souterrains n° 126, 1994). One can also refer to the document prepared by the AFREM, 1995 (Association Française de Recherche et d'Essais sur les Matériaux et les Constructions).

A major difficulty resides in the evaluation of the deformation characteristics of the concrete, for which no standard test is yet available. The analysis of numerous recent experimental results show that the values of E_b /σ_b are relatively scattered and that the evaluation of this parameter is closely related to the method used to measure the concrete modulus. Given the absence of standards in this respect, the approach proposed by the LCPC (Torrenti et al., 1999; Boulay et al., 1999) can be considered to limit the number of uncertainties associated with the testing equipment. This testing method leads to results that are relatively consistent and somehow agree with Figure 3.1. We recommend the use of this test method using 50 mm diameter samples with a length/diameter ratio of 2.

3.4- CONSEQUENCES OF THE EVOLUTION OF YOUNG SPRAYED CONCRETE PROPERTIES

Experience shows that support systems made of young sprayed concrete exhibit an interesting ability to adjust to ground movement and sustain, without breaking, important deformations. In fact, calculations run with modulus values of 20,000 to 30,000 MPa (corresponding to hardened concrete) lead to stresses in the sprayed concrete that largely exceed its strength.

3.4.1- STUDIES ON FRESH SPRAYED CONCRETE BEHAVIOR

To clarify this issues, several studies were undertaken in German speaking countries in the late 1980s, and more recently in Sweden (Chang, 1994), based on intensive laboratory testing programs using young concrete samples. The works of Peterson (1989) and Rokahr & Lux (1987) in Hanovre, those of Aldrian (1991) and Schubert (1988) in Leoben and those of Huber (1991) and Fischnaller (1992) in Innsbruck are worth mentioning. In particular, Peterson (1989) formulated a three-dimensional constitutive law similar to that of salt, which incorporates the three essential characteristics of young sprayed concrete:

• An instant elastic modulus that increases with time during the hardening process;

• A short term creep capacity that increases with the applied stress, and is even more apparent when the concrete is young (Figure 3.2);

• A deformation generated by hydration and shrinkage.

These laws allow simulating with precision the behavior of concrete measured during repeated tests in the laboratory, using a time-step calculation method.

The consequences of this particular feature of young sprayed concrete behavior, and especially of its creep capacity, have been formulated by Pöttler (1990). Using the above described law, Pöttler (1990) first modeled the construction of a tunnel over successive passes, with sprayed concrete liner support, and different values of the concrete modulus within the usual range. He showed that stresses in the concrete reached a maximum value at a distance of one diameter from the front (Figure 3.3), and then decreased due to the importance of creep, before stabilizing around a value of 4 MPa, and this, independent of the geometrical and geotechnical conditions considered.

This parametric study also demonstrated that the maximum normal stress in the concrete, at distance of one diameter from the front, could be approached with good accuracy by selecting a fictitious modulus for the concrete of 7,000 MPa. These results led the author to propose a simplified two-dimensional calculation approach, using this modulus as an overall parameter allowing to account for both the three-dimensional effect of the excavation at the front and the creep capacity of concrete.

It is important to note that these constitutive laws were established for dry sprayed concrete (usually used in German speaking countries) for which it is known that the creep rate is three to four times higher than for wet sprayed concrete, with this phenomenon being due to the higher proportion of cement paste present in dry sprayed concrete. From a more general standpoint, one should also recognize that the results obtained by Pöttler (1990) refer to a particular work configuration, and it that some caution would be advised when applying these conclusions to other tunnels supported with sprayed concrete.

Observations made in the Langen tunnel in the Alberg (Schubert, 1988) offer a good example of the stress evolution in the concrete. Figure 3.4 clearly shows the effect of each face advance during the first three days after installation: creep of concrete (in theory, assumed to lower stresses between each excavation stage) which, in that case, were largely compensated by the creep behaviour of the surrounding ground.

Figure 3.5, taken from the same study, shows the deformations measured with a pair of sensors located on the inner and outer portions of the sprayed concrete ring. The corresponding normal stresses show a reduction after a week, as predicted in

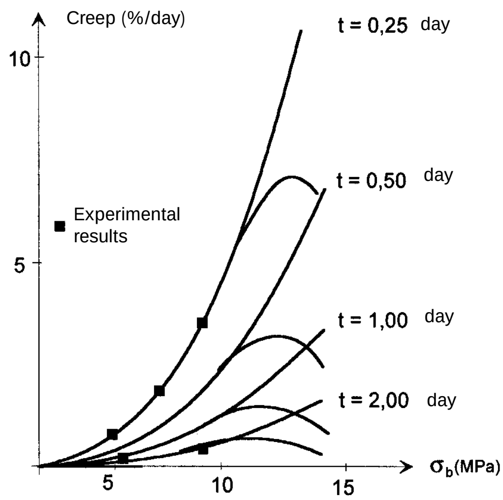

Figure 3.2 - Creep capacities of sprayed concrete of different ages as a fonction of the applied stress (from Pötler, 1990a)

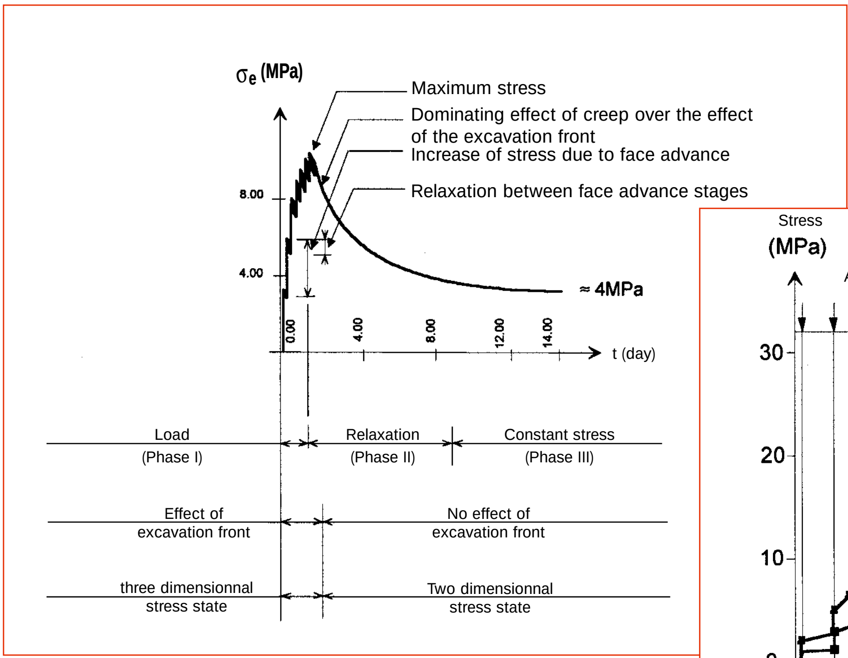

Figure 3.3 - Theoretical evolution of normal stress in sprayed concrete

Figure 3.4 - Langen's Tunnel : tangent strains in concrete with corresponding stresses after cach advance stage (after Schubert, 1988).

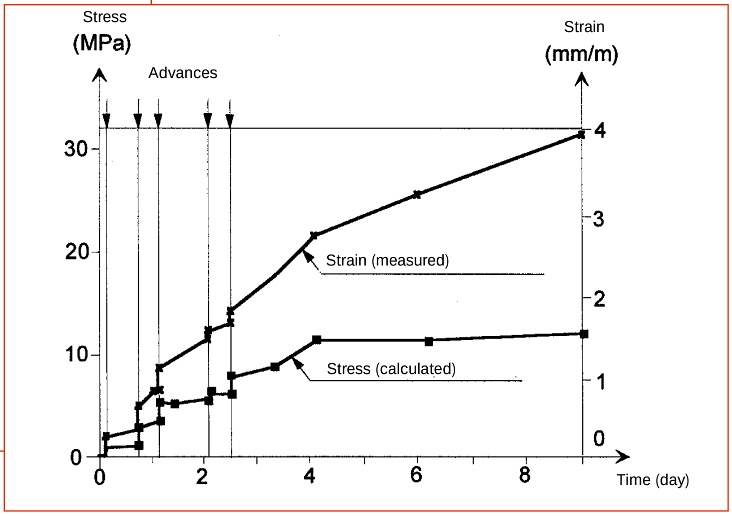

Figure 3.3. Radial and normal stresses both converge to a value around 5 MPa after a period of approximately 15 days, which translates into the disappearance of bending moments at the end of the monitoring phase. This result is in accordance with the observation that failure of sprayed concrete shells occur through shearing – not bending – as described by Rabcewickz and Sattler (1965).

3.4.2- OTHER STUDIES DEDICATED TO THE CREEP CAPACITY OF YOUNG SPRAYED CONCRETE

Different studies conducted by Neville et al. (1983) showed that creep of young concrete is dependent upon several concrete related factors:

- Age of the concrete;
- Composition of the concrete;
- Amount of water;

as well as external parameters such as:

- Duration of loading and load patterns;
- Ambient temperature and humidity.

It should be noted that concrete age is not the only criterion. Test results show, in fact, that a majority of the variations observed in the early creep capacity can be attributed to cements which do not react at the same speed. Likewise, for a given aging level, the lower the ambient humidity, the higher the concrete creep capacity. The use of setting accelerators will cause a significant increase in internal temperature of the concrete, and consequently, of the amount of creep. On the other hand, creep is less important with high performance concrete than it is with standard concrete.

For a given spraying technique (wet or dry), the amount of creep will be higher for higher short-term concrete modulus values. Of course, the sooner the loads are applied (i.e. for rapid tunnel excavation), the more important the final deformations due to creep

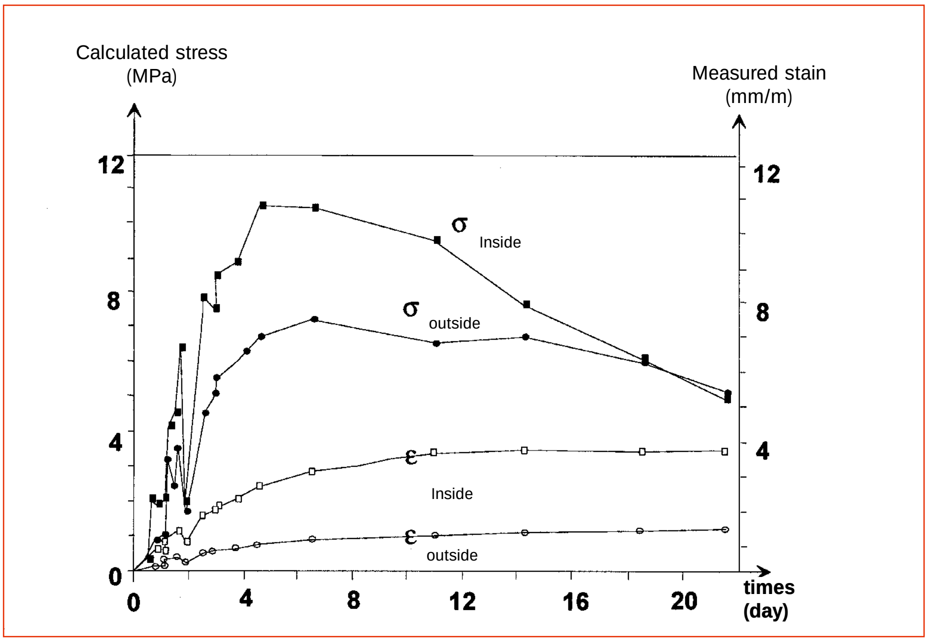

Figure 3.5 - Langen 's tunnel : strains measured at the inner and outer face of the concrete with corresponding stresses (after Schubert, 1988).

3.5- EFFECTS OF SHRINKAGE

Shrinkage phenomena can lead to residual stresses in the concrete, which will eventually translate into the apparition of cracks in the structure.

4- DESIGN OF SPRAYED CONCRETE FOR UNDERGROUND SUPPORT

The objective of this chapter is to describe the principal technical recommendations for the design of underground support systems. A brief overview of design approaches for underground openings is provided in the following sections before addressing the three types of sprayed concrete described in Chapter 2.

In every case, and based on good practice, it will be assumed that the excavation surfaces have been adequately drained so that:

• Washouts of the first few centimeters of concrete is prevented;

• No hydraulic pressure is present during the excavation and shotcreting phases.

It should however be noted that sprayed concrete can contribute to the stability of the opening only if the cohesion of the exposed ground is sufficient to maintain the overall stability for a few hours. Therefore, sprayed concrete cannot in any case be used as a substitute to preconstruction grouting, pre-support systems or sheeting, which are necessary for excavating in soft ground presenting no short term cohesion. For more information on the conditions for which sprayed concrete is appropriate, the reader can refer to the table presented in the documents of the AFTES Work Group #7, "Choix d'un type de soutènement en galerie" (Tunnels et Ouvrages Souterrains n° 1, 1974).

4.1- REVIEW OF AVAILABLE DESIGN METHODS

4.1.1- GENERAL CONSIDERATIONS

The present recommendations come in conjunction with the existing document titled "Réflexions sur les méthodes usuelles de calcul du revêtement des souterrains " prepared by the AFTES Working Group #7 (Tunnels et Ouvrages Souterrains n° 14, 1976), which they complement on specific aspects related sprayed concrete construction.

The design of underground support systems is typically performed using one of the following approaches:

• The load acting on the liner is first determined independently of the support system, and then applied to the liner according to the actual ground-liner contact conditions or,

• The ground/ structure interactions are directly taken into account in the definition of both the loads applied to the structure and the support reaction. Due to the intimate contact conditions existing between the ground and sprayed concrete, the latter is obviously more realistic.

It is important to point out that the design method should account for the behavior of the support system, and more specifically the Type of sprayed concrete to be used (as described in Chapter 2: Type 1, Type 2 and Type 3), and be adjusted in accordance with the requirements of each project phase that is considered (feasibility study, concept design, detailed design or shop drawings).

Finally, for openings where the magnitude of ground movements is an important design criterion, the design method should not address the required of structural capacity, but also provide a quantitative evaluation of the ground deformations. In this case, the design methods must make use of ground deformation parameters.

4.1.2- METHODS FOR LOAD EVALUATION

Two approaches are commonly used for the determination of the loads applied to the support structure: the limit state method and the displacement approach based on techniques such as the convergence/confinement method.

With the limit state method, the “load” applied to the support structure is obtained by using well established formula, as proposed by Terzaghi (1946), Protodiakonov, and Caquot, which all involve the analysis of a failure mechanism in the surrounding ground, generally independently of the presence of any support structure. Care must however be taken in using these methods to the fact that the support system must sustain the displacements induced in the ground before a state of limit equilibrium is reached.

On the other hand, the convergence/confinement method was introduced to consider, in plane strain 2D calculations, the three-dimensional effects pertaining to the interaction that develops between the ground and the support system during the excavation phase (Panet, 1995). It is worth mentioning that this method should not be viewed as a design method for sprayed concrete per se, but rather a method for evaluating the ground-structure contact stresses at equilibrium. With this in mind, this method can be used in conjunction with some of the techniques developed for the design of sprayed concrete support systems that are presented hereafter.

4.1.3- VERIFICATION OF THE STRUCTURAL STABILITY

The methods available for verifying the stability of the support structure are fully presented in Sections 4.2 to 4.4. They apply to all design methods, including:

• Punching of the sprayed concrete where it is used as a membrane between rock bolts, in which case the strength of the membrane in between the rock bolts should be checked;

• Buckling of the concrete: in this case, the verification consists in making sure that the structure is stable under the induced liner thrust, as well as eccentrically when applicable;

• Strength of materials types of calculations, allowing to verify that the values of the iner thrust, N and bending moment, M (or eccentricity e) generate acceptable stresses.

4.1.4- MAIN CHARACTERISTICS OF STANDARD DESIGN METHODS

One can differentiate between five major families of underground opening design methods: empirical methods (qualitative), semi-empirical methods, the subgrade reaction modulus method and the solid composite method.

4.1.4.1- Empirical methods

Empirical methods (qualitative) allow to determine the overal dimensions of the support system to be put in place. These methods are essentially based on a qualitative description of the ground mass and the conditions in which the opening must be excavated, which often translates into the use of index classifications (AFTES, 1978; Bieniawski, 1974 & 1989; Barton et al., 1974 & 1975, Barton, 1983). No calculation per se is performed; the approach is essentially empirical and based on a large number of observations which do not explicitly account for the actual ground-support interactions or any deformation related issues. These methods should therefore be restricted to Type 1 sprayed concrete (all phases of the preconstruction study), and may be used in the preliminary design of Type 2 and 3 sprayed concrete liners. Consideration should also be made to the fact that they are generally limited to specific types of grounds and completely rely on the quality of the ground characterization parameters used in their implementation.

4.1.4.2- Semi-empirical methods

A number of design approaches fall under this category. They are based on well-identified failure mechanisms of the ground and/or the support system. In general, these methods do not take into account the interactions between the ground and the support structure, or allow an evaluation of the ground deformations to be made. The approach consists in first identifying the "load" applied onto the structure and then analyzing the stability of the "structure" subject to this external load, irrespective of any interaction that may develop with the surrounding ground. These design methods are mainly adapted for Type 1 and 2 sprayed concrete at every stages of a project (particularly if the method convergence/confinement is used for estimating the "load"). They should not be used for Type 3 sprayed concrete, except at preliminary design stages.

Amongst these methods, the one proposed by Rabcewicz (1973) is of particular interest for historical reasons, as well as for the role it has played in the early underground applications of sprayed concrete support techniques (New Austrian Tunneling Method).

The Rabcewicz method considers the combined ground and sprayed concrete (and eventually rock bolts) components as a whole. It involves the equilibrium analysis of ground volumes, delineated by logarithmic shaped failure surfaces, with due account being made of all applied loads. This method is adapted to Type 2 sprayed concrete, for which it was originally developed. However, it has become rarely used in practice.

4.1.4.3- Subgrade reaction modulus method

This method consists in modeling the support system by means of "bar" elements and the ground with "springs". As a result, it allows to directly take into account the interactions between the ground and the support structure. Its practical implementation is performed in two steps:

• Evaluation of the loads: this can be achieved by means of semi-empirical methods (Terzaghi's formulation for example), the convergence/confinement method in the case of continuous media (including the effect of possible rock bolts), or using a block equilibrium approach in the case of rock masses; load evaluation is a delicate exercise which result will determine the final design of the support system;

• Evaluation of the stiffness of the springs used to model the ground stiffness reaction: in the simple cases of closed support systems which are sufficiently close to a circular shape, the evaluation of the subgrade raction modulus is derived from the deformation modulus of the ground by applying the simple equation $k = E / (1+\nu).R$ (with E being the ground's Young modulus, n its Poisson's ratio and R the radius of the opening). However, in many cases (horseshoe shape, no invert or invert with a large radius of curvature), the selection of a modulus values can be delicate in areas such as the tunnel walls, the invert or the vault footings. For linear sections of the support system, reference can be made to methods developed for the determination of the reaction modulus used in the design of foundations or retaining walls (elastic or pressuremeter method).

Provided these limitations are well understood, , this approach is well suited for Types 2 and 3 sprayed concrete for every phase of a project. However, it is unsuited for tunnels constructed with staged face excavation, as it is not possible in that case to model the effects of some intermediate excavation phases on the already installed support elements. It must be kept in mind that the calculated deformations may not be representative of the actual ground response. Another limitation is that the method only allows structural deformations to be evaluated, which means that an extrapolation is required if other parameters such as surface settlements need to be computed (e.g. shallow structures).

4.1.4.4- Solid composite method

The solid composite method models the surrounding grounds as a continuous media; it can be applied in different ways: finite elements, finite differences or equivalent, and even analytical methods for the simpler cases. It allows modeling of both the support structures and surrounding ground with due account of all construction phases (staged face excavation), as well as individual interaction mechanisms. Besides, it can also be used in its analytical form for the evaluation of the modulus used in the subgrade reaction modulus method.

It should however be emphasized that this approach which allows a high degree of sophistication (2D or 3D models, elaborate constitutive models, allowance for rock bolt inclusions and rock mass discontinuities) can become extremely cumbersome, as soon as a high degree of refinement is introduced and require the determination of numerous parameters that are difficult to accurately evaluate. In most cases, the approach is limited to simple models (2D models with allowance for tunnel face effects by means of the convergence/confinement method, simplified constitutive models involving a limited number of material parameters). Such models remain easy to implement and are usually found to produce satisfactory results in evaluating the overall response of the structure and the ground, both in terms of loads and deformations. The degree of sophistication should not overshadow the accuracy of the numerical predictions, especially when it comes to estimating surface settlements.

In this perspective, the solid composite method is well suited to the design of the "structural" types of sprayed concrete (Type 3 sprayed concrete), at the more advanced phases of the project (detailed design studies, especially when design is controlled by deformation criteria; shop drawings). On the other hand, the use of this method for Type 1 and even Type 2 sprayed concrete is not recommended (unless the control of the deformations is an important parameter). In fact, for such categories, the role of sprayed concrete is implicitly taken into account in the design of the support system through the introduction of improved (or at least non-reduced) mechanical ground characteristics (associated by the presence of sprayed concrete). These considerations may lead, in some cases, to neglecting the structural effect of sprayed concrete. As an example, the large caverns of the CERN (Boymond and Laigle, 1999) excvated at 60 meter depth through Geneva's molasses, were designed with no consideration of the sprayed concrete contribution to the support system, despite its relatively large thickness (20 cm).

4.2- TYPE 1 SPRAYED CONCRETE– PROTECTIVE LAYER

4.2.1- DESCRIPTION

This type of support is made of a relatively thin sprayed concrete layer directly applied at the excavation surface. The sprayed concrete may be reinforced with wire mesh or fibers. This relatively thin layer is not accounted for in the design of the support system, and stability is achieved by means of:

• The ground itself, protected by the sprayed concrete layer;

• The rock bolted ground;

• A sprayed concrete shell applied later (Types 2 or 3 sprayed concrete, as described in the following sections). In this case, the Type 1 sprayed concrete layer can be taken into account in the thickness of the final liner, provided the characteristics of the initial and final sprayed concretes are sufficiently close;

• Any other support system.

4.2.2- TECHNICAL RECOMMENDATIONS

This sprayed concrete layer is purposely thin, as a thicker layer could attract unwished loading and generate structural damage. The thickness is generally limited to 50 mm for tunnel sections over 30m^2.

This thin layer is placed immediately after (if not during) excavation and generally before the installation of any other type of support.

4.2.3- OBJECTIVES

The objective of this shotcrete membrane is (cf. § 2.1):

• To protect the exposed ground surfaces against rapid alteration by air or water;

• To provide a primary means of protection against limited ground fall-outs.

It can also be used as support for the installation of water barriers.

4.2.4- DESIGN

This type of ground support is mainly designed as a protective layer. It does not play any structural role and, as such, does not require any specific calculation. Design is solely based on empirical considerations.

4.3-TYPE 2 SPRAYED CONCRETE –STRUCTURAL LAYER

4.3.1- DESCRIPTION

This type of ground support is composed of a sprayed concrete layer combined with rock bolts and/or steel ribs. Rock bolts can be made of fiberglass or steel. Steel ribs can be of the H, lattice girder or TH types.

The overal stability of the excavation is not provided by the shell action of this sprayed concrete layer (cf. Type 3 sprayed concrete), but is rather based on the ability for the ground itself to mobilize its resistance with the assistance of the rock bolts or steel ribs.

This type of sprayed concrete can even be grooved to release structural stresses in the case of deep excavations (which precludes the use of heavy steel ribs and leads to the installation of sliding TH types of ribs).

4.3.2- TECHNICAL RECOMMENDATIONS

This type of sprayed concrete must be reinforced either by the introduction of wire mesh or fibers, in order to allow a minimal degree of ductility. Moreover, it would be too risky to rely on the early strength of the concrete alone.

In any case, design parameters should be validated through suitable testing. For example, the plate test described in the AFTES Work Group #6 document "Technologie et mise en œuvre du béton projeté renforcé de fibres" (Tunnels et Ouvrages Souterrains n° 126, 1994) is well adapted to the evaluation of the ductility of this type of support.

In order to be able to rely on the combined action of the sprayed concrete and rock bolts, the construction methods that are used must be provide some guaranty that load transfer can occur between the sprayed concrete and the bolts.

In situations where the sprayed concrete layer is cut to release stresses, it should be reinforced with wire mesh. Fibers are not considered to provide sufficient continuity for the stability of the concrete support placed between bolts.

4.3.3- OBJECTIVES

This type of support is intended to ensure the local stability of the excavation and to prevent ground fall-outs to (cf. § 2.2).

It is intended to prevent any local failure that could be a source of reduction of the self-stabilizing capacity of the surrounding ground. It also contributes to the appropriate response of rock bolts or steel ribs, particularly by preventing local decompressions.

4.3.4- DESIGN

This type of support must be capable of sustaining local loads induced by the surrounding ground and transfer them to the support system installed to ensure the overall stability of the opening (rock bolts or arch girders).

The loads carried by the sprayed concrete layer depend on the ground conditions and should be evaluated on a case-by-case basis, with due consideration of the following factors:

• geo-mechanical properties of the ground;

• location of the support elements;

• orientation of the joints (in the case of rock);

• properties and frequency of the joints (with particular attention to the shear strength that can be mobilized along slip planes);

• local effects induced by rock bolts or steel ribs;

• influence of ground stresses.

Once the principal orientation of cracks and the properties of the ground along these planes have been established, one can estimate the volume and therefore the weight of ground to be supported. In the more frequent case however where no crack systems can be identified - or where the principal orientation cannot be easily established - the weight of ground to be supported shall be evaluated using some appreciation of the overall probable ground response. Figure 4.1 shows a typical ground response mechanism where a bell shape mass of ground is acting on the sprayed concrete layer.

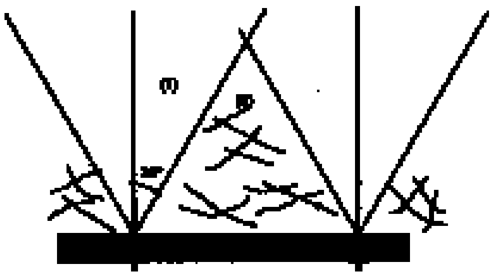

Figure 4.1 - Exemple schematic of liner loading (after Barett & McCreath, 1995).

(1) ground zone reinforced by bottin

(2) ground zone which might push on the liner

Based on experimental works, Fernandez-Delgado et al. (1981), Holmgren (1987) and Vandewalle (1992) proposed several possible failure modes for a sprayed concrete layer subject to a block weight loading:

• Shear failure, either on the perimeter of the supported block or by punching in the anchoring areas (rock bolts or steel ribs);

• Bending failure.

In the former (Figure 4.2), the shear resistance of the sprayed concrete is calculated

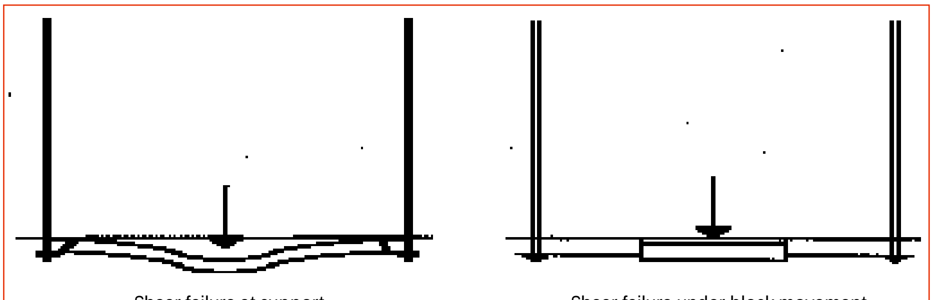

Figure 4.2 - Shear failure (after Barett & McCreath, 1995).

using the simple equation: R = u.t.τ_s, where u is the perimeter of the failing area, t is the thickness of the sprayed concrete layer and τ_s is the shear strength of the sprayed concrete. This last property must be evaluated with care; a value of 0.2 σ_b (σ_b being the concrete compressive strength) can generally be used as a rule of thumb.

For compressive strengths below 5 MPa – which is typically reached in a few hours- this equation is not applicable and the resistance of the sprayed concrete layer is achieved through other phenomena, such as wire mesh web action. This type of action provides some safety against loading of young sprayed concrete as could be caused, for example, by unidentified ground heterogeneities, although this should not be taken as a reliable means of ground support. In fact, sprayed concrete alone is not suitable for grounds where every square meter of exposed surface requires an immediate mechanical support or in cases where the loading rate would exceed the rate of strengthening. For this reason, sprayed concrete must be associated to other types of supports. In cases where a significant amount of confining pressure is required, the resistance against potential bending failure must be checked (Figure 4.3).

This verification can be achieved using conventional reinforced concrete design methods (refer to the Section 4.4 below for Type 3 sprayed concrete). However, when bending moments are not associated with compressive loads, these verifications rapidly reach their limits due to the low strength properties of young concrete. In this case, a minimum level of safety should be provided with respect to the post-failure behavior of the concrete by using:

• wire mesh, which will act as a “net” intended to capture falling blocks;

• fibers, which induce a more ductile type of failure.

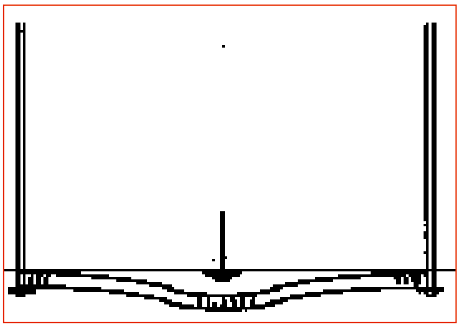

Figure 4.3 - flexural faulue (dafter Barett & McCreath, 1995).

4.4- TYPE 3 SPRAYED CONCRETE –STRUCTURAL RING

4.4.1- DESCRIPTION

This type of ground support is made of a thick sprayed concrete shell (hundreds of millimeters thick), which is capable to alone contribute to the overall stability of the opening. The concrete may be reinforced, with or without fibers. This shell may be associated to rock bolts or steel ribs with direct effect on the mechanical performance of the structure.

4.4.2- TECHNICAL RECOMMENDATIONS

This shell must have a relatively important thickness, in order to guaranty an overall response similar to that of an arch, as opposed to Type 2 sprayed concrete, where only local stability between rock bolts is sought.

The minimal thickness of this shell will be imposed by construction considerations (the excavation profile may be more or less irregular, depending on the ground conditions and the excavation method), with the objective being to guaranty at minimum the shell thickness is equal to the theoretical value used for design. the shell dimensions will also be function of the opening size and of planned construction phasing.

As soon as its thickness reaches 1 or 2% of the radius of the opening, the sprayed concrete doesn’t act as a simple skin anymore and shell effects must be examined to control disorders that may result from underestimating rigidity of the structure. Finally, the shell action can only be obtained if the construction method allows to ensure the continuity of the concrete shell in the transverse direction.

4.4.3- OBJECTIVES

The main objective of this structural shell is to guaranty the overall stability of the entire excavation (cf. § 2.3). It can also offer protection against local disorders (similar to the role of Type 2 sprayed concrete) and the first layers of sprayed concrete can be put in place immediately after excavation in order to protect the surrounding ground against rapid alteration (similar to the role of Type 1 sprayed concrete).

The role of the sprayed concrete shell is to limit the convergence of the excavation as well as to avoid any excessive ground relaxation, which would reduce its strength (loss of cohesion caused by excessive deformations along weak planes for example), and therefore limit its contribution to the stability of the opening. It also allows limiting surface deformations, which is important when construction takes place in an urban area or at shallow depths, or more generally, when excavation takes place in the vicinity of structures that are sensitive to settlements.

4.4.4- DESIGN

The design and verification methods of a sprayed concrete shell can be divided in two categories:

• Impact on ground movements, as estimated with displacement based methods (solid composite method for example) and/or contribution to the stability of the opening;

• Verification of the shell’s resistance.

Each category relies on different methods of analysis and different material property input.

4.4.4.1- Displacement based calculation and stability analyses

For displacement based calculations and the verification of the contribution of the support system, different methods can be used (cf. Chapter 4.1), depending on the actual project stage (concept design, detailed design, shop drawings), as well as on the complexity of the project and the sophistication of the construction method employed. The implementation of these approaches generally rely on the determination of a suitable stress release coefficient to reflect the ground response when the liner support is installed and of the support stiffness.

Regarding the former, current calculation methods allow the influence of the already placed sprayed concrete to be accounted for in the determination of the stress release coeficient at the front (new implicit method) : this effect which typically applies to very stiff support systems can however be neglected in the case of sprayed concrete shells.

The stiffness of bar or shell elements used in the model to account for the support system depends on two parameters: the thickness and deformation modulus of the shell. A suitable representation of the behavior of sprayed concrete can be obtained by selecting nominal values for these two parameters, given that both an upper or lower estimate would present some shortcomings. The value of the nominal thickness should be based on an evaluation of the overbreak volume and placement procedures.

A major issue with the determination of the deformation modulus is that it is crucial and critical, given that one can in principle not rely on one single value of this parameter, which would correspond to a given age of the shell and loading stage. In fact, the response of sprayed concrete shells is determined by the concurrent evolution of the loading (which magnitude increases progressively with the distance from the face) and concrete hardening processes, and subsequently by the deformability and creep properties of the concrete. Moreover, the evaluation of the concrete stiffness is made difficult by the fact that sprayed concrete is applied in successive layers.

Unfortunately, few studies have addressed this issue to date. On this basis, it is proposed to use the following approach, which is derived from the work of Pöttler (1990), and allows to account in a relatively simple manner for the specificities of sprayed concrete support systems:

• For the excavation and sprayed concrete placement phases, until the distance from the face becomes 2 to 3 times the diameter of the opening, a fictitious modulus shall be adopted for the calculations, whatever the actual composition of the sprayed concrete (provided it complies with current and accepted practice). This fictitious modulus is in the range 7,000 to 15,000 MPa, with the value 7 000 MPa being more appropriate for rapid excavation progress cases (sections smaller than 50 m2);

• When the construction phase takes place after hardening of the concrete (e.g. when resuming excavation in the case of staged face excavation), one shall use conventional formulas (derived from standards or other sources) for calculating the instantaneous or long-term deformation modulus.

It should also be reminded that the modulus value should be selected according to the purpose of the calculation. In particular, for a given project, lower estimates of the modulus should be used in the evaluation of tunneling induced ground settlements (e.g. for shallow tunnels), whereas upper estimates should be used in the evaluation of liner loads to ensure that these remain on the conservative side.

This approach aims at determining the maximum loads carried by the sprayed concrete support system. It should be noted that the portion of the load transferred at the early stage (before 3 days) could induce significant creep in the concrete. This phenomenon might be worth considering when evaluating long-term ground deformations, if the early share of loading is significant.

In the case where reinforcement with heavy steel ribs is contemplated, the thickness and modulus of the combined (concrete and rib) structure can be adjusted by introducing equivalent values where the contributions of the two components are in proportion to their respective inertia and area. On the other hand, wire mesh or lattice girders have little effect on the stiffness of the support system, and shall be neglected in the estimation of the mechanical characteristics of the support system.

In any case, the steps taken for the selection of the modulus value of sprayed concrete will have to be substantiated and clearly documented in the design documents.

A few additional points shall require particular attention:

• First, it is important to make sure that the assumed continuity of the shell is actually achieved on the job site, especially in sensitive areas such as the sections where spraying operations resumes (staged face excavation) or at the junction of the wall and invert;

• It should be kept in mind that because of its application method and load transfer mode, the sprayed concrete support system possesses some ability to adjust to the loads it is subject to. Particularly, the occurrence of bending moments, capable of exceeding the flexural capacity of the support system, leads to the formation of cracks, which in turn allow for stress redistribution to take place without affecting the overall stability. This is the case of areas where the shell can present abrupt changes in curvature, such as the crown of ogive shaped sections. In these areas, calculations will not reflect reality. Therefore, based on the verification principles that will be developed in the following sections and on existing standards, it is proposed to use the following approach:

- Calculate the stresses in the shell assuming an elastic behavior with no occurrence of cracking;

- Allow for bending moment redistribution in those points where the ultimate capacity of concrete is reached, either by recalculating the stresses after introducing plastic hinges at these points or by carefully calculating fixed redistribution values. Bending moment redistribution must be performed carefully, especially if bending can lead to a loss of contact between the shell and the ground (as in the case of a rigid shell not tied with rock bolts);

• When the finite element method is used, the attention of the reader must be drawn to the sensitivity of the results to the assumptions used to characterize the ground/concrete interface (risk of slippage at the the ground - concrete interface, which can lead to increased stresses in the lower part of the shell, and subsequent punching and/or settlement during bench excavation if a bench and heading excavation technique is used). Except in such specific situations, the appropriate contact condition to be used for the interface between the sprayed concrete shell and the ground is that of non-slippage, because of the placement method which allows an intimate contact to be achieved between the ground and sprayed concrete.

4.4.4.2- Verification of the shell resistance

The verification of the shell resistance consists in checking that the sprayed concrete sections possess sufficient resistance to support the stresses calculated using the above described approaches.

For distances to the front ranging from 2 to 3 times the diameter of the opening, the concrete strength to be used in the verification during the excavation and sprayed concrete placement stages shall correspond to the age of concrete found at 2 diameters from the face, which depends on the construction rate. For the other stages, the characteristic strength shall be used, since the stability of the section must be verified for the loads carried once hardening of concrete has taken place. In both cases, attention shall be paid to the scattering in mechanical properties of the sprayed concrete, which result from the placement method.

Young concrete strength shall be achieved using the principles presented for Type 2 sprayed concrete (sprayed concrete with guaranteed initial strength, use of fibers and wire mesh). The thickness value to be used is the same as that taken in evaluation of the liner loads.

The following principles apply for the verification of the sprayed concrete shell strength:

• For plain concrete, the method described in the text "Recommandations relatives à l'utilisation du béton non armé en tunnel", prepared by the AFTES Work Group #7 (Tunnels et Ouvrages Souterrains, 1998) shall be used;

• For reinforced concrete, the BAEL standard (French standards for Limit State Design of reinforced concrete) shall be applied with the following safety coefficient for the loads: 1.35 x 1.20 (BAEL's coefficient for dead load x a safety coefficient associated with uncertainties on the reinforcement encasement and the actual position of the reinforcement within the section).

Given that sprayed concrete shells tend to be of constant thickness, the most effective verification approach is to develop an interaction diagram (N, M) allowing the combined moment (M) and axial load (N) values to be checked against the envelope of allowable loads. Moreover, this type of diagram provides some indication of the potential effect of increasing the amount of steel and/or the thickness of the shell. In the latter, as the stiffness of the shell is changed, new calculations are needed to re-evaluate the stresses to be accounted for in the verification. Finally, a verification must be made for the shear load, V.

For sections including steel ribs, the loads obtained from the calculations must be redistributed amongst the ribs and the sprayed concrete; once this distribution is done, each element (steel ribs and sprayed concrete) must be verified separately, using existing standards for steel ribs, and following the approach developed above for the sprayed concrete component. The allocation of loads between the ribs and sprayed concrete can be obtained using one of the following approaches:

• Distribution of the axial loads and the bending moments in proportion to the stiffnesses and the inertias;

• Introduction of a homogenized composite structure subject to the applied axial loads and flexural moments, with the tensile portion of the rib acting as reinforcement.

4.5- CONSIDERATION OF SPRAYED CONCRETE IN THE FINAL LINER DESIGN

4.5.1- INTRODUCTION

This chapter addresses the case where a cast in-place concrete liner is placed inside a layer of sprayed concrete support system. Cases where sprayed concrete is used as final liner are dealt with in Chapter 6.

The quality and durability of initial liners used nowadays allow for the possibility to incorporate their effect in the design of the final liner, with obvious economical consequences. It is of course the Owner's Representative's choice to decide to do so, and as such it should be explicitly formulated in the tender and contract documents.

However, up until recently, the contribution of the initial support system to the design capacity of the final liner has been ignored, due to the following reasons:

• Lack of experience with the long term behavior of concrete shells, especially those made of guaranteed initial strength concrete, for which the admixtures used to achieve high early strength might affect long term characteristics;

• Risk of heterogeneity between the different layers;

• Risk of heterogeneity when resuming shotcreting, in the case where staged face excavation is used;

• Variability of mechanical characteristics which are affected by the quality of workmanship;

• Impossibility (contrary to sprayed concrete final liners) to easily monitor the response of the shell (visual inspection), as this would require the installation of expensive and complicated monitoring devices.

On the other hand, the quality of sprayed concrete support has been found to consistently improve over the years, due in particular to the following reasons:

• Its composition can be adjusted to match the contractual requirements;

• Preconstruction trials are systematically conducted to confirm that these requirements can be met with the proposed equipment and installation method;

• The quality of the concrete is checked through trials conducted throughout the construction period;

• The concrete mechanical characteristics can be improved by incorporating admixtures or fibers without adversely affecting long-term properties.

Moreover, sprayed concrete shells can be used along with steel ribs or lattice girders, rebar or rock bolts, with thicknesses often reaching 20 to 30 cm, which all contribute to their mechanical resistance.

4.5.2- SPRAYED CONCRETE NOT INCLUDED IN THE FINAL LINER DESIGN

Sprayed concrete support should not be accounted for in the design of the final liner in the following cases:

• Type 1 sprayed concrete used alone;

• Type 2 sprayed concrete, unless it is designed as a shell to form part of the final liner;

• Sprayed concrete placed in the invert during construction.

4.5.3- RECOMMENDATIONS FOR THE CONSIDERATION OF SPRAYED CONCRETE IN THE FINAL LINER DESIGN

For practical purposes, it is reasonable to consider that a minimum thickness of 30 to 50 cm of cast in-place concrete should be used in all sections of tunnels of standard shape which are more than 10 m in diameter.

Type 2 sprayed concrete, if designed as a "shell", and Type 3 sprayed concrete can be allowed for in the calculations. In this process, the following recommendations should be observed:

• The guidelines described in the document of the AFTES Work Group #6 (1994) on the application of sprayed concrete shall be used;

• The sprayed concrete composition shall be defined such that contractual criteria pertaining to structural durability are met, especially with respect to the aggressiveness of the environment and the compatibility between the aggregates, the cement and the admixtures (mainly with the alkali-aggregate reaction);

• The sprayed and cast-in-place concrete, where put in contact shall have compatible compositions;

• In cases where staged face excavation is used, the quality of concrete at the interface between subsequent sprayed layers must be checked;

• Depending on the ground type and excavation method, a nominal guaranteed thickness of sprayed concrete shall be defined in the contract and verified on site;

• Depending on the long-term risk of degradation of the sprayed concrete mechanical properties (related to admixtures used to increase the strength of young concrete), it may be appropriate to perform tests during the entire life cycle of the structure.

Generally, Types 2 and 3 supports are applied on top of a protective layer of concrete (Type 1 support). This initial protective layer shall not be included in the design concrete thickness, given the risk of alteration and cracking that may affect its mechanical properties.

Steel ribs or lattice girders, rock bolts and rebars incorporated within the sprayed concrete shell can be allowed for in the design calculations, provided their effective participation to the structural strength can be adequately appreciated and all necessary precautions against corrosion are undertaken.

4.5.4 – RECOMMENDATIONS FOR THE EVALUATION OF STRESSES IN THE STRUCTURE

Whatever the method used to evaluate the stresses in the structure (see Chapter 4.1), it is necessary to ensure that design results are consistent with the assumptions used in the calculations. Indeed, any stress evaluation that would not account for the long-term thickness of the sprayed concrete layer could not be used to evaluate its contribution to the resistance of the final structure, as this approach would cause the liner stiffness and subsequently the stresses to be underestimated.

Similarly, the thickness of the initial liner and design of the final liner should be checked separately.

Some degree of load redistribution shall be allowed for within the shell as defined in § 4.4. The deformation modulus of sprayed concrete to be included in the calculations shall be estimated using conventional formulas (specified or other) for the determination of the long term deformation modulus. When no water-tightness membrane is used, the sprayed concrete and cast–in-place concrete liners can be assumed to be in perfect contact, with water pressures (if any) being applied at the extrados of the sprayed concrete liner. If a water-tight membrane is used at the interface between the initial and final liners, it is recommended that water pressures be assumed to act on to the final liner. It is important, in that case to carefully analyze the structural response at the interface.

4.5.5- PLAIN OR REINFORCED SHOTCRETE

Welded wire mesh present in the sprayed concrete is usually not accounted in the calculations, particularly because of uncertainties related to its location. If reinforcement is required inside the liner, rebar shall be incorporated within the formwork. In cases where perfect bond is assumed between the two concrete layers, the amount (or lack thereof) of reinforcement shall be determined on the basis of a sole concrete layer of overall thickness. Design verifications using the estimated design loads shall be conducted according to § 4.4.

It is also desirable to ensure that a sufficient thickness of cast-in-place concrete is in compression (in any section). The magnitude of this minimal thickness may be specified by the Owner's Representative.

5- MONITORING

5.1- GENERAL BACKGROUND

Modern design and construction methods of underground structures regard monitoring as an essential element for safety and longevity.

It is particularly the case of underground structures where stability is primarily achieved through the self-sustaining capacity of the surrounding soils and rocks. These are, by nature, heterogeneous and anisotropic, which can only be modeled approximately in the analysis using simplified design methods. It is therefore essential to incorporate in addition to with the design process some monitoring approach that would allow to check the design and control the impact of the structure on the environment. Monitoring should therefore be viewed as an integral part of the design process, in a similar manner as the design approaches presented in Chapter 4. For this reason, the monitoring approach is detailed in the following sections. The reader may also refer to the document prepared by the AFTES "L'organisation de l'auscultation des tunnels" (Tunnels et Ouvrages Souterrains, n° 149, 1998) for more information. The main factors involved in the adjustment of the tunnel liner design due to monitoring observations are:

• The density and length of rock bolting;

• The thickness of the sprayed concrete layer;

• The length of each excavation stope;

• The degree of staging (provided such changes can be implemented at the working face);

• And lastly, the sprayed concrete thickness.

In this respect, the design of a sprayed concrete tunnel support can typically be considered part of the observational method.

5.2- MONITORING OBJECTIVES AND MEANS

The monitoring approach should embrace all elements of the supporting structure which is composed of the surrounding ground and sprayed concrete shell, and may include anchor bars, steel ribs and cast-in-place concrete. The instrumentation put in place is intended to monitor the response of the structure so that design parameters can be adjusted, as required, throughout the construction process. It should allow comparisons to be made between recorded values and those predicted at the design stages, as well as provide some comfort that observed measurements and variation rates remain acceptable.

A variety of methods are available to the engineer in this respect; they related to:

• Measurements of relative and total displacements;

• Measurements of stresses within the ground mass and in the different liner elements (sprayed concrete, steel ribs, active or passive anchors);

• Measurements of water pressures and flows.

The most widely used and reliable measurements are those of relative displacements. They are easy to take and their interpretation allows immediate adjustment to be made to the support system. Other measurements may be prone to errors that may result from complex monitoring procedures or difficulties found in installing the equipment or the benchmarks.

5.2.1- DEFORMATION MEASUREMENTS

One can distinguish three categories of methods used for measuring deformations:

• Topographic markers placed at the inner surface of the sprayed concrete shell;

• Measurement points placed in boreholes drilled from the tunnel;

• Measurement points placed in the ground from the surface or from an adjacent tunnel.

5.2.1.1- Inner Markers

Inner Markers most often consist of optical targets or anchor points for Invar wire measurements. These devices must be anchored at sufficient depth so that the actual displacements of the sprayed concrete and/or ground can be monitored. The accuracy of modern topographic devices allows a simultaneous interpretation of displacement records to be made, both in terms of convergence and settlement. The expected error is of the order of 3 to 5 tenths of a millimeter.

5.2.1.2- Ground measurement points installed from the tunnel

Displacements of the surrounding ground (with or without reinforcement) around the tunnel are measured using radial boreholes equipped with anchor points which displacements are monitored by means of extensometers. The accuracy of the extensometers is sufficient to monitor the displacements that can be expected, provided the anchors are properly sealed into the ground.

5.2.1.3- Ground measurement points installed from the outside

Measurement points placed from outside the tunnel are generally used for two particular types of tunnels:

• Shallow tunnels in urban areas;

• Large excavations such as hydroelectric power plant caverns.

In the case of urban tunnels, measurements are intended to monito the evolution of settlements at the surface or next to existing buildings. These measurement points consist of topographic surface markers, associated, in sensitive areas, with deep settlement markers or extensometers.

This apparatus (settlement markers or extensometers) are also used to monitor the evolution of ground deformations around large underground openings. In that case, the equipment is installed above the crown of the opening from a smaller (15 m^2) ancillary gallery excavated parallel to the opening. It is also worth mentioning an increasing use of electro-levels, in which measured rotations are used to derive ground settlements.

5.2.2- STRESS MEASUREMENTS

These measurements are primarily intended to evaluate the state of stress within the sprayed concrete layer and at the contact with the ground. They make use of pressure cells, installed as shown in Figure 5.1, or vibrating wire extensometers placed within the concrete. Each of these devices presents a number of advantages and shortcomings that should be taken into account when interpreting the results.

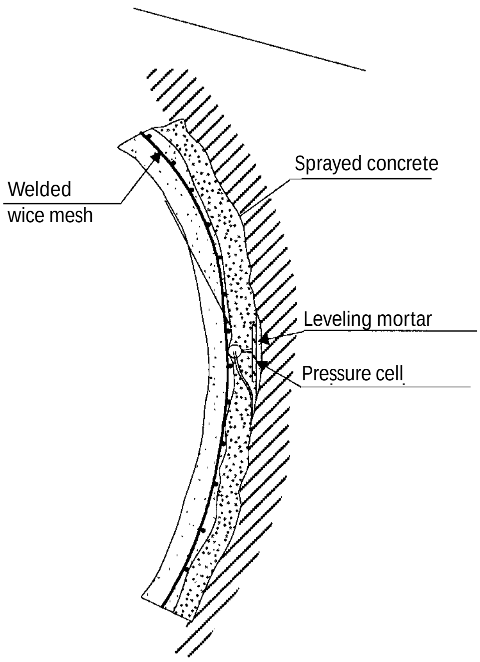

Figure 5.1 - Working principle of pressure cell

In the case of pressure cells, measurements are mainly influenced by the type of surface they are placed against, as well as the installation and measurement procedures. This is essentially true of radial cells ; the tangential cells are considered more reliable because they are better encapsulated in the sprayed concrete. Another feature of these devices is that they lead to measurements that are often erratic, which is the result of the actual displacements of the structure, as well as cracking and hardening phenomena within the young sprayed concrete (Golser et al., 1990).

Deformation measurements taken with the vibrating wire extensometers can be expected to be very accurate and reliable, provided the extensometer has been properly encased and is perfectly fit for purpose. With thin sprayed concrete layers (10 to 15 cm), the location of the device has little influence on the measurements. However, when the thickness of the concrete reaches 30 to 40 cm, bending moments may appear in the support. In that case, the location of the device has direct influence on the result and must be taken into account in the interpretation of the monitoring data. Moreover, the exothermic reaction associated with the setting of the young concrete affects the sensors' response; it is essential that this phenomenon is properly evaluated to achieve a satisfactory interpretation of the observed deformations.

The interpretation of the data also requires an accurate evaluation of the concrete modulus at the time the measurement is taken. Errors in stress estimates obtained with this device are mainly a result of in accuracies in tests performed on cores of the same concrete at the same age, which are assumed to be homogeneous and reflect the actual state of the concrete inside the structure. Recent research on the rheology of concrete has allowed significant progress in this respect.

It should also be mentioned that strain gauges are sometimes installed on steel ribs or rock bolts. These gauges are extremely fragile, and their placement, as well as maintenance, require special attention. Provided these conditions are met, they can provide valuable information on the state of stress of the structure.

Globally, stress estimates derived from deformation measurements are nowadays considered more reliable than pressure cell measurements, in spite of the assumptions that they require on the value of the concrete modulus.

5.3- MONITORING SECTIONS

Monitoring sections are intended to provide, all along the tunnel, the data needed to achieve a good appreciation of the geomechanical response of the ground and of the behavior of the support structure. One usually differentiates between standard monitoring sections and enhanced monitoring sections.

5.3.1- STANDARD MONITORING SECTIONS

These sections are easy to install, and, as a result, used at several locations along the tunnel. They consist ofmarkers placed on the inner liner surface to record convergences and settlements. The number of markers depends on the tunnel geometry and construction phasing. It should be at least three, inasmuch as this does not impede construction activities. This type of monitoring section is appropriate for the excavation stage as well as after completion of the works.

5.3.2- ENHANCED MONITORING SECTIONS

These sections (Figure 5.2) are more heavily equipped with sensors, as they are meant to provide information on both deformations and stresses. They consist of:

• Pressure cells (placed radial or tangent to the section) or extensometers placed within the concrete;

• Radial extensometers, which length and number depend on the size of the tunnel: it is recommended that a minimum of two anchor points be used with each extensometer; the length of this apparatus must be defined in accordance with the expected magnitude of displacements and should not be less than one diameter of the tunnel;

• Convergence and settlement markers placed on the inner surface of the liner next to the tips of the extensometers.

In the case of urban tunnels or large underground openings, these sections can be valuably complemented with settlement indicators installed from the surface or with extensometers installed using ancillary galleries.

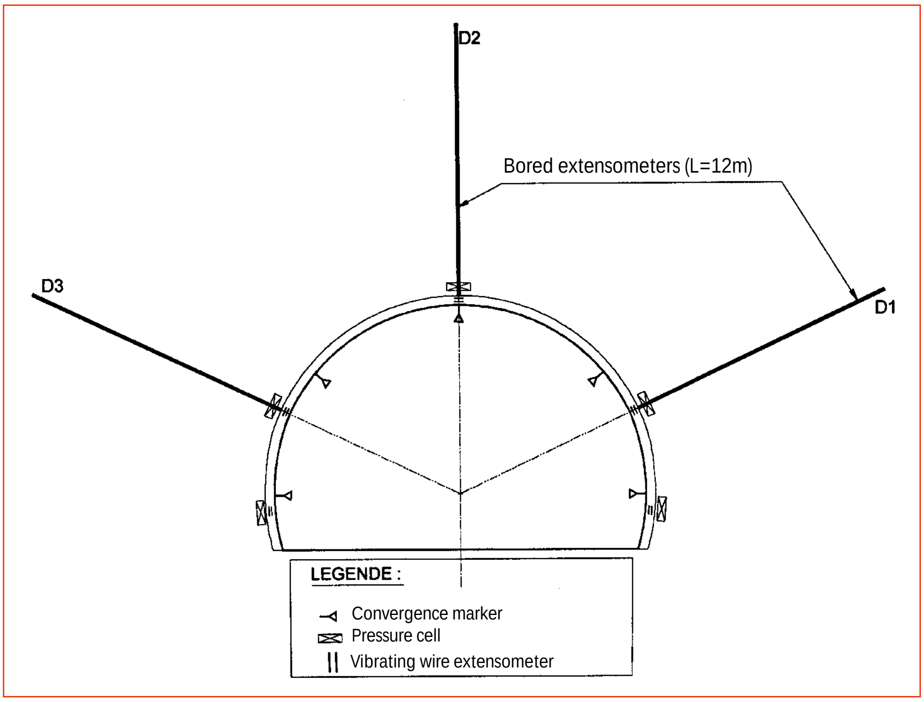

Figure 5.2 - Entranced monitoring section

5.3.3- SPACING OF THE SECTIONS AND FREQUENCY OF MEASUREMENTS

The spacing and type of monitoring sections should be selected in view of the type of anticipated geology. The monitoring system should be defined in accordance with the geomechanical properties of the ground and the depth of cover, as well as the environment of the tunnel or the underground opening.

For linear structures, standard monitoring sections can be placed at approximately 30 m intervals where geotechnical conditions are relatively homogeneous. In the case of large openings, their location should also account for geometrical changes in cross-sections, as well as the environment of the opening (intersection with a tunnel or adjacent tunnel).

These sections are more difficult to install, therefore more costly. For this reason, they will be preferably located, in the case of linear structures, in areas where important convergences are expected and at reference design sections. In the case of large underground openings, they will be distributed along the structure with a maximum spacing in the order of 50 m.

Whatever the type of monitoring section, the frequency of measurements should be left to the appreciation of the engineer responsible for the monitoring program or the design. This frequency should take account for the different phases of construction and the rate of observed deformations (in the particular case of surface settlements the frequency would need to be significantly higher, up to several per day, for monitoring sections located in the vicinity of the advancing tunnel face).

5.4- INTERPRETATION AND BACK CALCULATION

5.4.1- GENERAL BACKGROUND

The main purpose of the monitoring program is to verify the adequacy of the support structure with the geomechanical conditions that are actually encountered, and as such the measured stresses and deformations can be expected to stabilize with time. It is therefore essential to focus on the relative variations in measurements. The magnitude of deformations required to reach equilibrium depends on the depth of the tunnel and the characteristics of the ground. Moreover, in the case of urban underground structures at shallow depth, the deformations must be compatible with the sensitivity of adjacent buildings. In analyzing the results, one should therefore take account of the depth of the tunnel and its location, as well as its urban or non-urban nature. The interpretation of the results in terms of structural response therefore differs from a mere compilation and reduction of the monitoring data. It requires engineering know-how (refer to the document from the AFTES on "Organisation de l'auscultation", Tunnels et Ouvrages Souterrains, n° 149, 1998).

5.4.2- CONVERGENCE MEASUREMENTS

5.4.2.1- General considerations

Convergence markers or extensometers should be placed as close as possible to the advancing front, and the first readings taken immediately after installation. The distance of installation behind the face should be less than that equivalent to one stope or one day.

Design calculations based on the solid composite method allow to account for the deformations induced by each construction phase, as well as long term effects; it is important that these aspects be used in the interpretation of the convergence or settlement measurements. The methods proposed by Panet & Guénot (1982) and Panet (1995) can be used in order to compare long-term predictions with observed data. These methods provide some appreciation of the ultimate convergence, based on measurements taken over a period of several weeks to a few months.

Whatever the structure (tunnel or opening), the observed convergence rates, outside the zone of influence of construction, should always decrease with time. If this is not the case, some kind of reinforcement of the support system must be provided immediately. In sensitive urban areas, the allowable convergence rate may be reduced in order to achieve better control of surface settlements. Specific settlement measurements may be required in this case in order to adjust the construction phasing as needed. In all cases, the uncertainties pertaining to the design and construction of sprayed concrete structures require continuous monitoring, with real time use of monitoring data.

5.4.2.2 – Real time response of instrumentation data

Relative convergence measurements should be analyzed in real time in order to allow the designer to take corrective action on the support system when this becomes necessary. The concept of warning levels can be introduced to determine when such action should be triggered. It is however extremely difficult to assign any pre-established fixed value to this parameter, as it must be adjusted on the basis of the environment, depth of tunnel and behavior of the ground at "failure" (brittle failure, hardening, dilatancy, etc…). It is mostly the rate of deformation (velocity) or its variation over time that must be carefully monitored. Any sudden change in the rate of deformation must be interpreted as a potential risk and be treated consequently.

Computational results, given the number of assumptions required, must always be checked with observed data. Comparisons should of course be made with due account of the accuracy of measurements, especially with small magnitudes. However, the impact of these measurement errors tends to decrease when the rates and their variations are considered over a sufficient period of time.

5.4.3- EXTENSOMETERS PLACED WITHIN THE GROUND

Extensometers placed in the ground through boreholes allow to measure relative ground deformations and compare them to values capable of causing yield within the ground mass.

5.4.4- STRESS MEASUREMENTS

The difficulties of achieving reliable stress measurements in sprayed concrete and at the ground-concrete interface are described in section 5.2.2. For this reason, it is preferable to focus on the variations rather than total values of measured data. Factors such as the concentration and length of rock bolts have some influence on the stresses carried by the sprayed concrete layer. For example, when 4 to 5 m long rock bolts are used with a density of one or two per square meter, the ground pressure induced on the sprayed concrete liner is significantly reduced as a result of arching that develops between the bolts. Similarly, when no bolting is used, the heterogeneous nature of the rock or lack of contact between the pressure cell and the ground may cause some arching to develop over the pressure cell.

The quality of data obtained from tangential cells is dependent on the response of the structure: in the case of strong convergences, the sprayed concrete shell will tend to be subject to shear, and the pressure cell readings will in no case reflect predicted values. In such case, convergence measurements will provide the only reliable indications on structural safety.

5.4.5- BACK-ANALYSES

Back-analyses shall be based based on (1) total or relative deformations measured at enhanced monitoring sections (that are more heavily instrumented), and (2) geological and geomechanical surveying conducted at the face. Parameters for these analyses may be obtained through in situ testing using devices such as the dilatometer, flat jack or pressuremeter.

It is also suggested that analyses be best conducted in two phases:

• The first phase is based on simplified computational methods (e.g. analytical) and is aimed at evaluating the state of deformation of the support structure (purely elastic or elasto-plastic) and at identifying the most critical parameters. This phase should help verify if the basic design assumptions are correct. However, one must be aware of the inaccuracies that are inherent to the assumptions used in such approach and subsequent computational results. It would be unrealistic to try to reach a high level of accuracy in such back-analyses.

• Once the response mechanism has been identified, a finite element analysis can be considered. This would tend to be standard practice for large underground openings (hydroelectric plant, storage). The same considerations as indicated for the frist phase obviously apply as regards the accuracy of computational results.

6- STRUCTURES NOT LINED WITH CAST-IN-PLACE CONCRETE

6.1- INTRODUCTION

Sprayed concrete was used for the first time as final liner of an underground structure in the late 1960's. This practice has developed since then due to advances made in the understanding of the mechanical behavior of the concrete and the ground. It still remains uncommon however both because it is not suited to certain projects (with issues related to water tightness and surface roughness) and because of the reluctance of some stakeholders and lack of real case evidence.

On the other hand, sprayed concrete used as part of non structural liners has become relatively popular (Type 1 and 2 sprayed concrete), with applications in road tunnels (usually with low traffic), railway tunnels and hydraulic tunnels (particularly in Norway).

When used in a structural role (Type 3 sprayed concrete), it is generally complemented with an inner liner of cast-in-place concrete. Nevertheless, a few structures of various sizes and shapes have been constructed with sprayed concrete as final liner. The most remarkable applications include the Furka (14 km) and Vereina (19 km) railway tunnels in Switzerland and the Sèvres-Achères water treatment chamber (61 m long with 160 m² cross-section) in France.

Finally, it is worth noting that sprayed concrete can also be used as inner liner in the the refurbishment of older tunnels (S.N.C.F., S.I.A.A.P.).

6.2- AREA OF APPLICATION

Sprayed concrete final liners differ from cast-in-place concrete liners on the following aspects:

• The placement technique (no form work required, need for an appropriate construction ventilation system, ability to spray thin layers of concrete, ability to adjust the shape of the concrete shell to the actual excavated profile);

• The type of surface (higher surface roughness).

On the other hand, with the exception of young concrete - which is of lesser importance when it comes to final liner (in comparison with initial support systems) - sprayed concrete presents mechanical properties that are similar to those of cast-in-place concrete (with typical 28 days strengths of σ_b = 25 MPa to 30 MPa).

Consequently, the situations where the use of sprayed concrete as final liner could be of particular interest are:

• Short tunnels, tunnels with varying cross sections, underground intersections, for which it would not be economical to recur to prefabricated form works (e.g. the Chauderon railway station in Lausanne);

• Caverns;

• Structures where the introduction of form works is difficult (sewers tunnels, etc.);

• Tunnels with low operational requirements.

In these conditions, the main advantage of sprayed concrete used as final liner is cost reduction

• Reduction in the volume of excavated material, which can be equivalent to the thickness of the cast-in-place concrete ring (at least 30 cm thick) when its installation can be avoided;

• Reduction in costs and construction time, if the installation of a cast-in-place concrete ring can be prevented, even though this may lead to a slightly thicker layer of sprayed concrete. In the case of heterogeneous or fractured grounds where the amount of over-cutting is significant, substantial savings can be expected in comparison with the costs associated with the installation of a full ring of cast-in-place concrete.

6.3- SPECIFIC LIMITATIONS

Reservations are often put forward by designers, contractors and operators when it comes to sprayed concrete being used as final liner, for the following reasons:

• Difficulty to make the tunnel watertight;

• Surface roughness, air friction and sensitivity to dust;

• Heterogeneity and variability of the concrete characteristics;

• Difficulty to guarantee its durability.

Difficulty to attach inserts to the liner is also quoted as one shortcoming for this type of structure. These aspects are further developed in the following sections along with possible remedial steps that can be taken to cope with these limitations.

6.3.1- WATER-TIGHTNESS

In many cases, a structure entirely made of sprayed concrete will provide a level of water-tightness which is satisfactory to meet the operation requirements of the tunnel. Water ingress can be controlled using drains or a secondary non-structural shell (that can incorporate an architectural finish).

on the other hand, the use of sprayed concrete as inner liner is not recommended in the following cases:

• High water head;

• Highly pervious grounds (AFTES Classification, Tunnels et Ouvrages Souterrains, n° 28, 1978);

• Environmental conditions prohibiting water table drawdown;

• Functional requirement to achieve full water-tightness.

Some practical evolution is however foreseeable in this field in the near future. Of particular interest in this respect is the case of the railway station of Chauderon in Lausanne, where the water-tightness system, made of a geomembrane, was successively coated with a final liner made of a fine wire mesh, a dry-sprayed mortar (a few millimeters thick) and wet sprayed concrete. Feedback from this case history in the coming years will certainly contribute to expanding the scope of application of sprayed concrete used as final liner.

6.3.2- SURFACE ROUGHNESS

The use of sprayed concrete as final liner may result in specific provisions being required as regards operation and safety equipment, and possibly with the architectural coating; such provisions must be introduced at the design stage.

For road and motorway tunnels, the higher roughness of sprayed concrete walls results, on the one hand, in faster dirtying by vitiated air and, on the other hand, in increased air resistance, with subsequent incidence in terms of required ventilation capacity and associated equipment installation and operation costs.

It may also be necessary, in order to guarantee sufficient brightness and sensation of comfort for the user, to cover the vertical surfaces of sprayed concrete walls with cladding (in which case provisions shall be made to prevent the cladding to be torn off by vehicles).

For hydraulic structures, the poor hydraulic properties of the sprayed concrete surfaces can be appropriately overcome by the introduction of plastic coating (e.g. high density polyethylene). It can however be observed that a number of hydraulic transfer structures are lined with sprayed concrete, which tends to balance arguments on this factor of limitation. The effective roughness due to cross-section changes is in that case much more penalizing in terms of head loss than that produced by the roughness of sprayed concrete walls.

6.3.3- HETEROGENEITY AND VARIABILITY OF CONCRETE PROPERTIES

Current technology in terms of placement of sprayed concrete leads to:

• Some degree of material heterogeneity, especially within the first layer sprayed onto the ground, which water-cement ratio is difficult to control and contains accelerators that may result in reduced long-term strength;

• A variability of concrete properties that is probably higher than for cast-in-place concrete.

Moreover, the geometry of the sprayed concrete shell is necessarily either less regular than for cast-in-place concrete or of variable thickness.

Given these considerations, the following provisions should be made in the design process:

• strength characteristics should be taken lower than those obtained from cores taken in situ ;

• a nominal thickness equal to the minimum shell thickness should be used.

6.3.4- DURABILITY

Sprayed concrete has been used as final liner for some 30 years, which is less than the expected lifetime of tunnels. This lack of real case record on the long-term performance of such structures justifies some degree of caution. In practice, the Owner's Representative may elect to suggest the introduction a sacrificial thickness of sprayed concrete thickness in the design, in order to cope with the risk for degradation of the sprayed concrete mechanical properties in the very long term.

6.4- CONCRETE COMPOSITION

The composition and placement of sprayed concrete used as final liner must be analyzed and adjusted in order to guarantee its durability over the entire life of the structure. From this standpoint, the recommendations of section 4.5 relative to the conditions for accounting for the sprayed concrete layer in the design of the final liner remain applicable. In particular:

• Admixtures shall be selected such that they shall not deteriorate the long-term properties of the concrete. provisions shall also be made to verify, through very long-term tests, that the mechanical properties - notably strength - used for design are met ;

• Longitudinal joints, if required with multilayer placement, should be checked for quality and location (so that the presence of a discontinuity through the entire shell thickness can be prevented) ;

• Potential corrosion issues related to the use of metallic fibers should be addressed ; special steps should be taken (application of an additional non-fiber reinforced layer or allowance for a 2 to 3 cm sacrificial thickness in the design computations) to ensure the required resisting shell thickness is achieved ;

• The final geometry (thickness) of the shell shall be controlled in situ.

6.5- DESIGN OF THE FINAL SPRAYED CONCRETE LINER

From a computational point of view, two situations can arise:

• A Type 3 sprayed concrete support is used as final liner without any additional support. In this case, the principles presented in sections 4.4 and 4.5 apply, with the restriction that the thickness of the sprayed concrete liner should be checked for long-term conditions. The deformation modulus of sprayed concrete to be included in the calculation should be evaluated on the basis of conventional formulas (regulatory or other) for the determination of the long term deformation modulus (cf. Chapter 4) ;

• The final liner is made of one or more layers of sprayed concrete placed in lieu of cast-in-place concrete. In this case, the verification of the liner should be based on methods pertaining to cast-in-place concrete, with particular attention being paid to the evaluation of the concrete characteristic strength, σ_b which should allow for some degree of dispersion in relation to the spraying process. The loads applied to the structure should be evaluated using available conventional methods; Short and long term modulus values should be evaluated using conventional formulas (regulatory or other) for the determination of long term modulus (cf. Chapter 4). It must however be kept in mind that some degree of creep behavior must be assumed for the ground and/or liner for the loads to be transferred to the inner sprayed concrete layers.

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ADDENDA

SOMMAIRE

II- MECHANICAL PROPERTIES OF CONCRETE

1- TESTS ON SPRAYED CONCRETE

The following paragraphs present an overview of two studies on sprayed concrete.

1.1- STUDY 1

This first study was conducted by Solens-Alpes during the repair of the St-Martin-La-Porte's tunnel in collaboration with the SNCF, the CETU and the LCPC. This study was part of the BEFIM national project. The objective was to evaluate the elastic properties of young sprayed concrete, as early as a few days for standard concrete (sprayed concrete normally used in ground support) and as early as a few hours for the GIS concretes (Guaranteed Initial Strength). Four categories of sprayed concretes were tested:

• Classic concrete 0/8 premix S533 from TECHNIA;

• "GIS" concrete 0/8 premix S555 from TECHNIA;

Two FRSC (Fiber reinforced sprayed concrete):

• Classic concrete with an addition of DRAMIX ZP 30/50 from BEKEART to a dosage of approximately 15 kg/m^3 of fibers in the test panels and the slabs;

• "GIS" concrete with an addition of DRAMIX ZP 30/50 from BEKEART to a dosage of approximately 25 kg/m^3 of fibers in the test panels and the slabs.

The experimental program included compressive strength tests at 5 ages (3 specimens per age) with an evaluation of the elasticity modulus. Also, punching-flexural tests were performed at low speed on slabs where the load-displacement evolution was recorded until failure or apparent cracking (2 slabs per age) occurred.

Compressive strength tests were performed following the NF P 18.406 standard on specimens with a 7.4 cm diameter and a slenderness ratio of 2. The elastic modulus was evaluated using a LCPC J2P extensometer.

1.2- STUDY 2

These tests were conducted in the SNCF laboratory in St-Ouen by SIMECSOL.

The objective of this study was to identify a simple relationship between the compressive strength of young sprayed concrete and their modulus of elasticity.

Three types of wet and dry sprayed concrete were considered:

• Classic concrete B25 – 350 and 400 kg of CLK 45, 425 kg of CPA 55 PMES;

• FRSC (Fiber reinforced sprayed concrete) B25 – 350 kg of CLK 45 – 45 and 60 kg of metallic fibers;

• GISSC (Guaranteed Initial Strength Sprayed Concrete) B25 – 360 and 380 kg of CPA 55 PMES.

The experimental program included compressive strength measurements along with elasticity modulus.

Compressive strength tests were performed following the NF P 18.406 standard on specimens with a 6 or 6.4 cm diameter and a slenderness ratio of 2. The elastic modulus was evaluated by measuring the distance between the plates of the test apparatus.

2- RESULTS OF THE E/R_C RATIO (MODULUS OVER COMPRESSIVE STRENGTH)

Figure 1 presents the results obtained for the elasticity modulus and compressive strength for the two previously described studies.

The results presented by Laplante (1993) are also included in Figure 1 for comparison purposes. Tests were performed on B40 and B80 concretes. Compressive strengths of young concrete were evaluated, along with elasticity modulus on specimens having an 11 or 16 cm diameter and a slenderness ratio of 2. The specimen's deformation was measured with the LCPC J2P extensometer, identical to the one used in the first study.

Comments on Figure 1 are:

• The tests performed in the second study show that for any type of sprayed concrete used, the ratio of the modulus to the compressive strength is between 160 and 460, the average being 310;

• The tests performed in the first study show that this ratio is, on average, three times higher than that of study 2. Incidentally, these results are much closer to those reported by Laplante (1993), even if the latter were obtained on samples of ordinary concretes.

The type of device used for measuring the specimen's deformation is a key parameter in the evaluation of the elasticity modulus. Namely, the LCPC method, which reduces the number of unknowns by measuring directly the specimen's deformation leads to results that are less scattered and presumably closer to reality.

These results tend to show that the relationship proposed by Laplante (1993), based on the model developed by de Larrard and Leroy (1992), can yield a satisfactory estimate of the concrete's elasticity modulus by correlation with its compressive strength. The reader will also notice that this relationship provides a reasonable estimate of the

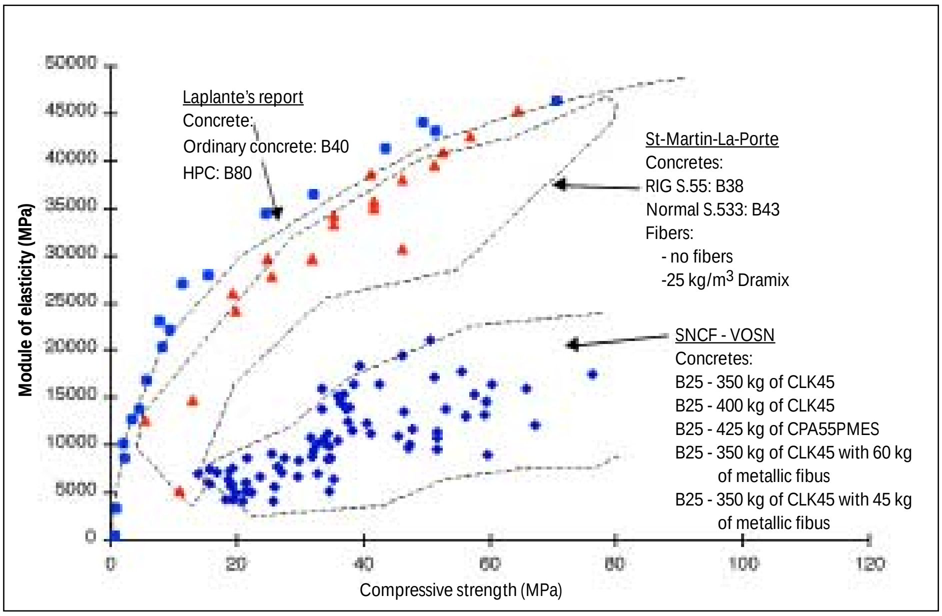

Figure 1 - Modulus of elasticity against uniaxial compressive strength

experimental values obtained on sprayed concrete specimens.

I- OBSERVATIONS AND IN-SITU MEASUREMENTS

1- BOIS DES CHÊNES TUNNEL

Characteristics:

Highway Tunnel (Highway A30) with a 130 m^2 section;

Cover: 30 m maximum;

Length: 300 m.

Other information:

Ground conditions:

• Toarcic marl;

• Sandy clay with gravely zones

• (c' = 100 kPa and φ' = 40o);

Staged face excavation (bench and heading);

Support: rock bolting and sprayed concrete, with lattice girder as necessary.

Measurements:

• Sections monitored with pressure cells, in areas where lattice girders were used;

• Convergence measurements in top half-section and in vertical sections;

• Stabilization of convergence at 2 to 3 cm.

Information on sprayed concrete structure:

Monitoring: a section of the tunnel was equipped with 22 pressure cells placed on the entire perimeter at the interface between the ground and the sprayed concrete.

Results:

• During excavation of the upper half: increased pressure and stabilization at 200-300 kPa at the crown and 100-200 kPa at the base;

• During the excavation of the stross: the horizontal convergence resulted in a reduction in lateral pressure and a slight increase in the crown;

• After spraying the concrete on the vertical sections, the pressure increased by approximately 50 kPa;

• In the long run (1000 days): the pressures tended to stabilize at 100-200 kPa. Some redistribution took place.

Note: dissymmetry between the right and left side of the tunnel made it more difficult to conclude.

2- THIAIS GALLERY

Characteristics:

Round gallery with a 9 m^2 section;

Depth: 60 m;

Length: 60 m.

Other information:

• Ground: Pantin marl;

• Shear strength: c' = 100 to 350 kPa and φ' = 20°);

• Modulus (pressuremeter): E_p = 80- to 100 MPa;

• Hand mining: 1 m/day;

• Support: 10 cm of sprayed concrete applied next to the face;

• Measurements:

– 12 relative convergence profiles and measurements by extensofor;

– Convergences remained very small (markers placed at 50 cm from the working face): from 1 to 4 mm on vertical wires and from 2 to 3.5 mm on the inclined wires;

– The extent of deformation zone was very limited around the excavation.

Information on the sprayed concrete structure:

Monitoring: a monitoring section was installed in the middle of the gallery (PM 32,70), with 8 Gloetzl cells placed behind the sprayed concrete;

Results:

• Results extremely different between the right side (North) of the gallery and the left side (impossible to explain based on ground conditions);

• Pressures measured shortly after the construction, and three years later, were very small and below 50 kPa.

Conclusions:

• Convergence as well as pressure measurements show very good stability around the opening;

• Sprayed concrete is barely loaded.

3- GALLERY OF THE MONACO TUNNEL RAMP

Characteristics:

Circular testing gallery with a 9 m2 section, perpendicular to the investigation gallery;

Depth: 200 m;

Length of gallery: 16.7 m.

Other information:

Ground: Trias clay:

• Black plastic clay with slickenside and marl-limestone with sandstone inclusions;

• Inclusions of clay or marl sections;

Excavation: by hand, approximately 1 m/day;

Support: 5 to 10 cm of sprayed concrete.

Measurements:

• 11 relative convergence sections and extensofors;

• Convergences in the gallery: 2 to 4 cm;

• Localized displacements; 4 to 5 m deep zones around the gallery.

Information on the sprayed concrete structure:

Monitoring: 2 monitoring sections each equipped with 12 pressure cells placed between the sprayed concrete and the ground.

Results:

• Around the gallery, pressures remained in the 200 to 500 kPa range;

• Some individual pressure cell measurements yielded higher values.

4- QUATRE CHEMINS GALLERY

Characteristics:

Experimental gallery:

Section: 12 m^2;

Length: 38 m;

Excavation: September 1977-November 1978.

Other information:

Ground:

• PM 0 to 30: superior cretaceous schistified marl;

• PM 30 to 38: crushed Cretaceous marl-limestone.

Excavation: roadheader.

Support:

• PM 0 to 16.5: ribs and lagging, followed with sprayed concrete;

• PM 16.5 to 22.5 (ring 1): 5 cm of sprayed concrete + wire mesh + HA 32 bolts;

• PM 22.5 to 28.5 (ring 2): 5 cm of sprayed concrete + wire mesh.;

• PM 28.5 to 33.5 (ring 3): sprayed concrete + wire mesh followed by a cast in place concrete liner;

• PM 33.5 to 38.0 (ring 4): fiber glass anchors; fiber glass and resin liner; collapse after 4-25-79.

Measurements:

• 13 convergence profiles

• 2 profiles with 3 extensometers, each

equipped with 3 rods;

• 3 profiles with glötzl cells.

Information on the sprayed concrete structure:

Monitoring:

Results:

• The convergence measurements allowed to clearly identify the displacement pattern. They follow typical power time laws;

• Maximum pressure: 1 MPa; most often at 0.2 MPa – irregular distribution;

• No differences between the responses of rings #2 and #3 (limited anchor role);

• Experimental convergence-confinement relationship: 5 cm of sprayed concrete + wire mesh; E = 12 000 MPa.

5- LAS PLANAS TUNNEL

Characteristics:

Highway tunnel – Highway A8 – bypass around Nice;

Section: 100 m^2 of interior section, 125 m^2 excavated in marl;

Maximum cover: 50 and 90 m;

Lengths: 140 and 220 m in marl.

Other information:

Ground:

• Plastic marl: σ_i = 4 to 7 MPa;

• c' = 100 kPa; φ' =27o.

Excavation:

• Heading: 50 m^2

• Stross: 50 m^2

• Sole: 25 m^2

Support:

• Sprayed concrete: 10 cm with 150 x 150 x 10 mesh

• Steel bars anchored with grout, L = 5.0 m, spaced at 1.5x3.0 or 1.5x1.5 adjusted on the basis of convergence measurements

• TH 21/48 arch girders at 3 m in some areas

• Temporary footings of 20 cm placed every week-end in the top half of section.

Convergence measurements: maximum 80 mm with an average of 30 mm.

Information on the sprayed concrete structure:

Initial section with 50 m cover:

• Radial pressure cells: uniform pressure of 150 kPa, which increases to 200 kPa during the excavation of the stross.

• Tangential pressure cells: they show large variations over time (stresses redistribution); rapid increases to 800-900 kPa and reduction to 400-500 kPa on the lateral walls and 200 kPa at the crown. Little variation during the construction of the stross.

Initial section with 90 m cover:

• Radial pressure cells: crown cells at 350 kPa, the vertical wall cells show identical pressures of 180-200 kPa.

• Tangential pressure cells: only one cell worked on the vertical wall: it reached 650 kPa before dropping to 300-400 kPa.

There are no long-term measurements available after placement of the inner plain concrete liner.

6- PESSICART TUNNEL

Characteristics:

Highway tunnel – Highway A8 – bypass around Nice;

Section: 100 m^2 of interior section, 125 m^2 excavated in marl;

Maximum cover: 65 m;

Length: 160 m in marl.

Other information:

Ground:

• Plastic marl: σ_i = 4 to 7 MPa;

• c' = 100 kPa; φ' =27o.

Excavation:

• Heading: 50 m^2

• Stross: 50 m^2

• Sole: 25 m^2

Support:

• Sprayed concrete: 10 cm with 150 x 150 x 10 mesh

• Steel bars anchored with grout, L = 5.0 m, spaced at 1.5 x 3.0 or 1.5 x 1.5 depending on observed convergence measurements

• TH 21/48 arch girders at 3 m in some areas

• Temporary footings of 20 cm placed every week-end in the top half section.

Convergence measurements: maximum 20 mm with an average of 5 to 10 mm.

Information on the sprayed concrete structure:

Initial section with 50 m cover:

Radial pressure cells: uniform pressures of 150 kPa, which increases to 200 kPa during the excavation of the stross.

Tangential pressure cells: 200 kPa for the cells in the tunnel's axis at the crown during the excavation, increasing to 450 kPa during the construction of the stross.

The pressure on the lateral wall increased to 900 kPa during the excavation of the stross and dropped to 500 kPa in the long-term.

There are no long-term measurements available after placement of the inner unreinforced concrete liner.

7- FURKA BASE TUNNEL (SWITZERLAND)

Characteristics:

Electrical railway tunnel, 1 narrow lane.

Length: 15.4 km

Section excavated: 26 to 42 m^2, most often in a horseshoe shape, otherwise elliptical.

Maximum cover: 1520 m; intermediate access point in the middle of the tunnel

Other information:

Ground:

• 11 km of St-Gothard's gneiss;

• Very strong granite on 3.5 km;

• A few fractured zones;

• Water ingress that could reach, locally, 100 to 200 l/s.

Excavation:

• Drill and blast: from 1972 to 1982;

• Sealing of many aquifer zones by polyurethane injection; collection of surface runoffs with half PVC pipes fixed by spraying resin.

Support: 16 types of supports (different ones every 20 m on average):

• On 55% of its length: 5 cm of sprayed concrete (not on the total section), without bolts or mesh;

• On 26% of its length: 15 to 40 cm of sprayed concrete with mesh and 4 to 11 bolts per meter (fiber glass bolts, anchored with resin);

• After carefully draining and cleaning of the rock with water jets, spraying of concrete;

• Little amounts of setting accelerator, hence the high ultimate strengths (40 MPa);

• Sprayed concrete final liner, put in place far behind the support.

Measurements:

• Numerous convergence sections with Iseth extensometers and borehole extensometers with automatic logging;

• Long-term monitoring on critical sections (1 measurement/month);

• Continuous implementation of monitoring results to determine the type of final liner and its moment of application, as for the Alberg tunnel (in such long and narrow tunnels, only sprayed concrete final liner offers that kind of operational flexibility);

• Local disorders (swelling of the face, spalling of the granite) well controlled, either by additional rock bolting or reinforcement of the section, until an elliptical shape is reached.

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8- CADI TUNNEL (SPAIN)

CHARACTERISTICS:

Two-way tunnel, on the Toulouse-Barcelona axis, through Puymorens;

Section: 82 m² on average (width 10.5 m at base);

Maximum cover: 980 m;

Length: 5 km.

OTHER INFORMATION

Ground:

• Paleozoic era with very complex tectonic, with faults and erosion thrust, made mainly of limestone and shale; graphitic shale of the Silurian period on 6% of its length.

• Ground is probably unpervious (no hydro geological comments).

Excavation:

• Drill and blast from 1982 to 1984, with 3.5 to 0.8 m passes depending on the ground, with top, heading and sole.

• Four excavation fronts: North, South and 2 others from the investigation gallery (length: 1.7 km)

• Construction time and cost within 1% of design values.

Support:

• 4 typical profiles consisting of 10 to 45 cm of sprayed concrete applied in successive layers (1 to 3) depending on the monitoring results, sometimes many months after excavation (R_c = 30 MPa); immediate rock bolting (3 to 4 m long bolts), anchored with resin (1 bolt/4 m² to 1 bolt/m² density); TH arch girders and rapid closing of the section in graphitic shale.

• No cast in place liner; water tightness provided by a polyethylene membrane placed on the crown and precast concrete walls (H = 4 m) on each vertical wall.

Measurements:

• Convergence measurements made with INTERFELS wires: monitored sections 20-25 m apart on average and as close as 10 m in poor ground conditions; 2 horizontal wires (1 reading/day to 1 reading/month);

• Monitoring was an essential element in checking and adapting the support system (thickness, bolting, time to first layer of sprayed concrete and between successive layers);

• One special monitoring section in the graphitic shale, with multiple extensometers and Glötzl radial cells that measured confinement pressures of 100 to 240 kPa.

Information on the sprayed concrete structure:

Variable convergence velocity, from several cm/day to 10^{-2} mm/day in the stabilizing phase;

In the Silurian, very strong convergence (up to 50 cm) were expected and dealt with thanks to a gradual stiffening of the crown, with the last layers of sprayed concrete being less and less loaded.

Monitoring of the long-term convergence during at least 10 years on 11 sections of 2 wires each; stabilization was reached everywhere (residual velocities of 0.1 to 0.5 mm/year).

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III- DESIGN OF SUPPORT STRUCTURES

1- UNDERGROUND BYPASS THE MONACO RAILWAY

General characteristics:

• Design: SNCF

• Construction: Group SOGEA-COGEFAR-BORIE- NICOLETTI-SPADA-GTM

• Construction period : 1994-1997

Geometrical characteristics :

• Width: 11 m to 25 m (underground rail station)

• Height: 11 m to 13 m

• Lenght: 2250 m

• Cover at crown: 70 to 180 m

• Water above the crown: 0 m

Support characteristics: variable depending on the ground conditions (see Table 1) and the selected profiles:

• Ground A: staged excavation, 5 cm of sprayed concrete + bolts

• Ground C: full face excavation: 27 cm of sprayed concrete and HEB

• Grounds B, C, or D: full face exvavation: 22 to 32 cm of sprayed concrete + steel ribs and bolts

Geomecanical characteristics
(see Table 1)

Design model for sprayed concrete:

• Elastic behavior with constant elasticity modulus equal to 10 000 MPa (short term)

• Allowable stress in concrete: 15 MPa in compression and 1.25 MPa in tension

• Shell reinforcement by the arch girders: modeled by homogenization

• Bolts modeled using the "equivalent pressure" approach.

N.B.: Once the cast in place concrete is in place and active, the bolts and steel ribs are "removed" in the model and the support sprayed concrete is kept with a long-term modulus of 5 000 MPa.

Ground	E_i (MPa)	c_u (MPa)	φ_u
A : Jurassic limestone and dolomite	4000	1	45°
B : Cretaceous limestone and tuff	3000	0,2	35°
C : marl, marl limestone and Miocene volcanic sediment	1400	0,1	35°
D : clastic Miocene	600	0,1	30°

Table 1

Expected results :

Section	Ground cover and depth	Settlement at crown (mm)*	Horizontal displacement in vertical wall (mm)	Stress in sprayed concrete	
				crown	Vertical wall
Station West GO	A / 75 m	4	1	< 1	2 to 3
West pre-station AGOL	C / 120 m	18	7	10 to 11	13 to 15
Tunnel Tu1	C / 135 m	13	4	6 to 7	7 to 11
Tunnel Tu2	B / 180 m	10	9	5 to 7	7 to 15
Tunnel Tu3	D / 70 m	8	3	4	2 to 5
	D / 110 m	16	6	7 to 8	3 to 10

* measured after placement of support

Monitoring:

- Approximately 40 sections equipped for displacement measurements (topometric)
- A few sections equipped with extensometers and pressure cells in the sprayed concrete

Partial results of sprayed concrete monitoring: Displacement measurements

Section	Settlement at crown (mm)	Horizontal displacement in vertical wall (mm)
GO	1 to 7	1 to 2
AGOL (top section only)	3 to 7	4 to 10
Tu1	15 to 16	6 to 10
Tu2	7 to 9	7 to 15
Tu3 (70 m cover)	15 to 17	4 to 5

2- CHANNEL TUNNEL CROSS OVER BRITISH SIDE

Main geotechnical characteristics :

	Short term Young's modulus (MPa)	Cohesion (MPa)	Friction angle	Comments
Blue chalk superior	825	250	39°	Horizontal joints
Blue chalk inferior	400/750	135/225	35°/40°	Horizontal joints
Tourtia	1000	275	43°	-
Stiff clay, layer 6	1000	200	37°	Slightly swelling
Gault clay	300	275	19°	Slightly swelling

General characteristics:
- Design: ILF (R Pöttler)
- Construction: TML UK
- Construction period : 1989-1991

Geometrical characteristics :
- Width: 21.20 m
- Height: 15.40 m
- Lenght: 164 m
- Cover at crown: 71.30 m

Support characteristics:
- Staged excavation
- Sprayed concrete shell: thickness ranging from 15 to 20 cm (1st layer) + 10 cm (2nd layer)
- Bolting: 1 bolt per 3 to 4 m^2 density.

Geomecanical characteristics
(see Table 1)

Design model for sprayed concrete:

Elastic-plastic behavior (see Table)

• Variable elastic modulus adjusted on the basis of the duration of the phase;

• Yield value: 21.25 MPa;

• For the initial phase (excavation and shotcreting) a "hypothetic elasticity modulus" is considered (HME).

The reinforcement of the shell brought by lattice girders and of the ground by the bolts are not considered in the calculations.

Main results expected:

• Settlement at crown: 40 to 50 mm

• Horizontal convergence: 30 to 40 mm

• Stresses in the sprayed concrete:

– Lateral galleries before crown excavation: 2 to 7 MPa

– Lateral galleries after crown excavation: 13 to 16 MPa

– Crown short term: 6 to 7 MPa

– Crown long term: 12 MPa

Monitoring equipment:

• 16 profiles with a total of 200 instruments:

– Tangential pressure cells (stress in the sprayed concrete): 36 placed on 2 profiles

– Triple extensometers (3, 6, 9 m) in the ground: 19 out of which 13 are on 1 profile

• Bolts equipped with strain gauges: 28

RESULTS OF SPRAYED CONCRETE MONITORING:

• Tangential pressure cells: compressive stress in sprayed concrete between 4 and 6 MPa (a few readings at 11 MPa)

• Radial pressure cells: stresses induced by the surrounding ground between 0.5 and 0.6 MPa

N.B.: the readings are insufficient before crown excavation to reliably evaluate the pressure on the inner sides of lateral galleries.

Age	Creep	Modulus of elasticity
0/14 d	"HME"	2500/1500
14128 d	1,0	15500
28 d to end of construction	0,5	20667
Long term	1,5	12400

N.B.: after completion of the internal cast in place concrete, sprayed concrete is ignored in the design of the completed structure.

3- CHAUDERON RAILWAY STATION (SWITZERLAND)

General characteristics:

• General contractor: Compagnie du Chemin de Fer Lausanne-Echallens-Bercher

• Underground Construction, shafts, station and tunnel: Consortium Losinger, Deneriaz, Reymond S.A., Locher

• Construction period : 1992-1995

• Ground conditions: aquitanian molasse topped with moraines.

Geometrical characteristics :

• Lenght: 710 m

• Width of the station: 12 to 20 m

Support characteristics:

• Staged face excavation (station);

• B30-40 concrete according to Swiss standards (B30 in France);

• Modulus: E = 20 000 MPa (which takes into account cracking of the sprayed concrete)

Design model:

• Given the size of the train station, initial design and phasing analyses were performed using the finite element method (for initial and final liners):

– 30% of the loads are redistributed through face deformation;

– 40% applied in the short term to the sprayed concrete and the lattice girders when using E = 20 000/2.5;

– 30% remainder of loads are applied to the support with a modulus of E = 20 000 MPa.

• Calculations are completed, for all sections, based on a ground reaction curve model calibrated against the finite element results at a few sections.

• Design of the sprayed concrete/lattice girder based on the BAEL rules (French Standard): iterative calculations where a new cracked section is determined for each (M,N) values.

• Thickness of the first sprayed concrete (30 to 40 cm) considered without any steel ribs or wire mesh, these are supposedly corroded in the long-term;

• Interior concrete for water tightness considered with its reinforcement;

• The inner and outer concretes form a monolithic layer;

• For safety, in the long-term,: verification with a resistance factor F = 1 for the sole inner concrete (and rebar);

• No creep analysis were made.

Main results:

• Finite element calculations:

– Uniform settlement of 3 cm, confirmed on site;

– Long-term: the long-term stresses supported by the sprayed concrete are evaluated assuming that the entire load of the ground above is applied.

• The Gloetlz pressure cells placed in the liners did not yield any result.

References

Presentation O. Tappy, Engineer SIA EPFL diploma, June 1995 – AFTES Work Group #20

4- DOMBES AND COTIERE TUNNELS

General characteristics:

• Tunnels are 500 m (La Dombes) and 300 m (La Côtière) long;

• Supported by steel ribs and sprayed concrete (classic B25);

• The crown of the La Dombes tunnel is 24 m deep and 14 m deep for the La Côtière tunnel;

• The entire excavation took place in yellow alluvium.

Finite element analysis:

• Calculations were conducted using the CESAR-LCPC FEM software;

• Phases of construction accounted for in the analysis of both tunnels: staged face excavation with subsequent placement of support and full section spraying, including the footing of the final liner;

• Phases of construction different than what was executed for the lower half section: calculations assumed full face excavation, whereas staged excavation was used with central stross and lateral support walls; in addition, support installation was delayed until excavation of the side drifts and rock bolts were abandoned;

• Support system considered: 200 HEB every meter with 25 cm of sprayed concrete and 4 HA 25 3.80 m long bolts on the lateral support walls;

• Support by steel ribs and sprayed concrete is included as an homogenized equivalent section; redistribution of calculated stresses in the ribs and the sprayed concrete according to their relative stiffness;

• Modulus of deformation taken into the model:

– For sprayed concrete:10 000 MPa for the short term and 15 000 MPa for the long term;

– For the liner: 30 000 MPa for the short term and 15 000 MPa for the long term;

Monitoring:

• Two profiles were instrumented:

– At PM 190 for the La Dombes tunnel;

– At the PM 44.5 for the La Côtière tunnel.

• Vibrating wire extensometers were fixed to the rib of one section, to monitor the rib deformations; it allowed the evaluation of the stresses in the arch rib and derive the stresses in the sprayed concrete;

• Results were interpreted using a modulus of 10 000 MPa for the short term and 7 500 MPa for the long term for the sprayed concrete and 22 500 MPa for the final liner.

Analysis of results and comparison between prediction and monitoring / La Dombes Tunnel:

• Stresses in the support at monitored section:

– The measured stresses during the excavation of the upper half section (phase 2 of the finite element calculations) are higher in the rib and the sprayed concrete than predicted by the FE analysis (twice as much) with a slight dissymmetry;

– The measured stresses during the installation of the slab (phase 6 of the finite element calculations) in the arch girder and the sprayed concrete are close to those predicted ones by the FE analysis, but remains higher than the predicted values for the upper half section of the rib.

• Deformations in the support at monitored section:

– The convergence measured in situ are almost identical to those predicted in Phases 2 and 6;

– In situ survey measurements are slightly higher than the predicted values for phase 2; they are much more important than the predicted values for phase 6 (4 to 5 times higher).

• Deformations in the support:

– The comparison is limited to the upper half section, the phases used to model the lower half section being completely different from what was finally done;

– The settlement associated to the excavation of the upper half is 1 to 2 times more important than predicted before the excavation of the lower section;

– The convergences are globally of the same order of magnitude as those predicted.

• Pressure cells at the monitored section:

– The various pressure cells placed at the support/ground contact indicated relatively small pressures;

– Only cells located on the East side are highly loaded, with a pressure in the order of 350 to 500 kPa.

5- MEYSSIEZ TUNNEL

General characteristics:

1800 m long tunnel;

Support made of a sprayed concrete shell along with steel ribs in the upper half section and bolts for the lower half section;

Classic sprayed concrete (B25 with 425 kg of CPA 55 cement);

Tunnel entirely excavated in gravel-sand molasses and marl-sand molasses;

Coring was done through the shell to evaluate the modulus of elasticity in the laboratory.

Finite element analysis:

Calculations made using the CESAR-LCPC FEM software;

• A number of finite element analyses were performed:

– At PM 280 (from PM 0 to PM 450, crown at 54 m deep),

– At PM 650 (from PM 450 to PM 1000, crown at 84 m deep),

– At PM 1210 (from PM 1000 to PM 1400, crown at 74 m deep),

• Phases considered in the calculations:

– Staged excavation with placement of support (lower half section completed in 2 steps);

– Full section spraying, including the footing of the final liner.

In the upper half section, support by steel ribs and sprayed concrete is modeled as a homogenized equivalent section.

Tests and monitoring:

• In situ testing with flat jack:

– Sprayed concrete shell equipped with flat jacks at PM 35, 85, 239, 475, 651 and 1015;

– The modulus of the sprayed concrete is estimated from the stress-deformation curves obtained with the flat jack test: a 3D finite element analysis was made to model the effect of a recess in the sprayed concrete shell; the following relationship was established between the deformation modulus of the concrete and the slope of the curves found by calculation: $E = 0.34*P/e$ where E = modulus (MPa) and e = displacement between the markers for a pressure P relative to the initial state where no pressure is applied to the jack (m).

• Sprayed concrete testing:

– Coring was performed at the same PM where the flat jack tests were performed.

Results:

• Pressure in sprayed concrete:

– For any section, the East side of the tunnel (left) underwent a more important pressure than the other side (West-right);

– The pressures were relatively small (in the vicinity of 2 MPa) except for PM 239 where it reached a value of 4.8 MPa;

– The evolution of the stresses over time appeared regular.

• Deformation modulus of in situ sprayed concrete:

– For any location of the test (except for PM 475), the value of the modulus increased over time;

– On the last testing campaign (February 25 and 26, 1992), the modulus varied from 5 470 MPa to 18 760 MPa (average of 11 545 MPa and a standard deviation of 4490 MPa); these results confirm the high heterogeneity of the sprayed concrete.

• Deformation modulus of sprayed concrete in the laboratory:

– The modulus measured in the laboratory are higher for the PM 239, 650 and 1015 (measurements made from August 20 to September 3, 1991) than those obtained with the fat jacks; they are lower for PM 35, 85 and 475 (February 25-26, 1992);

– The average values measured between August 20 and September 3, 1991 is 5921 MPa, with a standard deviation of 1449 MPa; for the tests of February 25-26, 1992, it is of 8578 MPa with a standard deviation of 3542 MPa;

Comparison prediction/monitoring:

The phases of construction correspond to the phases of the finite element analysis;

• Pressure:

– The long-term pressure measured in situ are always smaller (one fourth) than the ones predicted, except for PM 239 (left side) where the pressures are closer to those predicted, but still smaller (half);

• Deformation modulus:

– The modulus introduced in the finite element calculations are of 10 000 MPa for the short term, 7 500 MPa for the medium term and 5 000 MPa for the long-term;

– The modulus measured in situ are very scattered, but show a definite increase over time (except for PM 1475);

– The average of the last phase is 11 545 MPa, which is close to the value of 10 000 MPa taken in the short-term calculations and close to the value of 8 570 MPa obtained in the laboratory at the same date.

Notes:

The correlation between the flat jack measurements and the deformation modulus is linked directly to the hypotheses made for the 3D calculations; no parametric studies were made.

It is possible that the modulus measured in situ and in the laboratory are close to the value taken in the finite element analysis, but that the pressures found in situ are generally smaller than the stresses found in the finite element calculations.

LETERATURE REVIEW

The following text is a compendium of articles related to the use of sprayed concrete in underground works. These summaries were prepared by the AFTES Work Group #20 and represent part of the literature used to prepare this document, also presented by this working group. The names of the members of this working group and authors of each summary, are mentioned at the beginning of each text, along with the full reference of the original paper.

Summary of papers dealing with the design of sprayed concrete used in underground works (by E. Leca, SCETAUROUTE)

Heuer, R.E., 1974, " Selection / Design of Shotcrete for Temporary Support ", Use of Shotcrete For Underground Structural Support, ACI-ASCE, pp. 160-174

(1) Three types of sprayed concrete can be considered for design: placement of a protective skin preventing air or water weathering of the ground; support action to help the ground support itself, in the case of loads associated with fracture blocks for example; placement of a support structure, aimed at supporting all or a part of the loads induced by the excavation (for grounds with low resistance, function of the stress levels, or in the case of swelling grounds).

(2) The use of sprayed concrete is particularly adapted to the second type, as long as the support can only be effective after a certain amount of time, corresponding to the decompression of the crown; the third type is a little more delicate since there is a risk of failure if the sprayed concrete does not harden fast enough with respect to the period over which the ground remains stable and also if the placement (and setting) of the concrete is to rapid, which could lead to stresses exceeding its capacity.

(3)For the first type (protective skin), the recommended thickness of concrete is 2 in. (with local tolerance of 0.5 to 1 in.) for weathering of the ground by air; when water is present, it is recommended to rapidly construct a closed ring of sprayed concrete or reinforce the sprayed concrete skin with mesh.

(4) The following rules can be applied in the case of the second type of sprayed concrete. For tunnels with a diameter of 4 to

EXEMPLES DE TUNNELS ET OUVRAGES SOUTERRAINS DONT LE REVÊTEMENT INTÉRIEUR EST CONSTITUÉ DE BÉTON PROJETÉ

Structure	Usage	Year of construction	Section (m^2)	Lenght (m)	Cover (m)	Suppor system	Geology
HEHLRATH Tunnels (R.F.A.)	Road	1958/59	14,5	440	20	S.C. + Mesh + Arch girders GI 110	Brown coal. Ligh hydrostatic pressure
Luxembourg	Outlet	1961/62	14,8	880	35 m sous la ville	S.C. + bolts l = 1,5 m in lsandstone	More or less compact sandstone
MEXICO	Drainage	1968	60 à 140	90 000	50	S.C. 10 cm + mesh + bolts = 3 m	Half consolidated rocks, loose and watery, Rc = 200 kPa, clay
FURKA (Switzerland)	Train	1972 /82	26 à 42	1 368 (profil S4 + S5)	1 000	Dry S.C. + mesh + passive anchors	Good to weathered rock
Nuremberg Metro (R.F.A.)	Subway	1972	50	500	4,5 to 10	S.C. 15 cm + mesh + 3,5 m bolt + 15 cm wet S.C. final liner	Sandstone with clay lens
Lehrental East Deviation - ULM (R.F.A.)	Highway	1973	80	500	50	S.C. 20 cm + mesh + arch girders + 3 m bolts at 1,5 to 2,5 m	Molasses contact at crown, compact and cracked limestone at slab
LLORET (Spain)	Road	1974	70	150			
BOURGET lake gallery – Rhône	Hydraulic	1977 and going	6 to 7	12 000	1 000	S.C. + mesh according to ground conditions	Molasses and sandstone
CADI (Spain)	Road	1987	82	5 000		S.C. (10 cm to 50 cm per successive passes) + mesh + passive anchor	
BIELEFIELD Metro (R.F.A.)	Train	1987	35	104	5 to 10	S.C. support (15 cm) black fiber + lattice girders; liner, 10 cm wet S.C.	Compact clay
FRASDORF (R.F.A.)	Sanitation	1989		3 200	100	Dry S.C. (2 cm) + microsilica	Gravel, sand, salt + water head of 80 m
MUNICH Metro (R.F.A.)	Train	1990	38 to 52	60	8	Dry S.C. (15 cm + 10 cm + 10 cm) + mesh	Sand and gravel on top of compact marls; water table at mid-section
BRASILIA Metro (Brazil)	Train	1996	72	6 500	6 à 10	S.C. (21 cm + 20 cm) + lattice girder + mesh	Highly shrinking soft clay, water table at mid-section
VEREINA (Grisons Switzerland	Train	1994-99	39 to 46	19 050	< 1500	S.C. (15 to 30 cm) + bolts + ligh arch girders	Amphibolite and paragneiss
UNDERGROUND OPENING							
SACKINGEN Black Forest (R.F.A.)	Plant	1962/64	620	161	400	S.C. 30 cm + mesh + bolts = 3 to 4 m, 100 to 200 kN	Solid paragneiss with marked schistosity
Veytaux - Leman Lake near Montreux	Pumping plant	1967	645		100	S.C. 15 cm + mesh + 4 m resin bolts 160 kN + ties 1400 kN	Cracked limestone shale, permeable and subhorizontal
EFRINGEN KIRCHEN (R.F.A.)	Warehouse	1967	16 40 73 122	1 080 350 1 400 150	70	S.C. 15 to 20 cm + steel ribs + 3m bolts, meshed at 1,4 m^2 post-tensioning, wet mix	Limestone, clay pocket
WALDECK II (R.F.A.)	Hydroelectric plant	1971/72	1 540		250	Resin bolts l = 4 to 6 m, 12 t., meshed at 1 to 3 m + ties l = 20 to 25 m, 1700 kN + 5 cm S.C. and many meshes	Clayey shale and graywacke sandstone with faults
Hermillon - d'Echaillon - Arc Valley	Hydroelectric plant	1974	200 to 450	50	300	S.C. 8 to 10 cm + mesh + bolts, l = 2,50 m – Ø 25, meshed at 4 m^2	Gneiss
SEVRES-ACHERES Lot 6 (France)	Sanitation	1987	160	61	47	Wet S.C. (10 cm + 10 cm + 20 cm + mesh + TH girders + passive anchor	Crown: plastic clays, Walls: Meudon marl, Slab: chalk
CHAUDERON Train station (Switzerland)	Train station	1993	73 à 200	146	20	S.C. (30 to 40 cm) + mesh + lattice girders. Crown liner: on membrane, dry + wet mix S.C. 30 cm	Molasse
HECKARZIMMER Heidelberg (R.F.A.)	Warehouse		300 l = 25 m h = 10 m		150	S.C. 20 cm + 2 meshes + bolts Ø 26, l = 5 m, meshes at 1/5 m^2	Muschelkalk, dolomite, gypsum, sulphates, anhydrite clay
LORCH (R.F.A.)	Warehouse		26,5 to 65,4			S.C. 15 to 20 cm	Rhenan shale rock
MECHERNICH	Warehouse						
WEHR (R.F.A.)	Idem Sackingen						
SINGKARAK	Hydroelectric plant						Limestone, freestone (tuff)
DUL HASTI	"	1991-93					
ERTAN	"	1991-96					Diorite, gabbro, granodiorite
XIAOLANGDI	"	1995-98					Sandstone and marl

6 m: (a) for RQD > 75%, a thickness e = 2 in. of sprayed concrete applied at the crown is sufficient; (b) for RQD between 50% and 75%, a 3 in. sprayed concrete thickness is required; (c) for RQD between 25% and 50%, 3 to 4 in. is required at the crown and approximately 3 in. on the walls, and the rest of the opening; (d) for lower rock characteristics, an extra 1 in. is required on top of the previous case, except for unstable grounds (Type 3).

(5) These rules can apply to larger tunnels if the thicknesses are modified accordingly, proportionally to the power of the diameter's ratio (order of 1.25 to 1.5).

(6) In bad ground conditions requiring Type 3 sprayed concrete, it is possible to apply the empirical recommendations of the previous case (Type 2) if the ground is reinforced with bolts; however, the additional reinforcement brought by the wire mesh is not proven in this case, and it is advisable to increase, when necessary, the thickness of the sprayed concrete.

(7) The third configuration (Type 3) corresponds to either situation where the loads brought by the excavation exceed the capacity of the ground or to swelling grounds. In these conditions, the sprayed concrete must be designed as a ring of reinforced concrete using the limit state design rules; this situation corresponds to a thickness of sprayed concrete over 6 in. A first estimate of the support thickness is given by the following relationship:

$e = 2(pR / f'_c) + 2$ to 4 in.

where R is the radius of the tunnel, f'_c is the compressive strength of the concrete and p the pressure induced on the structure by the surrounding ground; this last parameter must be evaluated separately; the extra 2 to 4 in. are for additional safety, mainly to cover for the potential placement problems of sprayed concrete. This formula includes a global safety factor of 2, adapted for support design; the value of this global safety factor must be increased to 2.5 to 3 for the design of the final liner.

Morris, J.W., " Bureau of Reclamation Shotcrete Design Practices ", pp. 153-159.

This paper mainly insists on the economical and practical aspects related to the use of sprayed concrete:

(1) Sprayed concrete can be an economical support method for some tunnels

excavated with drill and blast, assuming it can also serve as a final liner;

(2) Small amounts of sprayed concrete (thicknesses of about 1.5 in.) can also be used in combination with steel ribs to guarantee stability in soft sensitive rocks; from an economical point of view however, it could be more interesting to increase the sprayed concrete thickness instead of adding arch girders;

(3) The use of sprayed concrete has a limited compatibility with the contractual context where the designer and the contractor are hired independently.

Barret, S.L.V., Mc Creath, D.R., 1995, " Shotcrete Support Design in Blocky Ground : Towards a Deterministic Approach ", Tunnels and Deep Space, Tunnelling and Underground Space Technology, Vol. 10, n° 1, pp. 79-89.

(1) This paper deals with the design of sprayed concrete used in combination with rock bolts for the support of underground openings in fractured rock. Rock bolts should be designed to hold blocks around the opening; the size of the opening and the level of fracture in the rock itself determine the size of those blocks. Even though sprayed concrete is only present to complement the rock bolt action, it is still essential to the stability of the opening.

(2) The paper also reviews some of the principals behind empirical design methods for rock support by sprayed concrete (Albert, 1965; Kobler, 1966; Cecil, 1970; Heuer, 1974) and proposes an analytical design approach.

(3) This design approach considers four failure modes: loss of adhesion between the sprayed concrete and the rock surface, shearing of the concrete liner by a falling block, flexural failure and punching shear of the concrete liners by the rock bolt head. The last two failure modes are possible only if there is a loss of adhesion between the concrete and the rock surface. Analytical relationships are proposed for each failure mode.

"Gebauer, B., Lukas, W., Kusterle, W., 1991, Monocoque Shotcrete Lining", World Tunnelling, October, pp. 357-360."

This article describes a support/lining method for tunnels based on sequential sprayed concrete layer applications:

(1) The support system is made of a combination of bolts, steel ribs and wire mesh associated with a layer of sprayed concrete.

(2) The other layers of sprayed concrete are applied by successive thin layers once the deformation rate of the temporary support is stable. The tunnel liner is therefore made of a homogeneous shell, including the temporary support sprayed concrete layer and the later applied sprayed concrete layers.

(3) It is generally accepted that the use of setting accelerating admixtures for the support concrete modifies the material and makes it more permeable in the long term. The layers sprayed after stabilization of the opening must, however, be watertight. Applying the sprayed concrete in thin layers can reduce cracking of the liner; the use of micro silica will allow for non accelerated mixtures.

(4) The use of a temporary support made of sprayed concrete allows for a redistribution of stresses generated during excavation in the surrounding ground. The construction phases can be optimized by monitoring the deformations of the structure during the work process.

(5) This process was tested on two sites in Germany: one 3200 m long sanitation tunnel in Frasdorf (Bavière), excavated at 100 m deep and under 80 m of water and a subway tunnel in Munich excavated 5 m in depth in granular ground under the water table. In the second case, the temporary sprayed concrete support is 15 cm thick and the two other layers placed to guarantee the long-term stability of the opening are 10 cm thick. The use of this method generated important savings to the project (especially with the thickness of the sprayed concrete limited to 35 cm instead of 50 cm for conventional approaches).

On the rheology of sprayed concrete (by J. Piraud, ANTEA)

"Schubert, P. (1988) - Beitrag zum rheologischen Verhalten von Spritzbeton. Felsbau, vol. 6, n° 3, pp. 150-153"

If one wants to evaluate the stresses in a sprayed concrete shell based on the full history of the measured deformations, one will need a constitutive law, function of time, for this material. The author used the work, now old, of England and Illston (1965), who proposed a numerical solution based on a time step analysis. In this approach, the deformation is composed of 4 contributions:

- An instantaneous elastic deformation,
- A delayed elastic deformation,
- A permanent creep deformation, strongly time dependent,
- A thermal contribution.

This constitutive law was accurately calibrated against creep and relaxation tests conducted in the laboratory of the "École des Mines de Loeben" (Austria). Note however that this constitutive law was adjusted for dry sprayed concrete; we know that for wet sprayed concrete, the creep values are only 25 to 30% of those obtained from the dry process, because of the larger proportion of large aggregate in the wet process concrete. The author then explains a practical application of stress calculations in a tunnel liner in the Langen tunnel in the Alberg. Numerous deformation measurements were made in the first days in the sprayed concrete shell, allowing for the tangent stresses to be estimated. This example is developed in Chapter 3.4.1 of this document (Figures 3.4 and 3.5).

Spikes associated with the advance of the tunnel front are easily visible on those figures, as well as the stress stabilization – tangent and radial – around a value of 5 MPa after 20 days. (cf. Pöttler, 1990, further in the text).

Lattice girders (by C. Bascoulergue, CAMPENONBERNARD)

"Dr. Betzel, 1988, Analyse statique et application de cadres réticulés utilisés en chantiers de tunnels (Static analysis and application of lattice girders in tunnel construction), Tunnels et Ouvrages Souterrains, n° 86, pp. 93-104."

The use of lattice girders in underground supports has recently developed due to the increase use of sprayed concrete in tunnel construction. Indeed, when ribs are required, it appears more interesting to use, instead of a beam shaped section, a lattice structure for which an intimate interconnection with sprayed concrete is achieved, allowing for a real reinforced concrete composite.

This will lead, for an equal support capacity, to a reduced sprayed concrete thickness and consequently a reduction of overall costs.

This article is divided into four sections:

• General specifications for ribs used in conjunction with sprayed concrete for tunnel support;

• Applications;

• Justification for immediate support;

• Justification of the sprayed concrete shell by considering the association of lattice girders – sprayed concrete.

General specifications for lattice girders used with sprayed concrete for support

Lattice girders are well suited to tunnel construction through the NATM (New Austrian Tunnelling Method) since they can be totally encased in sprayed concrete during construction. They allow for an easy access to fill the over-breaks. They can also be included as reinforcement in the evaluation of the support strength. The quality of the bond between the concrete and the steel is a function of the characteristics of the concrete, of the geometrical characteristics of the girder and of the spraying direction.

Applications

Lattice girders can be used for immediate support. Their isotropic stiffness offers a good resistance to buckling failure, either in the frame's direction or perpendicular to it.

The good bond between the lattice girders and the sprayed concrete makes for a system where both materials share the loads, which offers an additional support during the hardening of the sprayed concrete.

Lattice girders allow a longitudinal continuity in the sprayed concrete shell as opposed to standard beam shaped sections that create a discontinuity at each pass. This longitudinal continuity increases the stability and strength of the shell during excavation in poor quality ground.

Justification of immediate support

Immediate support at the excavation face is extremely important. An arch girder can be solicited as soon as an important load develops at the crown even if it is not encased in sprayed concrete. In this section, Dr Betzel offers a verification example under such loads. His verification takes into account second order effects, conforming to DIN 4114.

Justification of the sprayed concrete shell by considering the association of lattice girders – sprayed concrete

Once the lattice girder is encased in sprayed concrete and that it has set, the various bars of the web act as reinforcing bars for the concrete.

First, the author evaluates the strength of plain sprayed concrete section and, secondly, evaluates the increase in capacity of the sprayed concrete brought by the lattice girders. The calculations are function of the strength of the concrete at different ages. The strength of the reinforced sprayed concrete shell is evaluated according to the DIN 1045 standard and the special addendum 220.

The strength of the sprayed concrete shell reinforced with lattice girders is obtained by adding the admissible loads of the sprayed concrete and in steel. The capacity of the reinforced concrete obtained using a parabolic diagram method with the following deformation values:

ε_b = 2 0‰

ε_s = -2 0‰

Different curves show the increased capacity from the lattice girders. This improvement can reach 50% in some cases.

Design of the sprayed concrete shell (by J. Launay, DUMEZ-GTM)

Rabcewicz, L. v. Principles of dimensioning the supporting system for the 'New Austrian Tunnelling Method', Water Power, June 1969, July 1969, March 1973

The three papers deal with a tunnel liner failure and present a method to evaluate the required support.

The first observation of M. Rabcewicz is that failure occurred by shearing, and not by bending. This confirms Sattler's theory and the tests conducted by the author.

The second observation concerns the ground confinement brought by the sprayed concrete which allowed retaining the high shear capacity of the ground (E, c and φ) and also mobilize the strength of the ground created by this confinement pressure. This pressure is calculated using the shear strength of the sprayed concrete, the bolts and the ribs.

The third and most important observation is that the liner's strength is mainly related to the ground's capacity itself reinforced with bolts, and not the sprayed concrete. Sprayed concrete is a means to mobilize this capacity, not the principal player in the support of the opening per say. According to the author, one should not refer to sprayed concrete as a support method.

Finally, in the case of highly stressed grounds, it is essential to close the support shell in order to obtain a self-supporting structure. The stabilization of movements must be monitored through instrumentation of the tunnel. Validation of calculations can only be done by verifying the stabilization of the movements. This aspect is essential according to Rabcewicz.

Effect of creep in young sprayed concrete used for tunnel confinement (by J. Piraud, ANTEA)

Pöttler, R. (1990) - Konsequenzen für die Tunnelstatik aufgrund des nichtlinearen Materialverhaltens von jungem Spritzbeton. Felsbau, vol 8, N° 3, pp. 121-128.

Pöttler, R. (1990) - Time-dependent rock-shotcrete interaction: a numerical short-cut. Computers and Geotechnics, vol. 9, N° 3, pp. 149-169.

A realistic evaluation of a tunnel's support by sprayed concrete should take into account the evolution over time of the applied loads (consequent to the advancement of the excavation face) and that of the sprayed concrete properties (stiffening and creep). After analyzing the problem in a 3D finite element model with a complex time dependent constitutive law, the author showed that it can be replaced with an explicit 2D model with a linear elastic concrete behavior:

In the short term, the maximum stress found in sprayed concrete at approximately one diameter behind the front can be evaluated with good precision with a fictitious equivalent modulus E_i = 7 000 MPa;

After a few days, creep in concrete leads to a relaxation of the tangent stress in the support, which stabilizes after 2 weeks around a value close to σ_{LT} = 4 MPa.

The parametric study conducted by Pöttler shows that, these two values are acceptable for any depth, the diameter, the concrete thickness and the rock modulus. This conclusion – which corroborates experimental observations concerning the universality of sprayed concrete support – allows to rapidly estimate the stresses in a temporary support by using the characteristic curve method, and to verify them by measuring the deformation in the concrete shell.

Stresses in sprayed concrete in tunnels (by J. Piraud, ANTEA)

Golser, J., Rabensteiner, K., Sigl, O., Aladrian, W. (1990) - Kontrolle der Spritzbetonbeanspruchung im Tunnelbau – Berg- und hüttenmännische Monatshefte, Leoben, Vol. 135, n° 10, pp. 376-383.

This paper presents the results of a research conducted at the Mining School of Leoben (Austria) which included several laboratory experiments and in situ measurements, and modeling efforts aimed at determining a constitutive law for the behavior of sprayed concrete. Particularly, a time step method for the behavior of sprayed concrete was successfully calibrated against experimental results (cf. Schubert, 1988, above in the text). The objective was to evaluate the extent of a sprayed concrete shell unloading by using deformation values taken in situ.

On this point, Golser et al. (1990) consider that creep of young sprayed concrete is at the same time an essential property of this material (capacity to undergo large deformations without failure) and an essential characteristic to be determined.

Critics on direct stress measurements using hydraulic cells

Inherent defects of this monitoring technique were brought to light both through numerical simulation and laboratory experiments (cell encased in concrete placed under a load frame). These studies showed that such cells always yield short term pressure values that are too low and long-term values that are too high, without any indication of when the measured value is exact. Moreover, they do not return to zero after unloading. Their reliability is however better at high stress levels, especially if they are initially "pre-laoded" (up to 400 kPa) to improve contact.

Measuring deformations in a sprayed concrete shell

Golser et al. (1990) recommend, for future projects, to determine the stresses in the sprayed concrete using deformation measurements, much more accurate. This assumes that the placement of deformation monitoring devices are on both sides of the shell; using a few hypothesis (no traction, limit to compressive stress, etc.). One can then calculate the normal load and the bending moment in the sprayed concrete shell, and compare that to the allowable values for unreinforced concrete according the DIN 1045 standard.

A real calculation example of load N and bending moment M from deformation measurements taken from sensors located on both sides of the shell in a tunnel showed that even after reaching very high values after a few days (near 20 MPa), the stresses go down to approximately 1/3 of the maximum value. This corroborates Rabcewicz's old principle stating that the bending moments could be neglected for the design of sprayed concrete supports, either because they decrease over time or lead to cracking and subsequent formation of hinges.

Sprayed concrete final liner on a test section in the Munich subway (by J. Piraud)

Honnefelder, N., Theimer, G.U. (1992)– Einschalige Spritzbetonbauweise im Münchner U-Bahn-Bau. Der Bauingenieur, n° 67, pp. 393-399.

In a tunnel constructed using a conventional method, with temporary supports made of sprayed concrete possibly covered with a cast in place liner, we consider the cast in place concrete to take all of the loads at its final state. However, long term monitoring showed that the sprayed concrete layers retained some long-term support capacity which represented a safety factor not considered in the design.

Location and geology

It is this economical aspect that led the DYWIDAG Company to test sprayed concrete "single shell" final liner first in 1989 in the Frasdorf outlet (L = 3,2 km), and then on a test portion of the Munich subway (lot "6 West 5").

This test portion has a variable section of 38 to 52 m^2 and is located 8 m underground. The tunnel is at an intersection between compact ternary marls (bottom), sand and gravel (top). The water table is located at mid-height but can exceptionally reach the crown; during construction, surface pumps were used to lower the water table.

Construction method

The following method was used:

• Staged excavation excavation, bench and heading,

• Placement of a 5 cm layer of an accelerated dry process sprayed concrete to immediately seal the surface,

• High quality micro silica sprayed concrete (no accelerators) is sprayed to reach a total thickness of 15 cm,

• For planning reasons, a thick slab is cast in place,

• 6 months after the excavation, the sprayed concrete surface is water jetted (600 kPa), in order to guarantee an optimal bond with the next layer of concrete,

• Spraying of two layers of micro silica concrete, each 10 cm, 14 days apart; a total thickness of 35 cm of "active" sprayed concrete is thus obtained (used for calculations as well).

Interior sprayed concrete characteristics

Composition of 1 m^3 of fresh sprayed concrete (total mass of 2 370 kg/m^3):

• 190 l of water,

• 60 kg of micro silica slurry (including 50% water)

• 380 kg of 45F Portland cement,

• 1740 kg of aggregates, of which:

o 43% are 0-2 mm

o 23% are 2-4 mm

o 34% are 4-8 mm

The dry mixture is plant produced and oven dried. It is pre-wet in the tunnel and transported through thin stream method. The micro silica, which replaces the accelerators, is precisely added to the mixing water that feed the manually operated nozzle. This micro silica is characterised by its extreme fineness (specific surface of 200 000 cm^2/g); it has the advantage of cutting by half the amount of rebound while increasing the compaction and the overall strength of the concrete.

Particular care is provided in the presence of cold joints, for setting of the layer thicknesses, for securing the mesh reinforcing the second layer and for the curing of the concrete (regular spraying of each layer with 200C water for 7 days in order to reduce cracking).

QA/QC testing program

A rigorous quality control program was set forth for the materials, equipment, procedures and concrete thickness applied. The quality of the surface was an item that received particular attention: 50 pull out tests were conducted, yielding an average adhesion of 1.87 MPa (following the STV-SIB 878 procedure). The 28 days compressive strength is clearly above 50 MPa, both on samples taken from test panels and on samples cored in situ.

Water penetration depth measured according to the DIN 1045 standard did not go beyond 24 mm. Concrete temperature increased from 10 to 180C after setting.

Adhesion tests of the 2 interfaces of the 3 sprayed concrete layers were conducted both on samples taken from test panels and on samples cored in situ; they yielded results clearly above the minimum required value of 0.6 MPa. Indeed, the cold joints were difficult to identify on the samples, which clearly shows that a homogeneous shell was obtained even though spraying was done in 3 passes. Finally, shrinkage measurements have shown the positive effect of warm water.

We also noticed that the tunnel was watertight, almost no cracks were observed. Spraying on test panels containing reinforcing bars showed, after they were saw cut, an excellent encasement of the bars and joints, without shadowing effects.

Conditions for success and conclusions

A homogeneous sprayed concrete shell can only be obtained through excellent knowledge of the technology and a strong quality control program. The key elements responsible for the success of the projects are:

• Meticulous cleaning of all surfaces to spray (in order to guarantee adhesion),

• Prewetting of the surfaces prior to the application of the sprayed concrete (in order to limit concrete's water to be absorbed by capillarity),

• Careful watering of the surfaces after setting (curing),

• Reinforcement was tight and rigid, while avoiding high steel concentration,

• Vigilant control of reinforcement position and sprayed concrete thickness.

This single shell liner ended up 10 to 15 % less expensive than the usual solution, which planned for 15 cm of immediate "inactive" sprayed concrete + 35 cm of cast in place concrete. The economy comes essentially from the reduction in the volume excavated and the volume of concrete, as well as the suppression of the forms. This solution is especially indicated in the case of short tunnels, with variable sections or short bypasses, particularly for tunnels above the water table.