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# Some criteria to consider in final lining design and supervision in conventional tunnelling

von Munthe af Morgenstierne, Erik[(1)], Vélez Pérez, Héctor[(2)], Caro Perdigón, Pedro[(3)]

[(1)]*Marti Group Norway*

[(2)] *Technical Supervisor Engineer*

[(3)]*Associated Professor in School of Mines ( University Polytechnic Madrid , Spain)*

ABSTRACT: This paper aims to summarize all the main criteria to carry out the design and supervision of in situ concrete lining. It is shown what are the main points to make it easier the supervision. Once excavation, support and waterproofing phases are finished, a concrete lining shall be placed. This lining is not required for structural reasons but is important to place in the long run. This paper shall comprise the design criteria and aspects about placing concrete in situ lining and its equipment in the conventional tunneling.

## 1 Introduction

The economic importance of tunnel lining ranges between 20 and 25% of the project´s budget. Therefore, lining is usually the third work in importance, after excavation and support, and the parameters in supervision must be perfectly defined. The methodology is shown in Figure 1. That figure shows a diagram regarding the main matters that the authors have figure out at the tunnels´ supervision. Those matters are shown in chronological order as they appear in the work. Sometimes the solution is found at the site by the engineers or constructors.

## 2 Design criteria and aspects to consider in tunnel lining: Integral design

### 2.1 Aspects and previous criteria

Within the tunnel lining design we should consider the following questions: Why is tunnel lining necessary?, and what is its aim and purpose?

The answer to this questions may be mainly defined as follows:

It is necessary in order to obtain an inner cross section which meets the demands of the tunnel functionality and other specifications such as aerodynamic, cinematic, drainage rules, etc.

The main aim is to look for a structural security that enables to support loads, fluids and to keep a functional cross section in the long run.

Another function is to provide durability in the infraestructure in the long run.

We should consider the main design criteria and aspects in tunnel lining, as shown in the Table 1.

### 2.2 Final lining design

Currently there are two calculations models to design final linings:

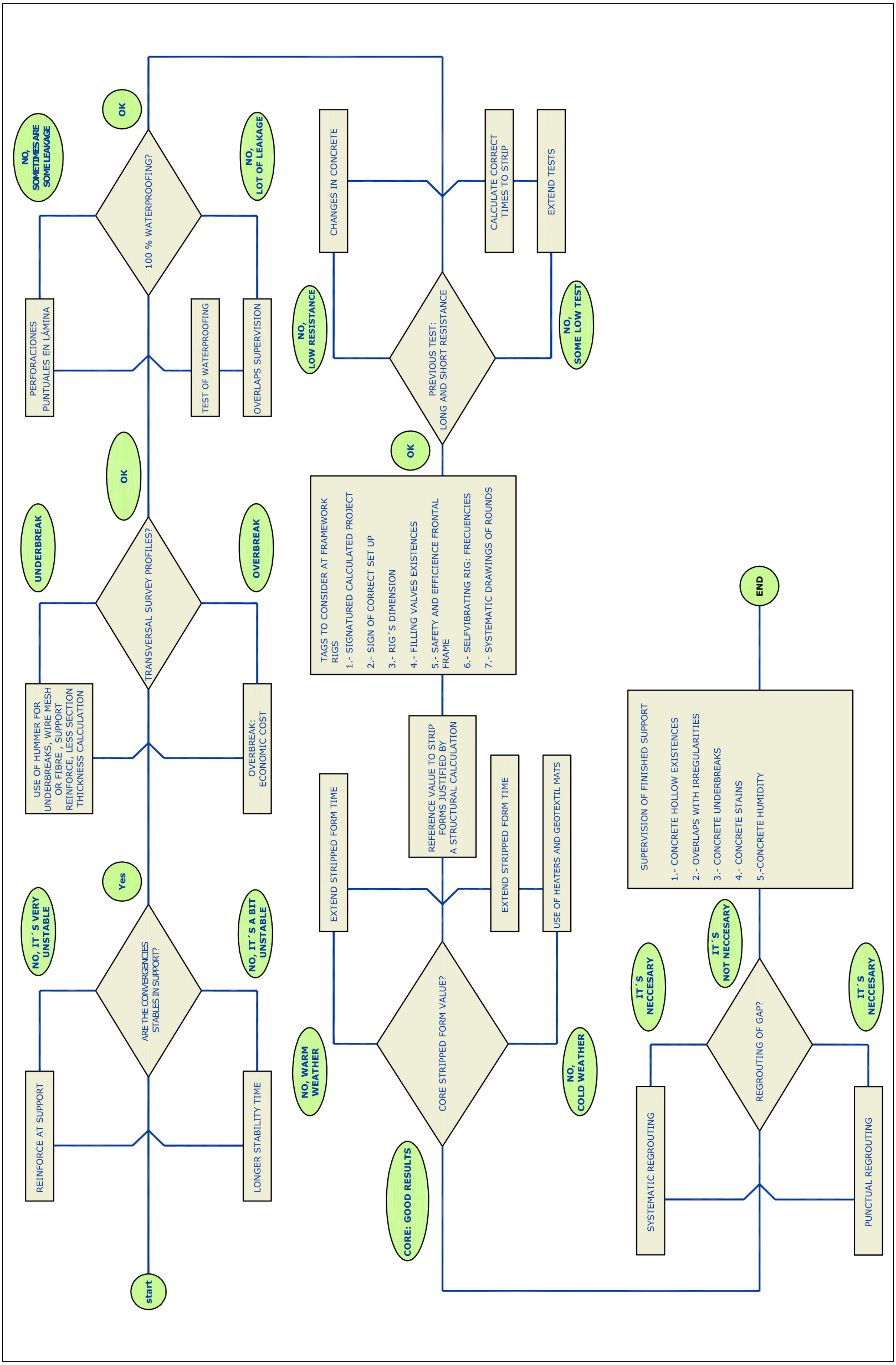


**Figure 1. Phases in lining conventional tunnel**

**Table 1. Aspects on final lining in tunnels**

| Criteria | Condition | Notes |
|---|---|---|
| Operational | Geometryc | Number of Tracks |
| | | Section lines |
| | | Cant gradient |
| | | Safety passenger routes |
| | | Services, Monitoring and signposting |
| | | Ventilation and aerodynamic |
| | Structural | External and internal loads |
| | | Tolerances |
| | | Tunnels and nearby underground structures |
| | | Drainage capacity |
| | | Long -term loads |
| Services | Durability | Tranversal joints, contact with gas pollution, air, wet, temperatures and their oscillations. Bad conditions such as frost-thaw cycles |
| | Materials | |
| | Fire resistance | |
| Enviromental criteria | Inside tunnel | Chemical agents |
| | | Water table |
| | | Possible presence of gas explosives |
| | Outside tunnel | Vibrations and noise |
| | | Settlements |
| | | Contamination and pollution of aquifers due to injections |
| | | Dewatering and drainage of aquifers |

Structural methods: These models are based on equilibrium limit model with simplified hypothesis. These are analytical calculations. The most important is "pipe formulation" studied in material resistance courses. Other analytical models are the Hyperstatic Reactions model and the Characteristic Curves model based on support applications.

Numerical models: These are divided into two principal methods: Methods based on finite elements codes (PLAXIS, ANSYS, PHASES, etc), and Methods based on finite differences codes (FLAC).

## 3 Aspects regarding materials to be used and the final product

The materials should meet the conditions established in the existing legislation and general specifications before starting the projects and the works. For in situ concrete linings the conditions are as follows:

The cements should meet the existing legislation. They must be resistant to sulphates in case of corrosive waters. Other types of cements could be used to reduce the time of unformwork or for other reasons if they respond to adequate justifications.

Water for mixer should be free of organic material, suspension particles, chemical products (sulphates, chloride, etc.). It is advisable, or even necessary to use additions which improve the concrete pumping to facilitate its implementation.

The characteristic resistance to compression (in 28 days) must be justified in the Project, particullarly in the drawings and general specifications, both in accordance.

To unformwork the concrete lining it is necessary to reach a minimun characteristic resistance to compression to bear its own weight, with coefficient of at least 1.25, although this factor could be substituted by reaching as reference resistance as we will see later.

To avoid segregation is advisable to get a good conection between aggregates, cement and high vibration (internal and external) in order to obtain a minimum density of fresh concrete al least of 95%. To obtain a minimun shrinkage and lack of crack risk.

Sometimes due to geotechnical problems, such as expansiveness, fluency or hollows, it is necessary to reinforce the lining. In this case the steel bars need to meet the existing legislation.

# 4 Aspects to consider previous the concrete lining

Before the starting of the tunnel lining we should make sure that the support is being effective. This is possible to know by monitoring.

In the case that the speed (measurements of convergences) show abnormal results we will reinforce the support with measurements as established by the grounds. Some projects have as reference value, in order to regard the convergences as stable, 0.15 mm/month. From the obtained results in the convergences we should monitor the condition of the sprayed concrete in order to find abnormalities in its surface, as cracks, water pressures, spalling, etc.

The second aspect to consider is the checking of topographic transversal profiles on supports, the most important thing is to avoid the the real line of sprayed concrete of support invades the theorical inner cross section. Certainly we should accept tolerances of up to 10-15% of the thickness, only in the case of occasional trespassing, for example in the ending of side walls. The common solution in these cases is to use the sprayed concrete or to use mechanical means until obtaining the desired thickness. The checking of the right performance of waterproofing is essential to rule out leakages in the linings. First we need to locate the areas with water presence on the support in order to identify the most unfauvorables chainages. We should distinguish between isolated water infiltrations which could be solved with the right overlapping, and areas with many water pressures with reinforcement of waterproof sheet and or trials tightness. On the other hand we should reach a tightness which avoids humidity.

Finally, it is useful to look at previous trials, not only of compression but also tensile of the concrete lining. It is advisable to compare the results of the short-term trials and long-term trials with the characteristics resistances that the project demands. The type of concrete, the kilos and types of cement, a consistency which allows pumping, reinforcement fibers, all of them are characteristics that need to be considered before starting the project and works.

**Figure 2. Checking concrete cores**

# 5 Main operation phases in situ concrete linings

The execution works in placing in situ concrete lining will have to check, to observe and to perform the following phases:

Preparing the surfaces and checking de inner line in cross section. To place cleaning concrete slab and/ or invert.

Execution of bases and starting side walls. Placing waterproof system. Placing drainage system. Placing concrete in vault. Injections of grout in gaps.

All the phases follow a logical order, thus the execution of the starting side walls must be always previous to the invert, and the execution of the latest previous to the execution of the vault in lining. It is important that placing concrete is made in only one-phase, that way there will not be joints between phases and therefore possible ways for percolated water. The inverts should be made with pumping equipment in bits of 15-20 m length. At the end of every bit there will be a transversal framework as a transversal joint. Furthermore, the starting side walls will have to provide a base to formwork carriage, these can stabilize ground pressures in the base of ribs. It is interesting to make them quickly, above all in squeezing grounds due to high deformations with horizontal convergences. These horizontal convergences may be stabilized with the starting side wall´s weight.

**Figure 3. Overview of some phases in linning conventional tunnels**

# 6 Formwork carriage features

## 6.1 Formwork carriages types

There are two systems of formwork carriages:

Formwork carriage self-bearing: It consists of a centering that bears a formwork equipment. This equipment consists of a structure with three o five steel panel formworks. These panels are moved through the tunnel by the carriage. It can work with three or five panels depending on the cross section tunnel per carriage. The steel panels of formwork are fixed to the starting side walls, so that the carriage is safely braced to prevent displacement. The carriage moves by two rails located on the starting side walls.

Formwork carriage self-leveled: It consists of a centering that bears a formwork equipment, usually with three steel panels. The carriage moves by two displacement hydraulic engines. Total displacement is obtained through two rails on the invert or slab of tunnel, near to side walls.

## 6.2 Important features to consider in formworks carriages

Firstly It is necessary to know the loads, initial displacements and asymmetric pressures of fresh concrete previous to calculate the carriage´s structure. The project´s calculations must contemplate the worst hypothetical scenario. This is necessary to be able to work in a safe interval.

Secondly it is necessary that the carriage and its structure are certified by “C.E “(European Community). This certificate C.E shows all the structure´s details , specifications and features given by the manufacturer. We must know all the features, materials and its quality control and its specific conditions. Next it is important a administrative document that shows “assembling equipment procedures in accordance with the manufacturer´s rules. Moreover this document must be signed and sealed by a Technical Office Engineer.

Last but not least, there are other specifications and features of formwork carriages to consider:

Size, wide, length, high and other dimensions: This is important to know the placing concrete cycles. These dimensions are necessary to know concretes volumes per work day. Hydraulic systems for vibration: frecuency and vibrating times.

Hollow tubes are necessary in quantities and layout. These tubes are important to prevent break up of the concrete mixer. Presence of warnning signals in the crown.

Windows to see concrete level. This prevents asymmetrical loads on the carriage´s structure during the placing of concrete. Frontal frame and a good system to build it and its joints. Studies of pitches in the tunnel to avoid accumulations of water. Furthermore these studies and features are important to prevent concrete hollows in the crown of the tunnel. Stirrup flanges to the carriage and hydraulic up-down frame engines.

The equipment shall incorporate gauges for measuring the pressure into the delivery line and a pressure regulating system. Pumping equipment, storage hoppers, and delivery pipelines must be lubricated at the start of each concrete operation. Safety systems to prevent accidents.

## 7 Checking the lining

There are three elements that need to be respected by the placing concrete and the formwork carriage:

Connections in T of drainage systems , be it straight to the principal duct.Taking of lands in case of the presence of ribs and if the works are railways.

Monitoring box to measure displacement in the long run.

Previous to the placing concrete we should topographically check the location of the formwork carriage. The surface of the starting side walls must be clean and without mucks. The formwork must be cleaned and to pour unformwork liquid on it that will facilitate its movement. We should make sure that the waterproof sheet does not break while the carriage is moving. During the process, the delivery note of concrete should be checked in order to verify that the concrete characteristics meet the demands of the Project and the fibers dosages are the agreed. The frontal frames are of great importance in the checking procedures as they support the máximum pressure and they should resistence to them, avoid the loss of concrete and breaks that could involve an incident. Besides it is necessary to avoid the drilling of the waterproof sheet. It is important to check the final stage of operations until the warning signals start pouring the concrete, which means the works are finished. The follow-up of the works can be summarized in the following figure:

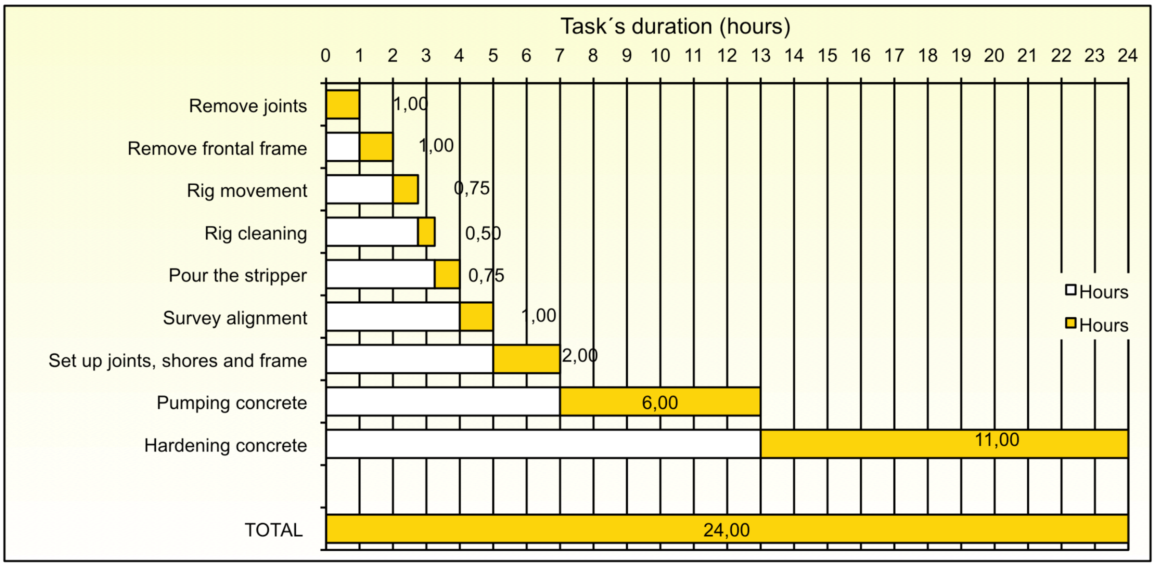


**Figure 4. Tak´s duration and cycle in situ concrete lining**

Lining´s unformwork is the most delicate phase in the cycle of the lining. An important decision consist on to know the time from the first concreting down to obtain the value of strength in the concrete lining. This value of strength is known as “ reference value to unformwork”. A typical value is 12,5 MPa of strength, but, this value must be checked with a structural calculation. Besides ,it is important that this reference value is compared with results of cores concrete inside tunnel and outside tunnel zone at difererents hours. It is important to know and to inspect the tunnel´s temperature.

## 8 Anomalies in the finished lining

The most important anomalies and their reasons and possible corrections are shown in the follow Table 2.

**Table 2. Principal anomalies in situ concrete linings**

| Concrete´s anonaly | Possible causes | Possible solutions |
|---|---|---|
| Concrete hollows in the low position of formwork | Cement grout is lost in concrete. Frame in base " no-tight". Consistency of concrete | A best frqme of the base to do it tight. Use of concretes wiht flow and sofy consistency. Make vibrating more time. Do not mix water in the concrete mixer. |

| Concrete´s anonaly | Possible causes | Possible solutions |
|---|---|---|
| Concrete hollows in side walls and heading | Poor vibrating. Dry consistency of concrete. Maximum size of aggregates and relation w/c. On heading finishes to place concrete before "warning pipes" starts | Make vibrating more time. Use of concretes with flow and soft consistency. Use of grout to repair. |
| Concrete voids in heading and others zones of arch | Finished to place concrete before " warning pipe" starts. Difficults and problems in concrete plant. | Frontal frame with specific boards. Use of reinjections with high quality cements. Reinforced of hollows. Use of foams. Use of monitoring in the fillings of hollows. |
| Concrete sticking in joints between formworks pieces | Bad tophographic checking. Clos e the formwork carriage at same time placing concrete | Setting and Checking tophographic. Revise structural calculations of formwork carriage. Chipping unformed surfaces. Possible influence in aerodynamic section. |
| Concrete hollows in frontal formwork | Frame frontal badly executed | Reinforced frontal frames with timbering. Use of foams to seal. |
| Displacements in headings | Checking calculations. There is " no hardening concrete" and there is collapses during unformwork | Periods of curing longer than project: It is important core values and reference values. Maximun radial displacement 1 cm in heading. The displacements must be assumed by the formwork calculations. |
| Unformed concrete finishes in side walls and heading | There is movement towards inner lining. Unformwork is made before time | The formwork structure should be reinforced. Do tophographic checking placing concrete. |
| Stains on the concrete surface | Liquid for unforwork: See it is dry or wet. Differents concretes types during to place concrete | Change liquid for unformworks: Do not use Gasoil. Do not use differents concretes. All the concrete must be made at the same concrete plant. |
| Water flowing on the concrete surface | Waterproofing sheet " no-tight". Some times there is broke-sheet placing the frontal frame. | Trivial problems: Drainage-sheet on the surface concrete lining. Important problems: Chipping the lining to waterproof again. Checking the frontal frame. |
| Water near starting side wall | Ducts for drainage are stalled due to weight concrete. There is not exist to the water in the tunnel. Bad checking in site of ducts. | Chipping in base to take out water towards principal duct. In the lowest point of tunnel prevents damed water. |
| Fissures on surface concrete | Loads in the support. Poor thickness in concrete. The temperature gradient from day to night is exceeded. Theer is "no hardening" concrete. | Reinforced with fibers and mesh. In cold and frost weather put heaters. Checking thickness. Cite gypsum as a witness or monitoring instrument to see fissures. |
| Formwork carriage elements | Elements of formwork carriage bad dimensioned, constructed and securely braced as to prevent changes about drawings and schemes. | New formwork carriage with a high cost. To repair and solve some problems in site. This is not important to aerodynamic section |

## 9 Safety behaviour regarding lining

One of the principal questions in the safety lining is the fire resistance. Fire resistance of concrete linings is an important design criterion and the relevant standard for the design of structural linings should be used. In general there are two basic options for fire protection linings:

External protection. In this case it uses applications of boarding or sprayed-applied coatings.

Internal protection. On the other hand it can be provided by adding polymeric fibers to the concrete with a dosages of around 5-8 kg/m$^3$.

Independently from the tunnels length, the following requirements for fire resistance must be checked:

Structure concrete integrity: It is important the thickness in concrete lining. This thickness is related to the maximum temperature in a fire during a time exposed. These parameters are developed in the curve “time-temperature” known as “EUREKA”.

Stability of materials: The fire resistance depends on the particular stability of materials facing fire and high temperatures. The minimum thickness may be 30 cm depending on the tunnel.

Additional measures for concrete lining: It is practical to add external or internal protection as described above. Other demanded characteristics to concrete lining and its materials are: lightness, good coat, corrosion resistance, chemical resistance, durability and fire passive resistance.

## 10 Conclusions

Firstly the most important factor in the design and checking of the in situ concrete linings is “the supervisor´s experience”. Secondly the concrete lining execution is a critical phase in the underground works and tunnels,therefore good technical office engineers are needed. In works-site and meetings the technical office engineer must give solutions to the problems which may arise. Next, the technical office engineer must look for good arguments to valid and design in situ concrete linings. These good arguments consist of the next areas:

Checking all phases and aspects in the design phase: Numeric and analytical calculations. This is an important fire resistance Checking all phases and aspects in work-site: General aspects as concretes, formworks carriages, waterproofing installed, drainage system and sequence of work within the tunnel.

Temperature monitoring the concrete. Reference core and reference value to unformwork.Transport of concrete. Concrete placing equipment Placing concrete and compaction. Curing and protection and construction joints. Detect and reform possible mistakes in the works. Types of formwork carriages: advantages and disadvantages.

Concrete finishes and unformed surfaces. Fixing bar and mesh reinforcement in hollows.Monitoring and inspection of completed structure. Fire resistance analysis.

To conclude, the technical requirements are more important than economic requirements therefore it is important the communications among different involved parts: Designer, Constructor Company, Technical Assistance Company and Manager Director Engineer to discuss and to solve the different problems which may arise and develop procedures to work in situ concrete linings.


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