

NEW LINE 9 METRO CONSTRUCTION BARCELONA, SPAIN

TUNNEL LINING: FIBRE REINFORCED CONCRETE

Product: Wirand[®] FF1, FF3, Fibromac FR

Problem

Expansion of the existing metro in Barcelona included 50km of new lines, intended to be completed in 2014. The expansion projects included Lines 9, 12 and 13. Line 9 will be the longest tube line in Europe, linking the airport in the west to Santa Coloma de Gramanet in the east. At 60m underground, Line 9 is also the deepest line on the Barcelona metro network. The line increases passenger choice, reducing the necessity to travel into the city centre to change trains and thereby reducing congestion.

The route of the tunnel is through highly varied geology ranging from solid rock to soft sand. It also passes beneath both the rivers in the city and highly populated areas. Also, the tunnel lies beneath sea level in the length near the port. The 12m diameter tunnel bores were to be lined with pre-cast concrete segments.

Solution

The Joint Venture Construction Consortia [UTE Gorg, UTE Linea and UTE Aeroport], used precast FRC segments for the lining to three individual sections of the 12.0m diameter tunnel, totalling some 11.7 km in length.

At the 3.8km long, Sagrera TAV-Gorg section, construction work began in 2003. An earth pressure balance, tunnel boring machine [TBM] was used to excavate the tunnel, with the precast lining segments placed ring by ring behind the machine, using a robotic arm.

During the boring/construction process, hydraulic jacks on the TBM push against the previously placed precast concrete segments as the machine cuts into the rock and soil ahead of it. Pressure values of up to 140MN [15,700 tons] can be reached, with a normal working range of between 90 and 120 NM. The excavated diameter of the tunnel is 12.1m and an overall lining thickness of 400mm, including the precast concrete final lining.

Segment fabrication

FRC tunnel ring segments were cast off-site and comprised 7 segments of 4.56m length [48degree length of arc] plus a 24 degree keystone, per ring. Each ring has going-length of 1.80m and is 350mm thick.

Client:

TRANSPORTS METROPOLITANS DE BARCELONA

Main contractor:

VARIOUS JV CONSORTIA

Products used:

WIRAND[®] FF1, FF3, FIBROMAC FR

Date of construction

2001 - 2012



Maccaferri dosage machine attached to batching plant



Large bags of Wirand[®] fibres ready for use



Computer controlled dosage machine at batching plant



Segment mould awaiting rebar



Filling segment moulds

Segments were cast in curved steel formers with vibration applied to consolidate the concrete mix and heat cured at between 40-50deg C for 4-6 hours, before de-moulding and stacking them in an open yard.

The original design for precast segments required 120kg of traditional steel reinforcement in the form of a fabricated cage, to provide the required structural strength. No fibre reinforcement was considered at this time.

An initial proposal of 30kg/cum of Maccaferri Wirand® FF1 steel reinforcement fibres was made in an attempt to reduce the amount of steel bar within the segments. Ongoing testing refined the fibre reinforcement and a new fibre, Wirand® FF3 with a higher L/D [length/diameter] ratio of 67 was developed, which offered improved performance.

Eventually, only 25kg/cum of Wirand® FF3 was found to achieve the same performance as 30kg of the FF1 fibres. Ongoing testing produced an optimised combination of 25kg of Wirand® FF3 fibres and 54kg/m³ of steel rebar offering the required structural performance (28 day compressive strength of 40MPa [5800psi]). An early age compressive strength of at least 20Mpa [2900psi] was also required to ensure sufficient crack resistance during the de-moulding and stacking.

Reinforcement fibres are added to the concrete mix via purpose made dosing equipment, of a design specially modified by Maccaferri, to ensure controlled introduction and consistent dispersion of the fibres. 5 feeder machines were installed in the batching plant producing segments for all three tunnel section.

To minimise seepage of water into the tunnel, crack widths were limited to 0.2mm, requiring a minimum 4-point loading flexural strength of 2.9MPa [4200psi]. Macro steel fibres, with high-strength / low-strain characteristics offer this performance; 25kg/cum of Wirand® FF3 offered a flexural strength of 3.5MPa.



Removing cast segment from casting plant



Precasting yard storage area



Completed segments



View of TBM at tunnel mouth

The inclusion of reinforcement fibres also helped;

- Reduce the flexural stresses experienced during de-moulding and stacking
- Controlled shrinkage and thermal cracking
- Improve resistance to accidental impact damage
- Improve resistance to the highly concentrated loads imposed during segment placement and the application of the jacking forces from the TBM

Fibre-only reinforcement

Some months into the tunnel construction programme, contractors proposed an alternative method of casting lining segments, this time without the inclusion of steel cage reinforcement and relying solely on steel fibre reinforcement for the structural integrity of the unit.

The high cost of steel cage reinforcement and reduced casting time/increased mould utilisation being the principal motivations behind the proposal. The proposal was a revolutionary step, as this had not been considered within the final-linings of tunnels.

In 2003/04, Laboratory trials were carried out in conjunction with Maccaferri at the University of Bergamo in Italy, to ascertain the viability. Fibre content was increased from 30kg/cum to 60kg/cum to replace the steel cage, yet maintain the required structural performance.

A series of measurements to evaluate the performance of the revised units and a full scale in-situ test was implemented, placing approximately 20lin.m of tunnel permanent final lining using segments reinforced with steel fibre only. It was concluded that the segments reinforced with 60kg/cum steel fibre could satisfy the requirements of the project without necessitating the inclusion of conventional steel bar, cage reinforcement.



Testing in progress to reduce rebar content



Tunnel portal showing diameter of tunnel



Tunnel heating completion, awaiting track laying

Despite the evident success of the trials, it was ultimately decided that the use of fibre-only reinforced concrete segments was a technological step too far for the project team, having already reduced rebar content from 120kg/cum to 54kg/cum through the use of fibres.

Fire protection legislation

Recently introduced Spanish legislation concerning fire protection in tunnels has obliged contractors to incorporate polymer reinforcement fibres into precast lining segments. Along with its steel materials, Maccaferri is also supplying Fibromac FR polymer fibres to the project.

At the conclusion of the works in 2014, the company will have supplied approximately 20,000 tonnes of steel and polymer reinforcement fibres to the Barcelona Metro construction project.



View of tunnel portal

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