WHEN CONTRACTOR IC ICTAS-ASTALDI came to fix the rebar for the secondary lining of the Riva Tunnel in Istanbul, it ran into problems. The 22m-wide tunnel required reinforcing bars up to 12m long to be fixed; this was proving difficult to do, introducing safety risks and causing damage to the sheet waterproofing membrane which sits between primary and secondary lining.

The solution was an unusual one for Turkey: using fibre-reinforced concrete to create the permanent secondary lining. Following careful evaluation and tests at Istanbul Technical University, designer EMAI International was able to demonstrate that by using high-performance steel fibres a fibre-reinforced concrete lining would be just as good as one reinforced using steel reinforcing bars.

The Riva Tunnel is one of three underground projects to use the new Dramix 5D series fibres which can be used to create a material which has a far greater residual strength after cracking than other fibre-reinforced concretes, behaving more like traditionally reinforced concrete. In each of the three cases, designers and constructors faced challenges around constructability or durability – or both – of the final lining which have been solved with the help of this new breed of fibre.

A 40-year story
Steel fibres have reinforced concrete since the early 1970s. It was the 1990s that saw the start of underground applications, in both shotcrete and precast tunnel lining segments. Back then, fibre-reinforced concrete was already being used for some permanent linings. Costain Taylor-Woodrow used it as a final lining in a ventilation tunnel on London’s Jubilee Line and Taylor Woodrow employed it on the refurbishment of the Victorian Brunel Thames Tunnel.

However a lack of regulation and standards hampered the spread of fibre-reinforced concrete for final tunnel linings. With the publication of international design guideline the fib Model Code for Concrete Structures 2010, this obstacle has been overcome and designers are gaining confidence in working with fibres.

This year there has been a flurry of additional guidance for fibre-reinforced segments: the American Concrete Institute’s (ACI) Report of Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments (ACI 544.7R-16); the International Tunnelling and Underground Space Association (ITA-AITES)’s Twenty Years of FRC Tunnel Segment Practice: Lessons Learned and Proposed Design Principles; BSI PAS8810:2016 Tunnel Design - Design of concrete segmental tunnel lining – Code of Practice; and ITAtech Guidance for Precast Fibre Reinforced Concrete Segments – Vol. 1 Design Aspects.

Fibre reinforcement in the secondary linings of Sprayed Concrete Lining (SCL) designs, such as those used for Crossrail’s station and platform tunnels, is also becoming more
commonplace. Designers now have the option of fibre-reinforced concrete for cast-in-situ final linings too.

Steel fibres come in different sizes, shapes and qualities with each having its own effect on the concrete behaviour and quality. The dosage of fibres needed to meet the desired structural performance will vary, depending on the characteristics of the fibre itself.

The behaviour of fibre reinforced concrete is more than a simple superposition of the characteristics of the concrete matrix and the fibres. To analyse the behaviour of this composite material, the way that the loads transfer between concrete matrix and fibre also have to be taken into consideration.

For efficient load transfer, three conditions must be satisfied. There must be sufficient exchange surface, governed by the number of fibres, their length and diameter; the nature of the fibre-matrix interface which allows for a proper load transfer; and the mechanical properties of the fibre such as Young’s modulus, tensile strength and anchorage strength which must allow the forces to be absorbed without breaking or overly elongating the fibre.

Bekaert Maccamerri spent five years developing the 5D fibre, trying many combinations of hook design and wire strengths in order to optimise the performance and cost. The goal was to create a fibre that could be used in structural applications such as foundations slabs, rafts, suspended structures – and the final linings of tunnels.

Dramix 3D – the name for the Bekar Maccamerri’s original steel fibre – and the Dramix 4D, which uses higher-strength wire both work in the same way. The kinked ends provide ductility to the concrete by slowly deforming as the wire is pulled out of the concrete. This is the mechanism that generates concrete ductility and post-crack strength. The Dramix 5D fibre, with four kinks at either end rather than two or three respectively, actually works in a totally different way to its siblings the 3D and 4D: a revolution rather than evolution. Rather than relying on the pull-out mechanism of the fibres to provide ductility, the 5D does not pull out but remains anchored, lengthening itself - as rebar does - to provide ductility.

The tensile strength of a steel fibre has to increase with the strength of its anchorage, otherwise it would snap causing the concrete...
**FACT FILE:**

**Client:** Ministry of Transportation, Turkey  
**Main contractor:** IC Ictas-Astaldi JV  
**Designer:** EMAY International  
**Application:** Secondary lining  
**Fibre:** Dramix 5D 65/60  
**Dosage:** 20kg/m³  
**Concrete:** C35/45  
**Timeframe:** 2015/2016

The Riva Tunnel in Istanbul will carry the Northern Marmara Motorway, which will run around the North of the city, bypassing the congested city centre and crossing the Bosphorus on the newly opened Yavuz Sultan Selim Bridge.  

JV contractor IC Ictas-Astaldi is constructing the 115km central section of the motorway between Odayeri and Pasaköy including the main bridge, viaducts and two sets of tunnels as part of a Build-Operate-Transfer (BOT) deal which will see the consortium run the motorway for 10 years. This is a prestigious project, representing the largest ever investment in infrastructure since the Turkish Republic was founded.

IC Ictas-Astaldi constructed the primary lining of the Riva tunnels, which runs through flysch, a combination of claystone and sandstone, using the New Austrian Tunnelling Method (NATM). The two four-lane tunnel, up to 22m in diameter, are 626m and 564m long.

It was the dimensions of the tunnels – and hence the need to fix very long rebars – that drove designer EMAY International to look for alternatives to the original design. EMAY decided on Dramix 5D fibres due to their superior performance when compared to 4D or 3D, retaining residual strength even after cracking.

An automated dosing system ensured that the right proportion of fibres was added to every batch of concrete. This provided assurance to contractor IC Ictas-Astaldi that the quality of the lining would be as-designed; a very important consideration given that this is a BOT project.

As well as achieving the main aim of removing the safety risks posed by the unwieldy lengths of rebar, using fibre-reinforced concrete led to some significant time savings: the lining was cast three times faster than a conventionally-reinforced lining would have been, with 350m³ pumped into place every day.

The future will definitely see more use of 5D fibres in the permanent linings of tunnels and shafts. Several projects are already being designed using the fibre and others are considering its use as an alternative to traditional reinforcement for the final lining. Other underground applications have included track slab inside rail tunnels and free-spanning slabs in car parks.

**FACT FILE:**

**Client:** BH Potash  
**Main contractor:** DMC Mining  
**Designer:** Arup  
**Application:** Shaft walls  
**Fibre:** Dramix 5D 65/60  
**Dosage:** 30 kg/m³ to 50 kg/m³  
**Concrete:** 60 Mpa  
**Timeframe:** 2013/2018

The Jansen Project sees the possible development of an underground potash mine in east-central Saskatchewan in Canada, 140km east of Saskatoon. Though the collapse of prices in the potash market means that a question mark hangs over whether the mine will go ahead as planned, contractor DMC Mining is already well-advanced with the construction of two shafts which will provide access to the mine.

The production and service shafts both have internal diameters of 6.5m, wall thicknesses that vary between 800mm and 1.1m and are 1,030m deep to reach down to the level of the potash deposits. A ground freezing exercise involving 89 freeze holes and monitoring wells was required before excavation of the shafts using Shaft Boring Roadheaders could begin in order to prevent water from underground aquifers flowing into the shaft.

Following behind the roadheaders, DMC Mining is slip-forming the shaft walls. By using fibres to reinforce the concrete, rather than traditional rebar, the whole operation becomes faster and safer – as it removes the steel-fixing step and the need to have additional people working inside the congested area of the shaft.

In August, BH Potash reported that the shafts were about 600m deep with 300 or 400m to go. “We’ll finish the shafts around 2018-2019 and at that point we’ll face a decision as to whether we actually start to construct an operation around those shafts and start to enter the market,” BH Potash CEO Andrew Mackenzie told reporters at the time.