The Lee Tunnel Beckton London, the Suppliers View

John Greenhalgh
Bekaert Maccaferri Underground Solutions BVBA, UK office

John has been with Bekaert >24 years of which some 20 years working in the UK & Ireland underground construction industry, the secondary lining discussed in the latter part of this article is we believe the first use of steel fibre concrete in a secondary lining of this type anywhere in the world. Dramix steel wire fibres are produced by Belgium based Bekaert for almost 40 years and are used in a number of applications (Ref 1) around the world ranging from industrial flooring to heavy duty port and harbour pavements, many precast concrete applications including sewer pipes and sewerage brings us to the topic of this article regarding the Lee Tunnel and that, it is based around the transportation of sewerage for treatment in the East of London. The London sewer system has been in existence since the mid 1800’s when Joseph Bazalgette instituted the design and construction of most of the sewers that still exist today in London. However now the London population far exceeds the original design capacity of the system and as little as just 2mm of rainfall overloads the system and thus about 40 million tonnes of untreated sewerage enters the Lee and Thames rivers. The project that is the basis of this article is the Lee Tunnel and is part of Thames Water’s Tideway Project and will run between the Beckton Sewerage Treatment Works and the Abbeymills Pumping Station in the East of London, and aspects of the use of steel fibre reinforced concrete will be discussed. (Fig 1)

The Lee Tunnel is a 6.9 km long tunnel with a finished internal diameter of 7.2 m – the largest to date steel fibre only reinforced tunnel in Great Britain, it comprises 5 shafts of various depths and diameters, 3 at the Beckton jobsite and the other 2 at the Abbey Mills jobsite and a unique and innovative secondary lining design to the tunnel that itself is currently under construction. The client Thames Water has employed a Joint Venture of Morgan Sindall/Vinci Grand Projets and Bachy Soletanche to undertake the design and construction of the project under the management of CH2M Hill at a value in excess of £635 millions. The 3 main elements of the tunnel project – the precast segmental lining, permanent lining to the shafts and the secondary lining are all reinforced with 3 different types of Dramix steel wire fibres and each element will be described in this article (Fig 2).

Segmental Primary lining

The segmental lining is a 7.8m internal diameter Universal ring at 35 cm thick (concrete strength class C50/60 to EN206) using 30 kgs/m³ Dramix 3D8060BG steel fibres, these fibres are 60mm long with a diameter of 0.75 mm (4600 fibres/kg or 2.9 km of wire per cubic/m) with 1 kg/m³ of Bonna (Adfil) monofilament micro polypropylene fibres - a 21 mm taper with 7 segments plus a key at 1.7 m wide – the >32500 segments were manufactured at the Ridham Dock precast facility owned by contractor Morgan Sindall who have produced their own segments for projects over many years there. The Dramix steel fibres were delivered in 1100 kg big bags so that the factories automatic dosing equipment would dose the steel fibres as another aggregate and maintain an efficient production regime.

Fig. 1

Fig. 2
Some of the main advantages of using steel fibres in segmental linings are, the reduction in damage to the precast elements during the manufacturing process such as de-moulding, handling, storage and transportation of the units, a reduction or a complete elimination of the traditional reinforcement cage is also possible in most cases – the fibre concrete has much better impact resistance and the crack width control is much improved and this improves the long term durability of the concrete element and also this benefit in effect reduces the risk of damage and therefore the volume of repairs to the units in the lining is also reduced (Ref. 8).

Convex radial joints were also used after extensive large scale testing at the BRE (Building Research Establishment) North of London, this joint type eliminates crushing of segment edges when or if significant bird-mouthing occurs, also assisting in maintaining a continuous line of contact and eliminates eccentric loading due to poor ring build that can occur from time to time (Fig. 4).

Summarised Beam Test results to EN14651 (3-point notched beam bending test) for Primary SFRC 50/60 tunnel lining (Psomas S., 2014 – ref. 12)

The innovations (Ref 2) used in this project are many and these start with the actual segment production – one of the main innovations with the segment production was the installation of the EPDM gaskets before casting the steel fibre concrete into the moulds and we believe this to be the largest project in the world to date where this operation has been undertaken (Ref. 3) (Fig. 3) the main benefit of this operation is that there is no fixing of the gasket after casting the segment and eliminates the use and storage of solvents in the factory and more importantly no time delays.

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One of the most innovative ideas used in the manufacture of the segments for the Lee Tunnel was a concrete maturity monitoring system (START) that controlled the development and thermal shock potential (Ref. 4) and provided a constant monitoring of the segments in production and this exercise was undertaken were

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savings in cement and energy used in the curing chambers proved beneficial in terms of cost savings in the segment production process.

Dramix steel fibre reinforced concrete segments have been used in the UK for over 20 years and in many tunnels ranging from the London Underground system to the Docklands Light Rail Extension (Ref. 5) – sewer tunnels, water supply tunnels and electricity cable tunnels within the capital and some total of >130 km of steel fibre segmental lined tunnel exists in the Greater London area – this is purely steel fibre segmentally lined tunnels – not including several SCL works such as currently at the Cross rail project and casted in-situ projects such as the East London Line better known as The Brunel Tunnel (Ref6) . The segment ring build was successfully completed in December 2013.

Permanent Shaft Linings

In total there are 5 shafts ranging in diameters of 22 m to 38 m and to depths to almost 100 m at the deepest point in ground that comprise of a sequence of made ground, Alluvium and River Terrace Gravels overlying Tertiary age clays and sands with occasional pebble beds which in turn overlie chalk (A soft sedimentary carbonate limestone-type rock) (Ref. 7 & 14), the initial ground support was undertaken using conventional diaphragm walling techniques up to 98 m in depth.

Before work started on the permanent lining within the shaft, research was undertaken at the concrete laboratory of NV Bekaert SA in Belgium in relation to drying shrinkage and crack width control using different dosage rates of the Dramix steel fibre – 3D 6535BG – this is a 35 mm long steel fibre with a single hook at each end (Fig. 5) and a diameter 0.55 mm (14500 fibres per kg or 8 km or wire per cubic/m) – (image of the rings Fig. 6) also a number of concrete mix designs were considered and at the same time, jobsite trails were undertaken using preliminary slip-form shuttering for casting trails to achieve the desired surface finish also long continuous beams for crack control purposes were also casted – (Figs. 7 & 8 )

Beam Test results to EN14651 (3-point notched bem bending test) for Inner SFRC 50/60 pump shaft lining (Psomas et. al., 2014 – Ref12) – High residual strength values.
The first 4 [of 5] shafts are in similar ground conditions and no surprises were encountered during the sinking of the shafts I believe – the four major components (Ref. 6) of the shafts in terms of the structural requirements were:

1. The diaphragm wall
2. The base plug
3. The slip-formed inner lining
4. The annulus infill

Traditional reinforcement steel bar cages were used in the diaphragm walls with a bentonite support fluid, these were some of the deepest D-Walls sunk in recent years in the UK the author was informed. The innovation continues at the Lee Tunnel now with the secondary permanent lining of the shafts – 3 are based at the Beckton site and the fourth at Abbey Mills – there will be a fifth shaft in the summer of 2015 located at the Abbey Mills location and will be constructed in the same method. This construction methodology is trademarked as Slip Stress TM by the Designer (MS UnPS) of Beckton Pumping Station and Abbey Mills Shaft G.

The main features of this type of construction was the elimination of most of the traditional reinforcement – the actual slip-forming was double sided and was casted as a chimney or a cylinder – some traditional reinforcement remained at the base of the shafts where the tunnels came in and out of the shaft bases due to shear and other loadings – however the permanent shaft linings worked in hoop compression and were sat on a slip membrane, this construction technique allows the shaft lining itself to move (‘restraint-free’) and eliminates the potential for any restraint – induced cracking within the shaft walls.

The annulus concrete – this is the mass concrete used to infill between the diaphragm wall and the inner shaft lining. The wet concrete exerts the hydrostatic pressure that pre-compresses the inner shaft lining. During operation the shaft will be filled with water, which will exert an internal hydrostatic pressure on the shaft lining wall. The internal hydrostatic pressure will be counterbalanced by the locked in stresses the external groundwater pressure in combination with the percentage of ground load transfer from the permanent support from the D-wall. As a result of this transfer mechanism there is no significant tension development in the lining and thus any need for traditional steel bar reinforcement (Ref10) is eliminated (for Pump shaft, see Ref 15).

Secondary Inner Lining

Generally inner linings that are reinforced are done so for the following reason “Traditional reinforcement may well be used where tension is forced onto the inner lining, so for example hydro / sewer tunnels with a high internal head / pressure which places the inner lining into tension and therefore to prevent cracking and to resist the tension in the lining then the reinforcement is required, but eventually I see fibres being able to take the place of bars if tension is not too high (Ref 9 Mr Martin Knights CH2M Hill London)

The design and fabrication of the traditional reinforcement in such a tunnel as the Lee Tunnel would have been a logistical challenge to the construction team at the jobsite – an estimated 17000 tons of reinforcing bars (ref 12) would have had to have been delivered, stored, transported underground and fixed into position – with steel fixers working at height off work platforms of some description in what is technically a confined space and consuming valuable time within the programme – you may argue that this operation would have been undertaken as the concrete pours progressed anyway but the logistics of moving the high volume of bar reinforcement through the tunnel would be and is a high risk operation and puts addition numbers of operatives and equipment underground and in the immediate vicinity of the concrete works.

Generally when considering the use of steel fibres in concrete – with common dosage rates of steel fibres as most people understand, say 30-40kgs/m³ – is that the steel fibre concrete exhibits strain softening behaviour in bending – most steel fibres today have a single hooked end at each (Fig. 5) as were the two Dramix fibre types used already in the segmental lining and the permanent shafts linings, however for the secondary lining within the segmental primary lining of the tunnel itself – MVB JV have decided after much research over the last year or so to use the relatively new 5D Dramix steel fibre (Fig. 9).

This has a double hooked end and a much higher wire tensile strength than the 3D standard Dramix fibres previously used. These changes to the fibre geometry and technical characteristics provides the 5D fibre concrete with strain hardening in bending properties that enabled the Designer (MS UnPS) of the secondary inner lining to verify the governing design situation for structural crack control (ref.11&15).
All hook ended steel fibres, when under loading tend to deform / straighten out by pulling out of the concrete and so a controlled deformation occurs providing the energy absorption that can be measured by beam and plate testing, however the Dramix 5D steel fibre has these double hooked ends and these remain anchored in the concrete, the wire itself is some 2300 MPa and this elongates some 7% just as traditional reinforcement behaves and this is what provides the steel fibre concrete element with the bending hardening properties and therefore provide designers with more opportunities to design steel fibre concrete structures both underground and surface structures.

By researching on a large scale see above and by careful examination and analysis of the results the Designer (MS UnPS) & MVB JV decided to replace the standard traditional reinforcement with the 5D Dramix steel wire fibres – so removing some 17000 (ref 12) tons of bar with >2000 tons of the 5D Dramix steel fibre and eliminating the very large and difficult logistical challenge that would have been placed before the contractors underground team.

However before work could start underground with the secondary lining, much work was required to establish a suitable concrete mix design that would pump up to 250 m and virtually self-compact itself in the enclosed shutter within the tunnel lining. The concrete mix design (and final refinement) has taken almost 6 months to be in a position to work well and maintain its performance after pumping such distances and while not a great distance compared to some projects it still has to be able to almost self-compact with very little vibration. – it isn’t designed as a self-compacting concrete – the contractor wishes to avoid any risk of the steel fibre segregating, fibre distribution has been checked on the early pours and the indications are that there is excellent fibre distribution based on retrieved cores from the first pours in the works that suggest that the two principal orientations are in hoop and longitudinal direction, further analysis is being considered using X-ray photography.

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Rakesh Kumar Khali, Life member, TAI and has been awarded Indira Gandhi Shiromani Award on 24.11.2014 for his outstanding individual achievements and distinguished services to the nation, at India International Center Multi Purpose Hall, Max Muller Marg, Lodhi Road, New Delhi-3 by India International Friendship Society, New Delhi.

One seminar was also organized by IIFS on Economic growth and National Integration on this occasion. Mr. Shekhar Dutt, Former Governor of Chhattisgarh, Mr Gangu Ram Mushafir, Hon'ble Speaker of H.P. Vidhan Sabha and Dr. Bhishma Narayan Singh, Former Governor of Tamilnadu & Assam were the main speaker.

Prestigious Indira Gandhi Shiromani Award along with certificate of excellence was presented jointly by the Chief guest Mr. Shekhar Dutt and Dr Bhism Narayan Singh, in a glittering function befitting of the great event.

Rakesh Kumar Khali receiving the award from Mr. Shekhar Dutt and Dr Bhism Narayan Singh