International Practices and Technology in Sealing Precast Tunnel Linings

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1. Introduction:
Around the world there are varying design philosophies regarding the sealing of precast segments inclusive of variations in gasket width, durometer, material and groove design. The sealing procedures are based on regional design and/or local past construction practices. Because of the new technologies in the development of rubber compounds and a better understanding of long term gasket stress relaxation (long term performance) a common basis has been developed and accepted on an international basis for the design of gasket sealing systems. This paper will address the international practice and the key components used in designing a segment sealing system in accordance to accepted international design practices.

Gaskets for precast tunnel linings have to ensure that the gaps between the different concrete segments are sealed securely for the whole lifetime of the tunnel. The gaskets have to cope with the water pressure the tunnel is exposed to. This water pressure has to be tightened under all tolerances that can occur during the erection process. The two main tolerances concerning this is the displacement between the segments (offset) and the opening between the segments (gap).

The following sketch is about to show this:

![Sketch showing gap and offset](image)

The tightness of the system is reached by the compression of the rubber gaskets. By compressing the gaskets a deflection force is created which leads to the sealing of the system.
The values of those tolerances are influenced by the circumstances during the erection process and by the linking system between the segments either. This value is given by the contractor choosing the system of the erection process.

The following paper will consider the requirements to a tunnel gasket considering a tunnel project with the following dimensions, all the values are subject to this assumption:
- OD 6.55 m / ID 5.95 m
- Working pressure 5 bar / Design pressure 10 bar
- Circumferential distance 20.6 m
- 4+2 Segments (12+4 connectors)
- 20.4 m / 16 = 1.28 m per connection
- Angle of connection system: 25°
- Security factor for connection system: 1.25

2. Differences in groove design:
Generally the design of the gasket groove can be divided into two categories, the sketch below will show the difference between the categories:

![Groove designs](image)

1 Additional groove on intrados
2 No additional groove on intrados

Partially the area of the gasket groove is designed with an additional groove on the intrados of the gasket. This is done because of statically reasons, to avoid excessive loads in this area and to prevent spalling of the concrete edges of the segments.

The selection of an additional groove leads to a lower extent of the groove flank on the intrados. But the groove flank on the intrados is very important for the stability of the gasket system itself and leads therefore to a lower performance of the chosen gasket, compared to the design without additional groove.

To cope with this lower performance a stronger gasket has to be used, stronger gaskets cause higher deflection forces and this causes higher forces brought into the concrete.

The following diagrams show the performances of the different gaskets that have to be chosen according to the different groove situations (maximum offset of 15 mm and maximum gap of 5 mm to be considered):
Without additional groove on intrados, the gasket type 18-882 is sufficient:

With additional groove on intrados, the gasket type 19-882 is no longer sufficient:
To cope with the additional groove, a stronger gasket has to be placed in:

Advantages of placing an additional groove on the intrados of the gasket area:
- The stresses to the concrete caused by the deflection force of the gasket can be reduced
- Therefore the risk of concrete spalling due to excessive loads caused by unforeseen placement of the segments can be reduced

Disadvantages of placing an additional groove on the intrados of the gasket area:
- The performance of the gasket gets lower, therefore a stronger gasket has to be taken
- Stronger gaskets create higher deflection forces, the erector of the TBM and either the connection system has to cope with this additional forces. (The solution shown above will create approx. 30% higher forces compared to the system without additional groove.)
- Referring to the example above, the costs for the gaskets will be approx. 15% higher.

3. **Influence of segment linking systems to tunnel gaskets**

Different segment linking systems allow different values of tolerances during the segment erection process.

The offset of the segments to each other can be influenced, as stated above this is one of the main values to be considered during the evaluation of a tunnel gasket.

The following sketches show two typical connection systems, the influences to the sealing system will be shown later on.
Standard connection system with steel bolts:

This connection system usually allows offsets up to 15mm.

Balljoint connection system either with steel bolts but with ball system to center the segments:

Applied correctly this system will reduce possible offsets to 5 mm.

Reducing the possibly occurring tolerances has a considerable effect to the gasket system, due to the smaller range the gasket has to cover it can be smaller in width and the strength of the gasket can be reduced either.

The following example including calculations and choice of gasket types show how the gasket system is influenced and how the values of the different systems will change:

(The diagrams of the deflection forces are force-time graphs, the force is recorded beginning without contact of the gasket surfaces, the gaskets are pushed together until a complete closure of the segments is reached, after this the gasket force begins to
decrease due to the short time relaxation of the compound, the following relaxation is recorded during a time period of 5 minutes.)

3.1 Standard connection system:

Due to a maximum of 15 mm offset a 33 mm wide gasket has to be chosen:

The deflection forces of the chosen gasket are as follows:
Calculation:
Deflection force: 43 kN/m

Force per bolt: max. F = 43 kN/m * 1.28 / cos 25° = 56.5 kN
with safety factor: 56.5 kN * 1.25 = 70.6 kN

3.2 Balljoint connection system:

Due to a maximum of 5 mm offset a 26 mm wide gasket can be chosen:

The deflection forces of the chosen gasket are as follows:
Calculation:
Deflection force: 20 kN/m

\[
\text{Force per bolt: max. } F = 20 \text{ kN/m } \times 1.28 \times \cos 25^\circ = 28.2 \text{ kN}
\]

with safety factor: \( 28.2 \text{ kN } \times 1.25 = 35.3 \text{ kN} \)

Advantages of a sealing system with reduced tolerances:
- TBD erector forces can be reduced (amount acc. to example is about nearly 50%)
- Connection forces can be reduced (amount acc. to example is about nearly 50%)
- Smaller and cheaper connectors can be chosen
- The needed space for the connection system and for the gasket system can be reduced
- Smaller and therefore cheaper gaskets can be chosen (amount acc. to example is about nearly 25%)

4. Differences in requirements considering compound values:

Considering the values of hardness, tensile strength und ultimate elongation there are two different requirements, the difference can be separated in those who rely on the older British tunneling standard (established 2000) and those who rely on the German STUVA standard (2005). The BTS requirements are 60-75 IRHD for hardness, tensile strength >1500 psi and the ultimate elongation should be at least 300%.

Those three values are sufficient to characterise the sort of rubber that is used for the gaskets, but the values are not applicable for having any conclusion about the capability of the sealing in general.

As there are different compounds with different hardness classes existing nowadays, the German STUVA standard that was established in 2005 considers this fact. A chart was created that considers three hardness classes and the related values of tensile strength and ultimate elongation.

The main gasket manufacturers consider this as the best way to cope with the different formulations of the different gasket compounds, hopefully the industry will follow those recommendations one day.

Different formulations, different values:

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Test method</th>
<th>Hardness class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>IRHD</td>
<td>ISO 48</td>
<td>56 – 65, 66 – 75, 76 - 85</td>
</tr>
<tr>
<td>Tensile strength, min.</td>
<td>MPa</td>
<td>ISO 37</td>
<td>9, 9, 9</td>
</tr>
<tr>
<td>Elongation at break, min.</td>
<td>%</td>
<td>ISO 37</td>
<td>300, 200, 175</td>
</tr>
</tbody>
</table>

General conclusion:
Different design philosophies take place in different segment designs. Those different philosophies are regionally grown and might be coherent to regional traditions in the construction process.

As the tunnel business is completely internationalised nowadays it is often difficult to understand the regional traditions for people being involved in this process but not being familiar with the regional preferences.

We believe that considering regional conventions and linking them with internationally obtained experiences could be the best possible way to achieve progress, technically and economically.

However, to reach this it is essential to keep up discussions and to respect the global needs of the project. After being able to understand the needs of the project it will be easier to find out the local requirements of the specific components.