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SEALANT BEHAVIOR OF GASKETED-SEGMENTAL CONCRETE TUNNEL LINING

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ABSTRACT

Gasket sealant behavior along the joints of segmental concrete tunnel lining depends on the gasket-gasket and gasket-groove contact loads, bonding between the gasket and gasket groove, gasket lateral extrusion, and the roughness of the groove. For well-designed gasket, leakage through the gasket is expected to occur by hydrojacking at water pressure approximately equal to the gasket contact pressure. Hence, an increase in the gasket contact pressure is expected to result in an increase in the water pressure at leakage. As the gaskets are made of polymer materials, after compression, gasket contact loads are expected to drop with time due to relaxation. Reduction in the contact load with time is expected to affect the gasket sealant capacity before built up of the ground water pressure. Gasket-gasket and gasket-groove contact loads depend on many factors such as the stiffness of the gasket material, gasket shape and volume, gasket groove size and configuration, gasket base configuration, and the amount of gasket compression. In this work, gasket in groove mechanical and sealant behavior were experimentally investigated. Two types of gaskets were considered: open base gasket (for the LA Metro Tunnel, USA) for low design water pressure (less than 90 psi), and closed base gasket (for Inland Feeder Arrowhead Tunnel, USA) for high water pressure (up to 600 psi). The work focused on gasket-in-groove load deformation behavior and gasket sealant potential including the effect of gasket contact loads, relaxation, extrusion, and the change in joint gap during water pressurization. The effect of gasket base conditions (fingers with open base vs. closed base) on the gasket sealant behavior was also considered in this work. Conceptual model that explain the leakage behavior of the gasket-in-groove as water pressure is applied was developed.

Keywords: Tunnel, Segmental Lining, Gasket, Leakage, Conceptual Model

INTRODUCTION

For tunnels constructed below water table, control of water leakage is one of the most important problems that needs to be considered in lining design. Presence of gases, such as hydrogen sulfide or methane may cause serious safety problems if the gas and water leak into the tunnel. One of the solutions to this problem is to install membranes between the initial and final linings to serve as a barrier for gas and water flow. For a single-pass lining system of bolted precast concrete segments, most of the tunnel leakage will take place at the lining joints. Leakage through the joint system can be minimized by properly designed and installed gaskets extending around the four edges of each segment. In some situations, sealing the joint system of the lining is not only needed to achieve a dry tunnel, but the sealing is necessary to preserve the water table as in the case of the Inland Feeder Tunnel in USA (Cording et al., 2001 and Shalabi, 2001).

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One of the factors that affects the joint opening of segmental lining with staggered longitudinal joints is the relative stiffness between the adjacent rings. Under non-uniform ground load condition, as the lining deflects under different vertical and lateral pressures or due to ground shaking by an earthquake, two adjacent rings with staggered joints will have different deformed shapes. Rotation at the joint will cause relative movement between the rings along the circumferential joints. The relative movement between the rings is expected to be maximum at the T-shaped joint, as shown in Figure 1 (Shalabi and Cording, 2005).

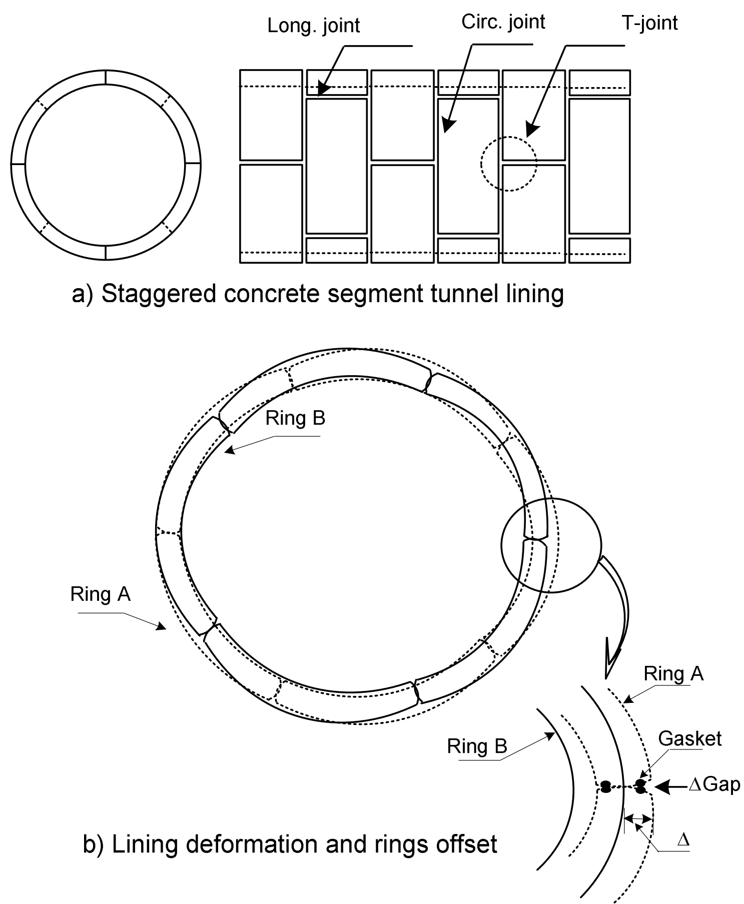

Figure 1. Deformation of two adjacent rings under non uniform ground loads

Very few studies were performed to investigate the gasket sealant behavior. Paul (1978) based on water leakage tests conducted on picture frame gasket configuration, found that leakage took place at the gasket-groove interface as a result of gasket-metal bond separation. Girnau (1978) based on short-term water leakage tests on rib gaskets found that the T-joints are the places were most leakage took place. Paul (1984) declared that leakage at the gasket-gasket interface is related to the contact pressure between the gaskets. Kurihara et al. (1988) found that as the ratio of the gasket volume to the gasket groove volume increase, the gasket sealant capacity increase, while for the gaskets of the same volume ratios, the sealant capacity depends on the gasket shape. Marriot (1989) pointed out two major problems with gasket as sealant materials. These are the invert tunnel seal and tunnel steering. According to Marriot, muck materials or flowing of saturated sands may trapped between the gaskets and reduce the gasket sealant efficiency.

The objective of this study is to investigate and evaluate the gasket-in-groove mechanical and sealant behavior. This includes gasket-in-groove stiffness and relaxation and their effect on gasket contact pressure and gasket extrusion, which in turn affect gasket-in-groove sealant behavior.

TESTING PROGRAM

The first part of the testing program focused on the short-term load deformation behavior of the gasket under loading and unloading conditions. It also included the long-term gasket behavior (gasket relaxation), in particular gasket relaxation at constant joint gap. Four types of gaskets were tested. For LA Metro, one gasket made of ethylene-diene monomers (EPDM) and the other two gaskets were neoprene (Ex1026 and Dev1092). For Inland Feeder Tunnel, Vertex gasket made of polyisoprene was tested. The LA Metro gaskets have fingers at the base (open base) while Inland Feeder gasket has a closed base.

The second part of the testing program focused on the gasket in groove sealant capacity to prevent water from leaking into the tunnel through the joint system. EPDM and Vertex gaskets were investigated. Leakage tests were performed with gasket in groove using machined steel picture frame device. Figure 2 shows the testing device and setup. Tests were performed at different joint gaps and water pressures. Water was applied through the inlet hole, and the air was evacuated from the outlet. Nitrogen gas was used to get the cell water under pressure. Total loads were monitored using load cells. Water leakage was monitored visually around the gasket.

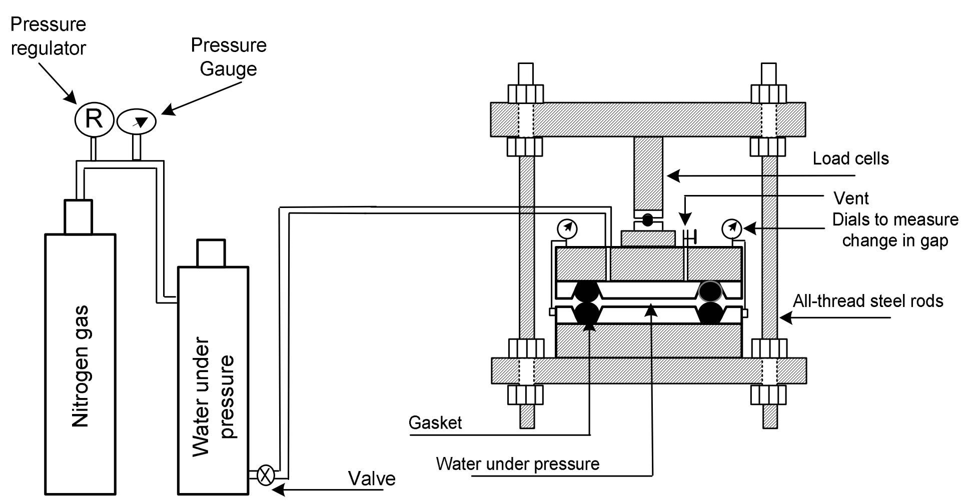

Figure 2. Steel picture frame device for water leakage tests

ANALYSIS AND DISCUSSION

Short-term gasket-in-groove mechanical behavior (gasket stiffness)

The results of gasket load-deformation tests show that there is a significant effect of gasket geometry and gasket-groove configuration on the gasket load-deformation behavior. The test results show three distinct compression zones as shown in Figure 3. In the first zone, which is about 5-12 % of the gasket compression, the load increases with gasket deformation with a decreasing slope. In the second zone (6-22% gasket compression), the load deformation curve is almost flat, while in the third zone, as the gasket becomes confined, the load increases with gasket compression with an increasing slope.

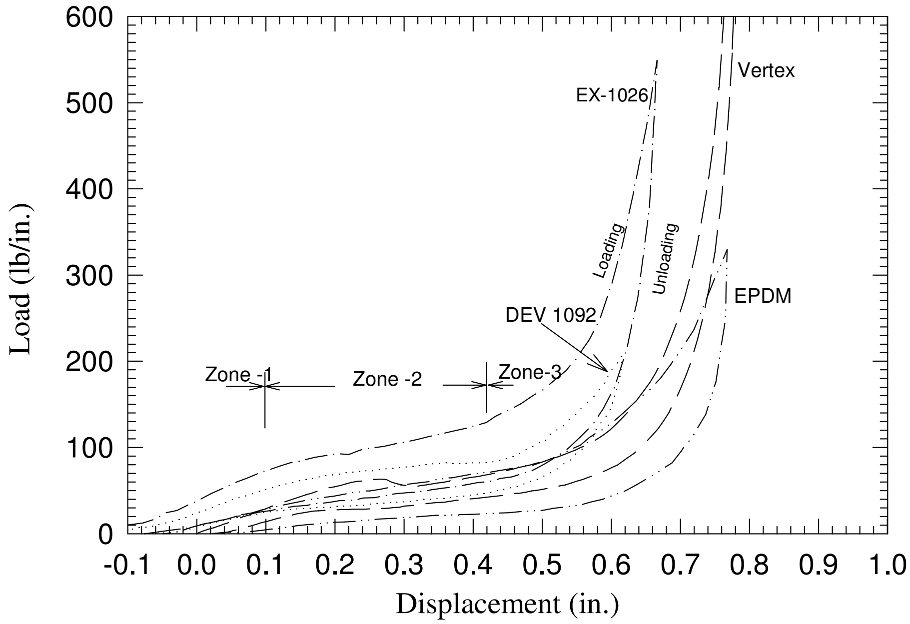

Figure 3. Load-deformation curves of the tested gaskets loaded at 0.5 in./min.

The increase in the contact load in the first zone is due to the initial compression of the circular holes of the gasket. In the second zone, as compression continues, the holes enter a state of collapse and the gasket carries almost a constant load. In the third zone, after the circular holes have collapsed, and the gasket legs deformed, the gasket starts to fill the groove and approaches a confined state. This leads to an increase in the gasket stiffness and the rate of load, especially when the gasket itself starts to fill the joint gap at the edges of the gasket groove. Figure 4 illustrates the mechanism of gasket compression.

Long-term gasket-in-groove mechanical behavior (gasket relaxation)

Results of relaxation tests on the tested gaskets show that there is a considerable reduction in the contact load with time. Figure 5 shows that the relation between contact load and logarithm of time is almost linear. If the results of relaxation are extended to cover the entire period of the tunnel life (about 100 years), the reduction in the contact load is expected to be between 53% (Vertex gasket) and 65% (Ex1026 gasket) of the maximum initial contact load. These values are based on the assumption that there is no water pressure is applied to the gasket.

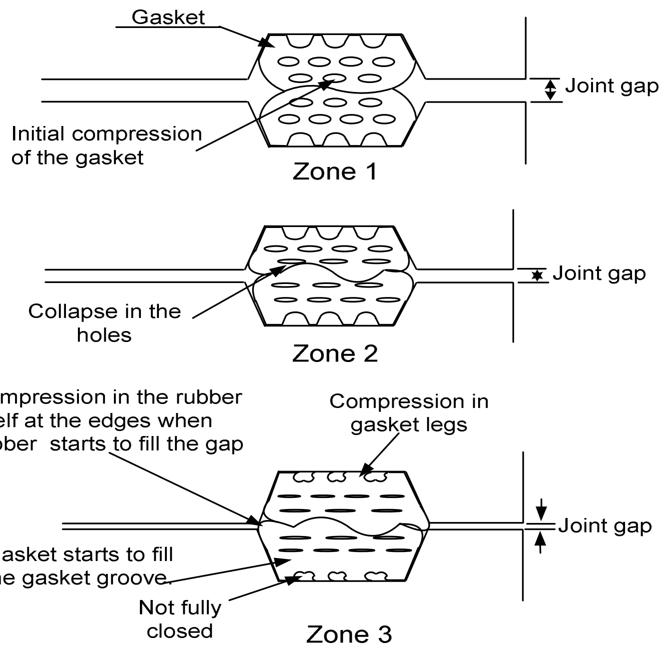

Figure 4. Mechanism of gasket compression as the joint gap decreased

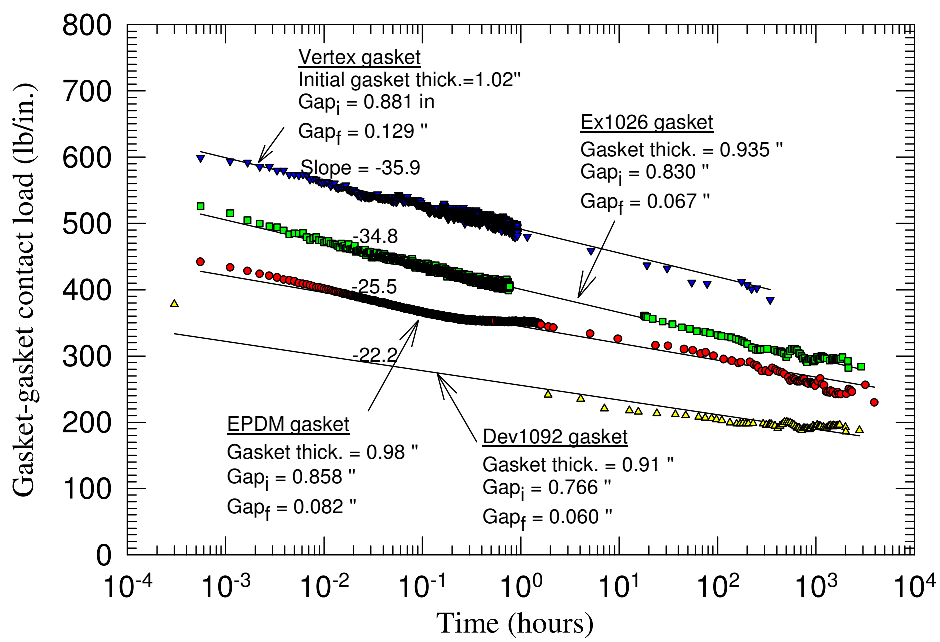

Figure 5. Long-term relaxation of the tested gaskets

Open-base gasket-in-groove sealant behavior

Waster leakage tests in the picture frame steel device show that as the joint gap increases the water pressure at leakage decreases. By comparing the gasket –gasket contact pressure with water pressure at leakage, EPDM gasket (with open base) shows that leakage occurred at water pressure 65% of the gasket contact pressure, as shown in Figure 6. It was believed that leakage through the gasket would occur by hydro-jacking at a water pressure approximately equal to the gasket contact pressure. The difference in these pressures at leakage can be explained by the geometry of the open base gasket and the effect of de-bonding between gasket and gasket groove and reduction in the effective normal stress at the gasket-groove interface, as illustrated in Figure 7. The increase in water pressure increases the gasket lateral displacement, which in turn tends to distort the gasket inner leg. This allows the pressurized water to immigrate and fill the space between the inner legs. The built up of water pressure between the gasket legs reduces the effective normal stresses on the next adjacent contact area. The progressive reduction in the effective normal stresses leads to leakage at the gasket-groove interface.

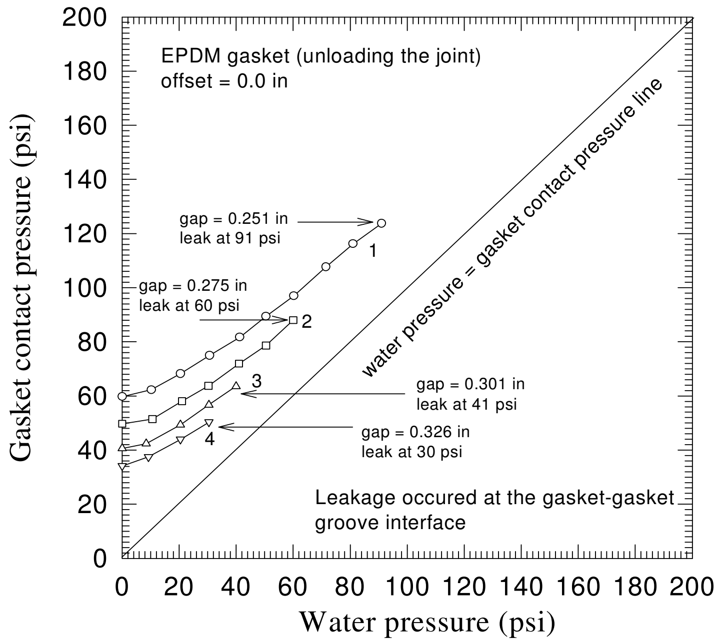

Figure 6. Gasket contact pressure vs. water pressure (EPDM, open base)

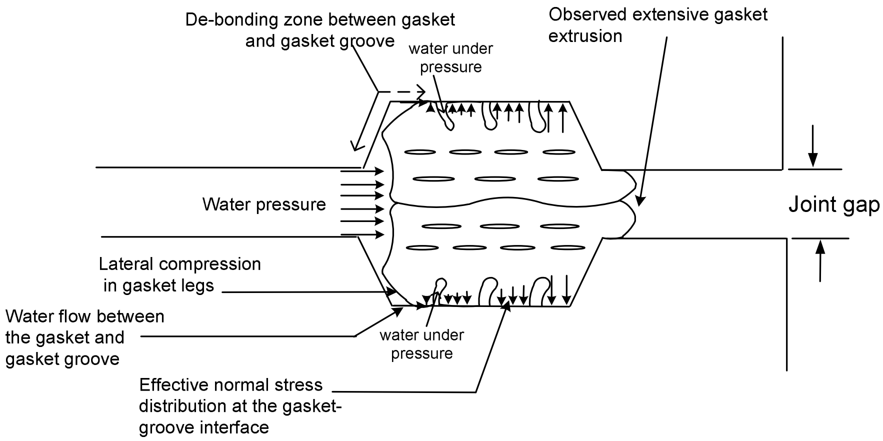

Figure 7. Mechanism of progressive leakage at gasket-gasket groove interface as the water pressure increases (open base gasket)

Closed-base gasket-in-groove sealant behavior

Water leakage test results on vertex gasket (Polyisoprene) in which the stiffness of the testing frame allowed the joint gap to open during water pressurization show that the relation between gasket contact pressure and water pressure of the tight joint is different than that of the more open joint gap. For joint gap greater than 0.196 in., curves 1 and 4 in Figure 8 show that the gasket contact pressure increases with the increase in the applying water pressure, while for initial joint gap less than 0.196 in., curves 2 and 3 in the same figure show that the gasket contact pressure initially decreases with the increase in water pressure then increases after a certain value of water pressure. This behavior is mainly due to the effect of joint opening. For initially tight joint gap, joint opening causes a considerable decrease in gasket contact load as can be seen from the load-deformation curve (Figure 3). This effect is considered more efficient than the increase in the gasket contact load due to gasket lateral compression. For more open initial joint gap (flat part of Figure 3), reduction in gasket contact pressure due to unloading (joint opening) is less than the increase in gasket contact pressure due to gasket lateral compression. In these tests, water leakage was observed at water pressure very close to the gasket-gasket contact pressure (curves 1 and 4).

Results of water leakage tests on Vertex gaskets under no change in joint gap during water pressurization (keep tightening the knots during the tests to preserve the initial joint gap) show that for all ranges of joint gap, gasket contact pressure increases with the increase in the applied water pressure (there is no initial drop in gasket contact pressure due to pressurization), as shown in Figure 9. In these tests, Leakage was observed at the gasket –gasket interface when the water pressure approached the gasket contact pressure.

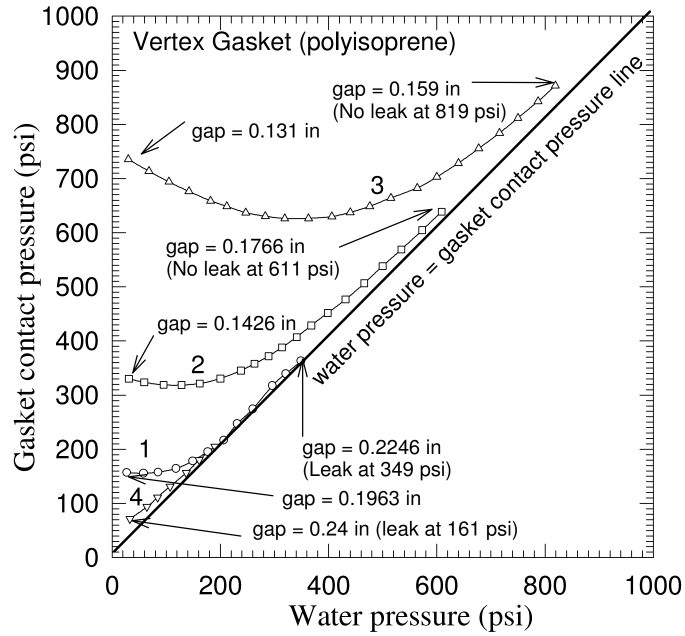

Figure 8. Gasket contact pressure vs. water pressure for Vertex gasket. Joint gap changed during water pressurization (closed base)

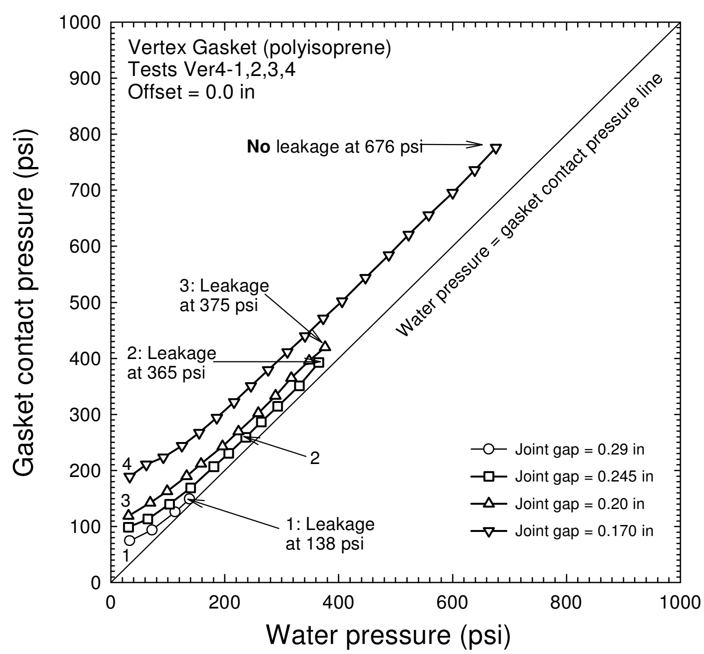

Figure 9. Gasket contact pressure vs. water pressure for Vertex gasket at different joint gaps. No change in joint gap during water pressurization

Gasket behavior as gasket is compressed and water pressure is applied (conceptual model)

The investigation has led to a model that explains the leakage behavior of well- designed gaskets (closed-base gaskets) as water pressure is applied. Figure 10 illustrates key aspects of the model.

It is clear that the gasket contact pressure results from a combination of the initial compression of the gasket to the desired gap and the water pressure applied laterally to the gasket. The forces required to initially compress the gasket can be predicted from the load-deformation curves. Next, consider the effect of the water pressure. If the gasket were solid (no holes) and completely confined in the groove, then the Poisson's ratio would be 0.5 because the gasket material is quite incompressible. In this case the water pressure would result in an equal internal pressure in the gasket in all directions as shown in Figure 10A; thus the contact pressure between the two gaskets and between the gasket and bottom of the groove would be equal to the water pressure. However, before the holes in the gasket are closed, the gasket is not solid. Further, it is not completely confined, due to extrusion into the gap. Therefore the "effective" Poisson's ratio will be less than 0.5, and the application of water pressure will result in a change in contact pressure that is less than the change in water pressure as shown in Figure 10B.

Gasket contact pressure versus water pressure relation for the polyisoprene (no gap change during water pressurization) is shown in Figure 9 and summarized in Figure 11. At low water pressure, the increase in contact pressure from the initial contact pressure in significantly less than the water pressure applied. At this stage, the holes are partially open and the effective Poisson's ratio is low (Figure 10B). As the water pressure increases, the holes in the gasket become closed, further volume change is small, the effective Poisson's ratio approaches 0.5, and the increase in contact pressure becomes equal to the change in water pressure (Figure 10C). The water pressure versus gasket contact pressure curve then parallels the 1:1 line of equal water pressure-contact pressure.

If the water pressure approaches or equals the contact pressure, hydrojacking can occur between the gaskets, resulting in leakage. In some tests, the water pressure-gasket contact pressure curve approaches and then follows close to the 1:1 line over a significant range of water pressures, and leakage could occur at almost any point in this range. In this case, the water pressure at leakage may be erratic and affected by small variations in the gasket and gasket groove conditions.

For properly designed gasket, it is expected that leakage will occur between the two gaskets when the water pressure approaches close to the total gasket contact pressure. Vertex gasket (closed-base) performed as described above. Gasket with legs (open base), leaked between the gasket and gasket groove at lower water pressures than the gasket contact pressure because of bending and progressive leakage at the legs of the gasket.

Required initial contact pressure for a given water pressure at leakage (closed base gasket)

The data support the conclusion that leakage for the polyisoprene and neoprene Vertex gaskets may occur as the water pressure approaches approximately 92% and 96% respectively of the total gasket contact pressure, which leads to the following relationship for Pw_l, the water pressure at leakage:

$$Pw_l = mPc_l = m(Pc_i + \Delta Pc) \tag{1}$$

where Pc_l is the total gasket contact pressure at leakage, Pc_i is the initial gasket contact pressure, ΔPc is the change in gasket contact pressure due to application of the water pressure, Pw, and m=0.92 for Polyisoprene gasket and 0.96 for the neoprene one.

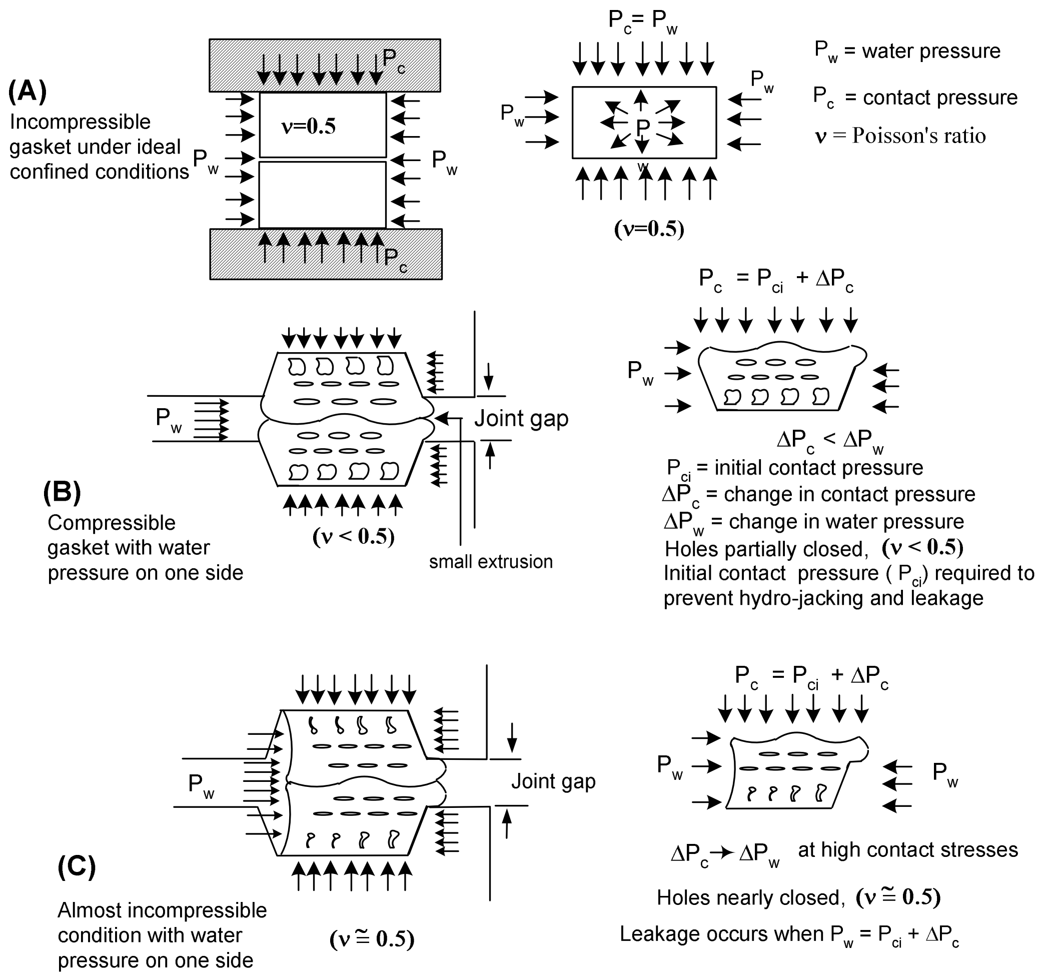

Figure 10. Illustration shows the relationship between gasket contact pressure and water pressure as the Poisson's ratio increases with pressurization or compression

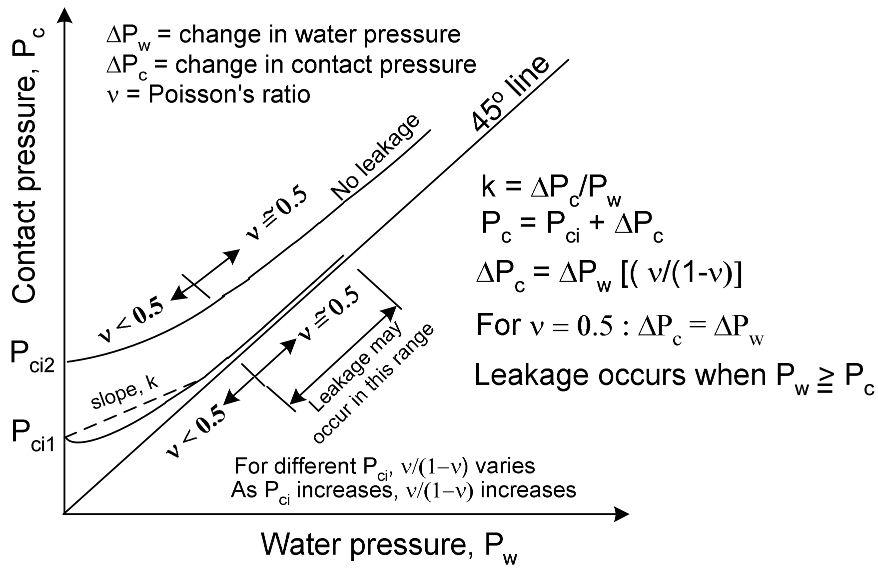

Figure 11. Relation between gasket initial contact pressure, P_{ci} and water pressure, P_w

The ratio between the change in gasket contact pressure and the water pressure, k=ΔPc/Pw, can be determined from the water pressure tests in which the forces acting between the gaskets are measured. For a gasket confined in a gasket groove, increasing the water pressure will cause the holes in the gasket to be compressed. At high gasket contact pressures, the gasket will approach an incompressible solid, which can undergo no volume change (Poisson's ratio,ν, approaches 0.5) so that an increment of water pressure will produce an equal increment of change in gasket contact pressure. For a laterally confined gasket:

$$k = \nu/(1-\nu) = \Delta Pc/Pw \qquad (2)$$

combining equations 1 and 2, at leakage, $Pw=Pw_l$:

$$Pw_l = m(Pc_i + kPw_l) \qquad (3)$$

or $$Pc_i = Pw_l[(1/m) - k] \qquad (4)$$

The parameters ν and k increase as the gasket pair is compressed and the voids in and around the gaskets are closed. The change in gasket contact pressure, ΔPc, largely controls the amount of gasket compression and its volume, thus ν and k are function of ΔPc.

Figure 12 is a plot of Pw vs. ΔPc obtained from the water pressure test results for the Vertex polyisoprene and neoprene gaskets. For a given water pressure at leakage, Pw_l, the change in gasket contact pressure, ΔPc is determined from Figure 12, and the k (which is ΔPc/Pw) is then obtained. Initial gasket contact pressure is then obtained by substituting k in equation 4 with the corresponding m value. The size of the required joint gap for a given water pressure at leakage is obtained by first determining the initial contact pressure (Pc_i) for a given contact pressure at leakage (Pc_l) using the above equations. Pc_i is then located on the gasket pressure-deformation curve to obtain the corresponding joint gap.

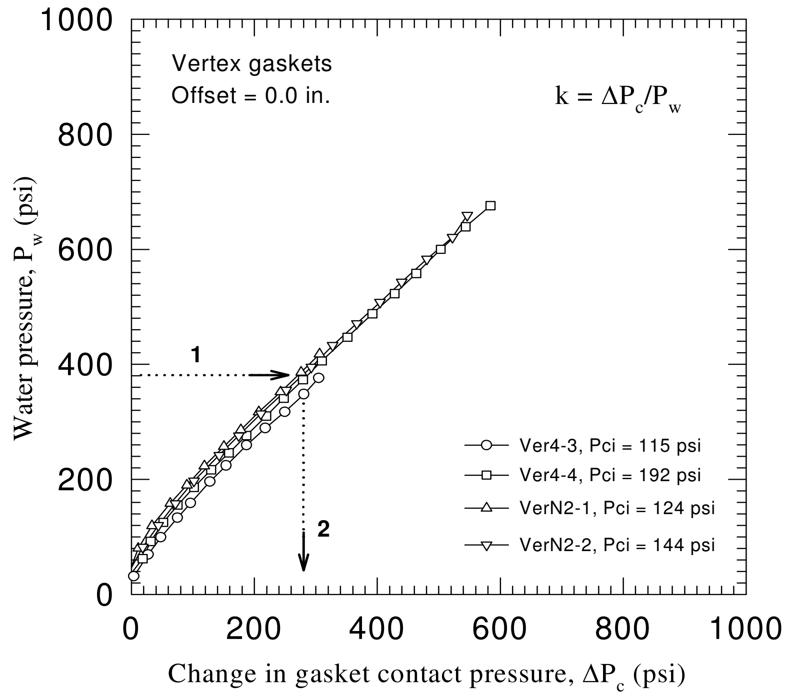

Figure 12. Relation between water pressure, P_w and change in gasket contact pressure, ΔP_C

CONCLUSIONS

Experimental program was designed to investigate the mechanical and sealant behavior of the gasket-in groove segmental concrete tunnel lining. Based on the results of the tests, the following conclusions were drawn:

1) The load deformation curves have three distinct zones, which result from the combined effect of gasket opening, compression, and gasket confinement inside the groove.

2) Gasket contact loads are higher during loading than unloading at the same amount of compression. The difference in contact loads between the two loading conditions depends on the gasket material.

3) For open base gaskets, water leakage took place at the gasket to gasket groove interface at a water pressure significantly less than the final gasket contact pressure. Progressive reduction in the normal stress at the gasket to gasket groove interface due to water filling the spaces between the gasket legs as they distort and bent was the main reason of leakage.

4) For closed base gaskets, leakage occurred between the gaskets by hydro-jacking when the water pressure approached or equal the gasket contact pressure.

5) Gasket contact pressure results from a combination of the initial compression of the gasket to the desired joint gap and the water pressure applied to the gasket.

6) For closed base gasket, the gasket initial contact pressure can be predicated for a given water pressure at leakage based on the conceptual model. The corresponding joint gap for this water pressure can be estimated by locating the gasket initial contact pressure on the gasket pressure-deformation curve.

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