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SIMULATION OF COATING BEHAVIOR IN BURIED SERVICE ENVIRONMENT

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ABSTRACT

A test apparatus, commonly used in the district heating market, has been successfully adopted to evaluate the functionality of various coating systems for their resistance to soil stress induced in the axial direction due to thermal changes in the pipeline. Coating systems investigated includes 2-layer polyethylene (2LPE), 3-layer polyethylene (3LPE), fusion bonded epoxy (FBE), cold-applied tape, heat-shrinkable sleeve with mastic adhesive and heat-shrinkable sleeve with hot melt adhesives. The results showed that the most critical properties of a coating's ability to resist soil stress are the cohesive strength and strong adhesive strength. Coating systems with a softer adhesive component are more sensitive to soil stress, particularly at their exposed edges. However, the study shows that proper selection of the coating system can meet soil stress requirements.

Keywords: Soil stress, 2-layer polyethylene (2LPE), 3-layer polyethylene (3LPE), fusion bonded epoxy (FBE), heat-shrinkable sleeve, hot melt adhesive, mastic adhesive, tapes, longitudinal pipe movement.

INTRODUCTION

As the exploration of "energy" continues to expand its limits, so are the requirements for the coatings used in the corrosion protection of pipelines.

It is understood that the best method for preventing corrosion on buried pipelines is to prevent the migration of corrosive species to substrate surface with the best available barrier coating. Unfortunately each coating system is a "compromise" of desirable properties and coating stability in soil is one of the many factors to consider in its development.

A buried pipeline experiences various types of soil stress and magnitude depending on burial depth, soil type, soil compaction, wet and dry, freeze and thaw cycles, seismic activity, operating temperature, pipe size, etc. These stresses can be classified into four categories [1]:

1) Static load due to the soil and pipe weight. This is particularly troublesome with rocky backfill where coating damage can occur due to penetration;
2) Axial stress due to pipeline expansion and contraction
3) Circumferential stress due to pipeline lateral movement at bends
4) Random direction due to soil swelling and shrinkage caused primarily by clay soil during wet and dry cycles.

The magnitude of the stress on the pipeline depends on the stress transfer function between the soil and the coating. When the coating strength is less than the stresses introduced by the soil, the coating will fail and lead to corrosion of the pipeline.

One of the major contributors to soil stress is the axial stress induced by variation in pipeline operation temperature that results in pipeline expansions and contractions. Since most coatings are based on organic polymeric materials with temperature dependent mechanical properties, these thermal changes exacerbated the affect of soil stress and necessitated the use of much higher shear resistance products to withstand the mechanical stresses acting on the coating.

While it is impossible to simulate the various conditions with a single test, the “soil box” described in this paper can definitely help when dealing with the forces acting exclusively along the longitudinal direction of the pipe caused by thermal expansion and contraction.

The soil box test procedure originated from the District Heating Industry where the pipelines are subjected to multiple cycles of expansion and contraction. The acceptance criteria for the field joint protection system is 100 cycles. In the Oil and Gas Industry, an accepted number of cycles has not been determined. However, it clearly will be less than 100 cycles since expansion and contraction cycles are much less frequent.

Coating System Evaluated

The evaluation program covered the following coating systems and heat shrink sleeves:

- ### Extruded Polyethylene

  Two-layer PE (2LPE) coating systems are those that consist of an adhesive layer and a protective polyethylene extruded topcoat layer. Blast cleaned pipes are directly coated with a mastic-based layer, commonly known as sealants for their excellent sealing properties, followed with a polyethylene topcoat. When heated, this type of adhesive flows into the surface profile on the pipe surface, thus conforming as closely as possible, just like a perfect seal.

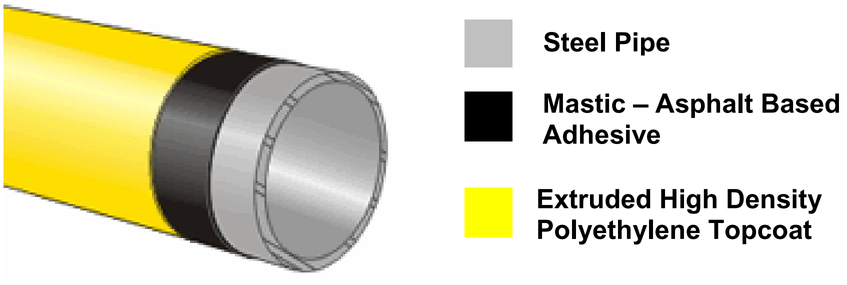


FIGURE 1 – 2LPE Coating System

Fusion Bonded Epoxy

Fusion Bonded Epoxy (FBE) Coating System consists of one layer of epoxy that is powder coated onto steel pipes at temperature of approximately 230°C to 250°C. This product can be used for oil and gas transport at temperatures between -40°C to 105°C.

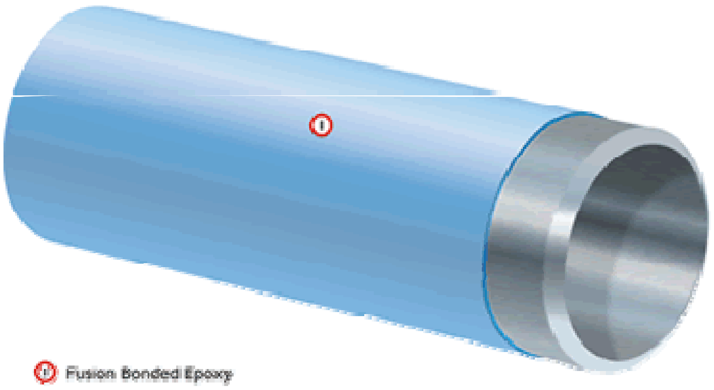


FIGURE 2 – FBE

3-Layer Polyethylene

3LPE systems have a primary epoxy layer, an adhesive layer, and then an outer backing. The addition of an epoxy layer gives the coating system greater chemical bonding properties often resulting in higher peel and shear strength qualities. The adhesives in a three-layer system are often hot-melts. Coupling epoxy and hot melt-based adhesives within a pipeline coating system has successfully resulted in maximizing the overall strength and cathodic disbondment resistances of such coatings.

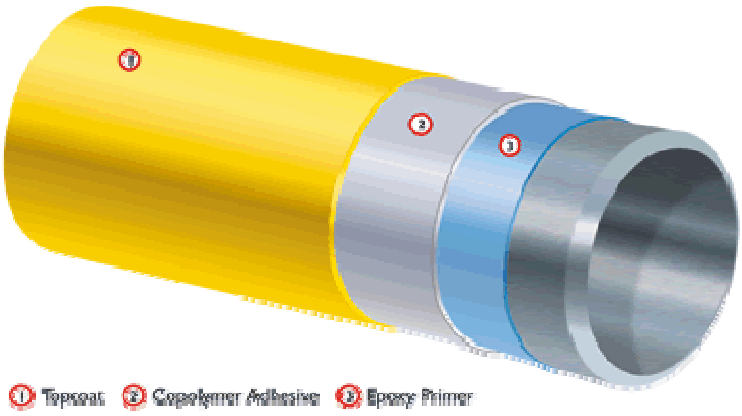


FIGURE 3 – 3LPE

- **Cold-Applied Tapes**

Cold-applied tapes have been one of the first methods of protecting pipelines and girth weld areas. They consist of a sheet of polyethylene coated with a pressure sensitive adhesive. The pressure sensitive adhesive (tacky) is what makes the tapes bond to the areas to be protected and to themselves without the use of any heat. Pressure and/or a primer during the wrapping operation is usually adequate to achieve bonding.

FIGURE 4 – Cold-Applied Tape

- **Heat-Shrinkable Sleeves**

For over 30 years, heat-shrinkable sleeves (Figure 5) have successfully been used to protect girth welds from corrosion. They consist of a heat-shrinkable polyethylene sheet coated with an adhesive (mastic or hot melt).

- Type of adhesives
- Thickness of adhesives
- Thickness of polyethylene
- Polyethylene % stretch
- Molecular weight of polyethylene, etc.

can be varied according to the requirements of the pipeline. Because of the 20% to 30% stretch in their cross-linked polyethylene, sleeves can be applied with torches and made to recover very tightly around the areas to be protected.

FIGURE 5 – Heat-Shrinkable Sleeve

EXPERIMENTAL PROCEDURE

Test Method: Longitudinal Pipe Movement Test [2]

Apparatus. The apparatus consists of:

- Steel box (150 x 100 cm) filled with a soil mixture of sand and gravel
- Pump to circulate the heated oil inside the sample pipe
- Reversible electric drive with limit switches to control the distance of travel
- A main panel controls key variables such as:
    - Distance of travel
    - Speed of travel
    - Pipe temperature
    - Number of cycles

Vertical force is applied to the soil by way of a pressure plate driven by an air piston, thus maintaining constant force even as the soil settles and compacts during the course of the test. Figure 6 is a schematic of the apparatus and Figure 7 showed the control panel and the pneumatic cylinder for pressure application to simulate burial depths.

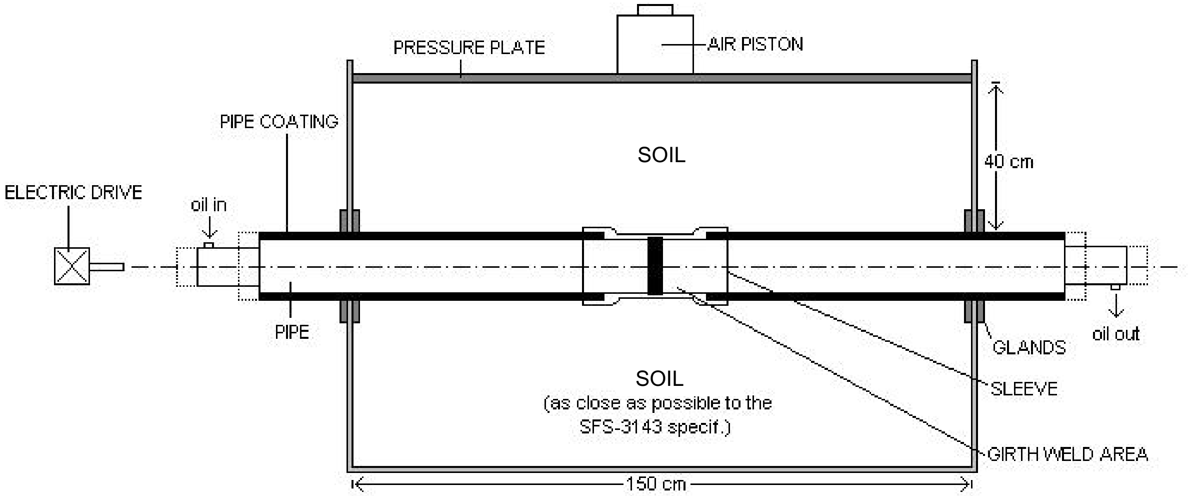


FIGURE 6 – Schematic of the Soil Box Apparatus

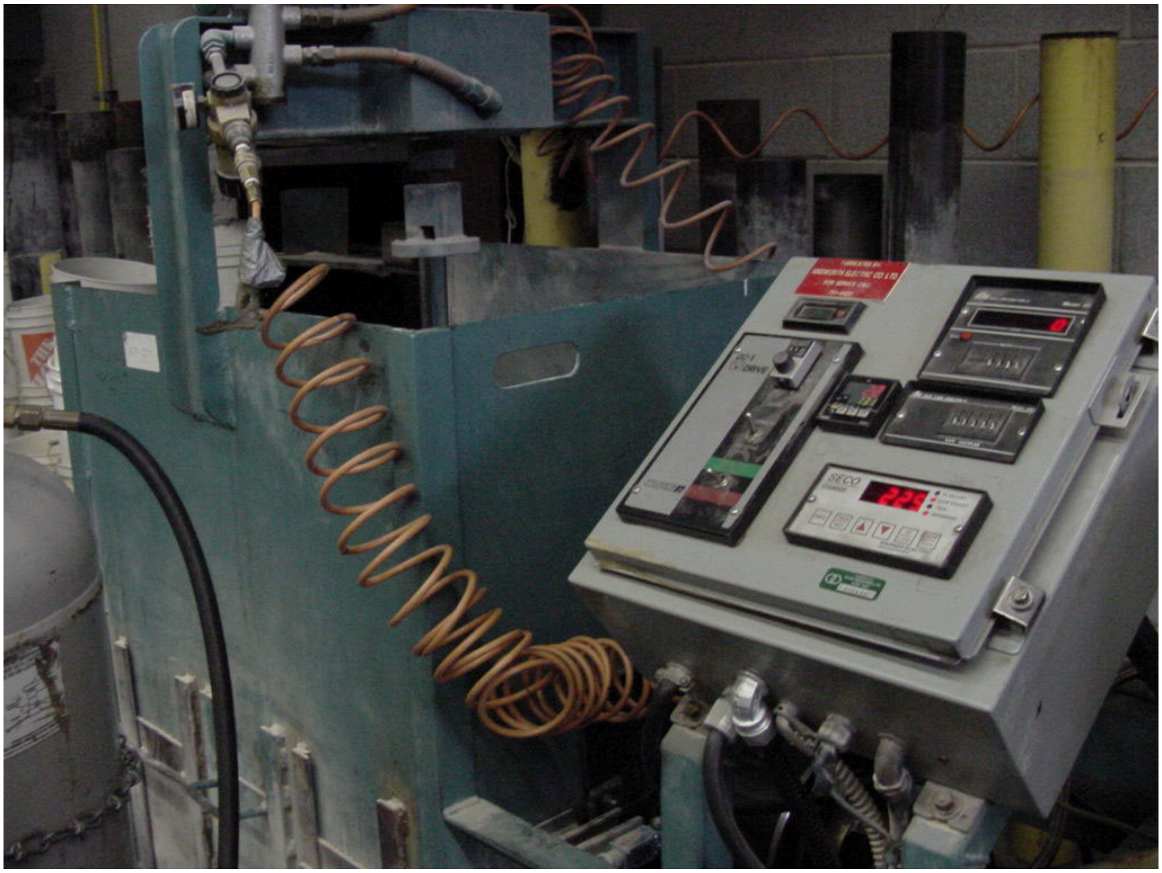


FIGURE 7 – View of Apparatus Showing the Control Panel and the Pneumatic Cylinder for Pressure Application.

Sample preparation. For coated pipes e.g. FBE, 2LPE and 3LPE and Tapes, the samples tested were approximately 54 inch (1.37 m) long. For Heat Shrinkable Sleeves, the samples tested were applied in the middle of a 54 inch (1.37 m) long steel pipe as illustrated in Figure 6.

Soil Description. Samples of soil in a typical backfill may contain soil, silt, gravel, rocks, organic matter, twigs, etc. For the purpose of this study a mixture of dry soil and gravel was used in all cases.

Procedure

Coated sample is placed into the Soil Box and partially covered with a mixture of soil and gravel. The rubber glands are then placed over the pipe and the whole assembly mounted in the box. After assembling the ends of the box and bolting the gland flanges into place, the pipe sample is secured to the actuating piston, and the box filled with soil to a level approximately 40 cm above the top of the pipe. The pressure plate is then placed on top of the soil and a force (1,400 kg) is applied to simulate an approximate six feet burial.

At the beginning of testing, the cycle meter is set to zero and the cycle control at the desired number of cycles.

The oil is allowed to circulate and to heat up until the surface of the pipe/sample reaches the desired test temperature.

The distance of travel is set to 7.5 cm.

The speed is set at 1 cm/min “forward” and 10 cm/min “return”. These are the settings the District Heating Association uses to simulate heat ups and cool downs.

After completion of the test the pipe/sample is removed and examined for:

Coatings:

- Abrasion damages
- Wrinkling
- Tearing
- Shifting/disbondment

Sleeves:

- Penetration of soil under the sleeve
- Displacement of the sleeve from its original position
- Wrinkling
- Tearing
- Holes
- Integrity of the closure system
- disbondment

Tapes:

- Wrinkling
- Integrity of overlap
- Soil penetration
- Tearing
- Disbondment

RESULTS

TABLE 1
VISUAL EVALUATION - TESTED AT 23°C

# of Cycles	**2LPE**	**3LPE**	**FBE**	**Tapes**	**Heat-Shrinkable Mastic Sleeves**	**Heat-Shrinkable Hot Melt Sleeves**
20	No Change	No Change	No Change	No Change	No Change	No Change
40	No Change	No Change	No Change	Minor Lifting	No Change	No Change
100	No Change	No Change	No Change	Major Wrinkling	Some soil penetration	No Change
150	No Change	No Change	No Change		Wrinkling and Shifting	Closure Lift-up
250	No Change	No Change	Minor Scratches			Minor soil Penetration
500	Minor Scratches	Minor Scratches	Minor Scratches			Major soil Penetration
1000	A few major scratches	Minor Scratches	A few major scratches			

TABLE 2
VISUAL EVALUATION - TESTED AT 60°C

# of Cycles	2LPE	3LPE	FBE	Tapes	Heat-Shrinkable Mastic Sleeves	Heat-Shrinkable Hot Melt Sleeves
20	No Change	No Change	No Change	No Change	No Change	No Change
40	No Change	No Change	No Change	Major Wrinkling	Some soil penetration	No Change
100	No Change	No Change	No Change		Wrinkling and Shifting	No Change
150	No Change	No Change	No Change			No change
250	Minor Scratches	Minor Scratches	Minor Scratches			Minor soil Penetration
500	Minor Scratches	Minor Scratches	Minor Scratches			Major soil Penetration
1000	A few major scratches	Minor Scratches	A few major scratches			

OBSERVATIONS

- All the samples showed no change after 20 cycles.
- Most samples passed a much higher number of cycles than usually expected even for the District Heating Industry.
- No major differences were observed between the two types of polyethylene coatings. Their performance was similar even at 60°C. Even the 2LPE with the soft mastic adhesive withstood the longitudinal pipe movements.
- Major scratches on the surface only occurred at ~1000 cycles, well above any expectations.
- FBE showed no difference in performance when tested at 23°C or at 60°C. Its performance was equivalent to that of 3LPE. However, scratches appeared at an earlier time and were more numerous.
- PE and FBE coating damages were strictly abrasion related. The imperfections become evident after approximately 500 cycles. This is an incredible number of cycles if one considers that even in the District Heating Industry, where the temperature changes frequently, 100 cycles is the requirement.
- Tape(s) – wrinkling and soil penetration were observed at room temperature and 60°C. Poor adhesive bond allowed the soil to penetrate between the PE layers after only a limited number of cycles.

Sleeves (Mastic Type): Soil penetration and wrinkling was observed. This predominantly occurred at the overlap area where the closure was. The thicker the overlap, the more readily soil penetration seemed to occur. As expected the Mastic sleeves performed much better at 23°C than at 60°C.

Sleeves (Hot Melt Type): Soil penetration was the major type of damage observed. In one sample the closure had been lifted and delaminated. Similar to the mastic sleeves, soil tended to penetrate around the areas with the highest profile e.g. overlap area.

Mastic Sleeves performed better than Tapes but not as good as the Hot Melt Sleeves. The higher Shear resistance of the Hot Melt adhesives accounted for the difference. The hoop stresses in the Sleeves Backing and the lower number of exposed edges explained why the Mastic Sleeves performed relatively better than the Tapes.

DISCUSSION

Types of Coating Failures

There are several types of coating failures observed, particularly as the severity of the test increases. Coating failure depends on several factors such as temperature, burial depth, magnitude of shearing stress and the number of cyclic shearing stress applied.

(1) One of the failures can occur between the adhesive and the pipe as shown in Figure 8. This occurs when there is a loss of bonding of the adhesive to the pipe metal. As the pipe shifts, the adhesive(s) that were not perfectly bonded to the pipe and have lift up at the edges, allows for easy soil ingress. With each movement, the soil is pushed further in. Once the soil reaches the pipe surface, water can follow immediately. Poor application practices or surface preparation being the major causes of failure. It is important to point out that proper application with these coatings yields excellent results.

FIGURE 8 – Failure due to Soil Ingress.

(2) Another example of failure is between the adhesive and the top coating as shown in Figure 9. This is caused by the inadequate bonding between the adhesive and the polyolefin top-layer. This occurs when the interface friction (adhesive shear strength between the adhesive and the coating) is much weaker than the soil friction (adhesive shear strength of the soil and the coating). Clay soils are well know for tenaciously sticking to the coating and causing the pipe to move inside its own coating [3]. Wrinkling and/or displacement of the protective layer at the girth weld are one of the typical signs.

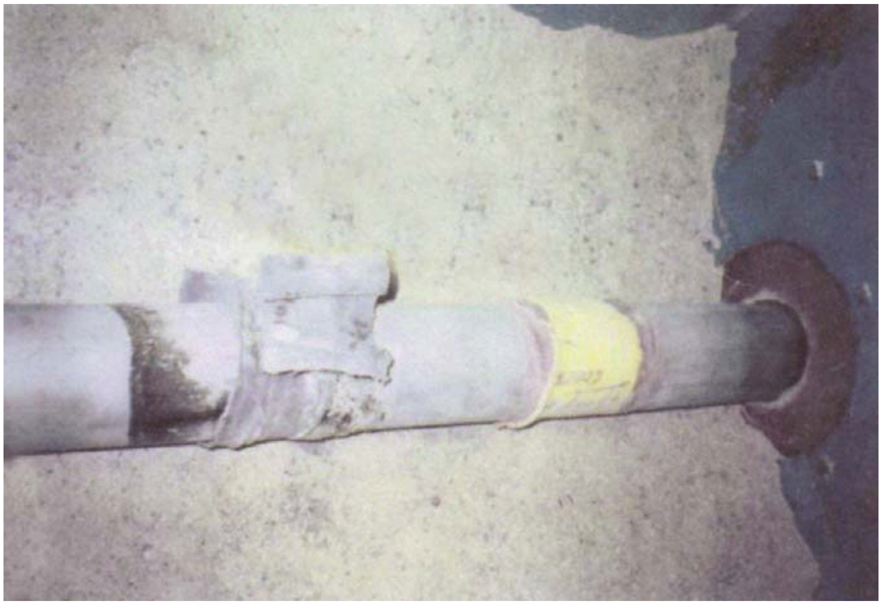


FIGURE 9 – Soil Ingress between Adhesive and Topcoat

(3) Another example of failure, which yields similar problems to the failure shown above, is that occurring within the adhesive itself. When the internal strength of the adhesives (cohesive strength) is weaker than its adhesive strength to the top-coat or weaker than the soil strength to the coating, the pipe can again move inside its own coating. Wrinkling, with very soft adhesives, can occur after only a few cycles as illustrated in Figure 10. These types of products are easy to apply and very forgiving about pipe surface preparation and temperature of application. These products perform best in minimum shear situation and/or when used under low soil stress.

FIGURE 10 – Failure due to Low Cohesive Strength of Adhesive

(4) Another example of failure (Figure 11) that was frequently observed during the evaluation was at the overlaps. This was predominant when many overlaps were present. The causes for the failures were determined to be due to the inadequate adhesion between the adhesive and the polyolefin film from the previous layer, coupled with the fact that every 3-4 inches (76-101 mm) there were an exposed edge (weak point). The more overlaps (exposed edges), the higher the chance for the soil to get underneath the coating and to the metal.

FIGURE 11 – Failure at Weak Overlaps.

(5) Other examples of failure (Figure 12 and 13) that were observed when testing Cross Head Extruded Polyolefin or FBE Coatings were mostly abrasion related. In this test program, none of the abrasion imperfections were severe enough to cause failures. Only small scratches and a few minor indentations were observed. However, with a rocky backfill, sharp stones can penetrate the surface of the coating and as the pipe shifts, cause severe scratches on its surface. This phenomenon has not been examined in this test program.

FIGURE 12 – Minor Scratches on Extruded PE Coating Surface.

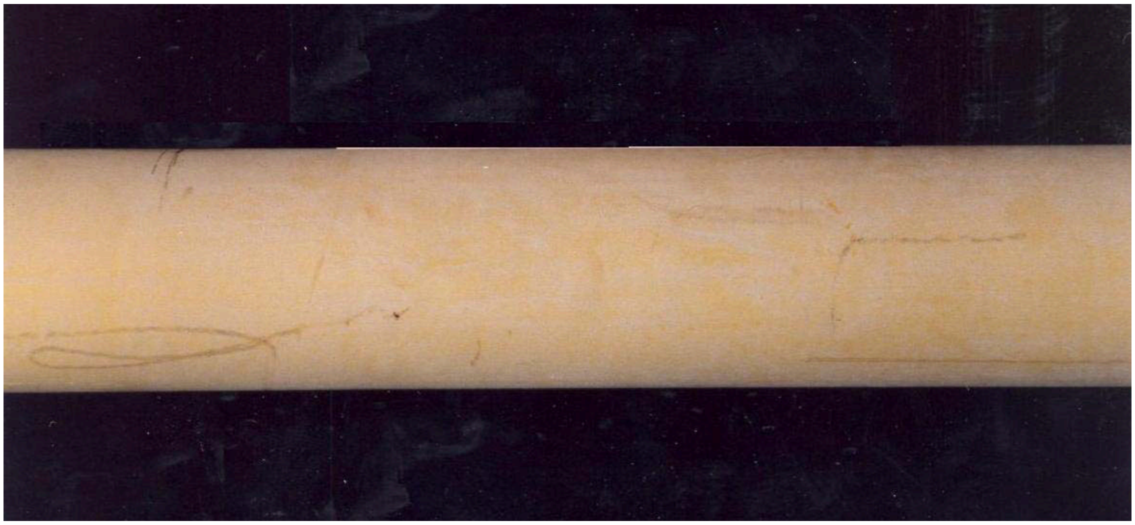
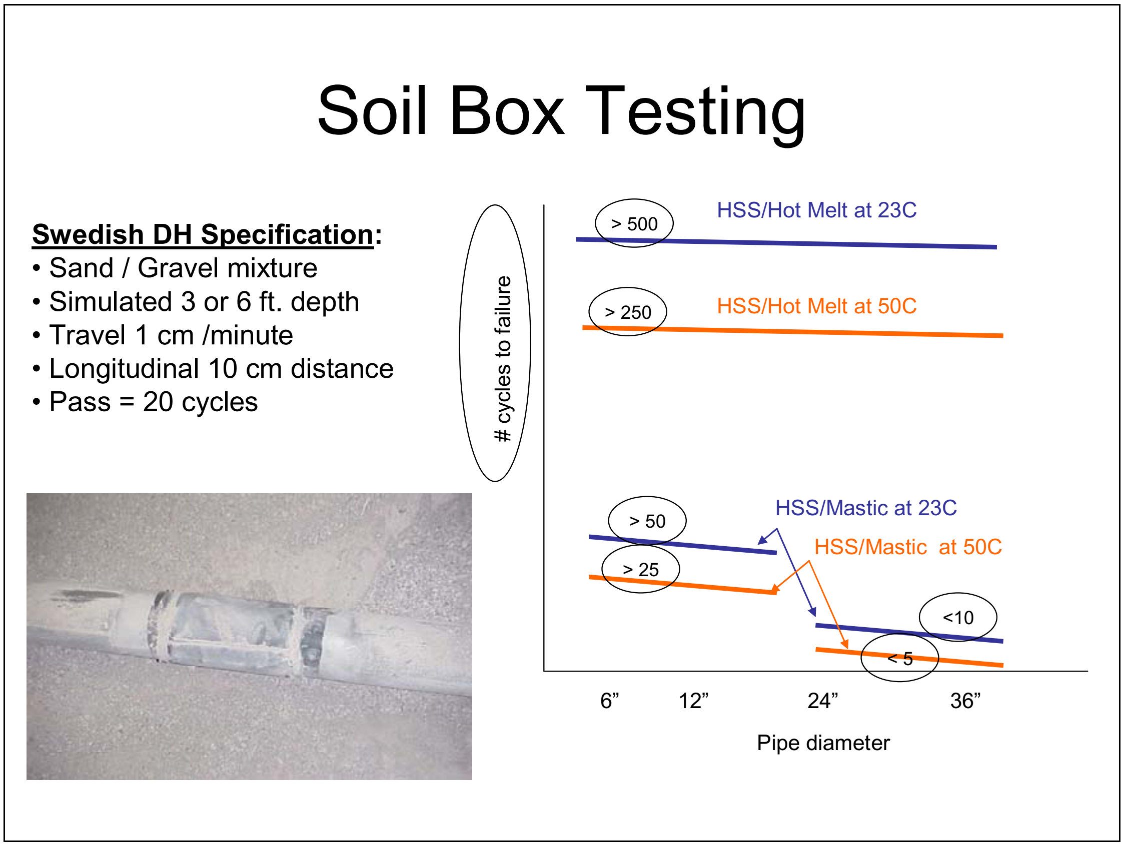


FIGURE 13 - Scratches on FBE.

Cohesive Strength of Adhesive on Soil Stress Resistance

Analysis of the failure modes above demonstrated the importance of the cohesive strength of the coating systems, particularly with coatings having overlaps in the topcoat such as tapes or heat-shrinkable sleeves. Figure 14 showed the relationship between heat-shrinkable sleeves with adhesives having different cohesive strength. Hot melt adhesives vary slightly with service temperature and are relatively stable at all pipe sizes. In contrast, mastic adhesives are more temperature sensitive and pipe size dependant.



Soil Box Testing

Swedish DH Specification:
- Sand / Gravel mixture
- Simulated 3 or 6 ft. depth
- Travel 1 cm /minute
- Longitudinal 10 cm distance
- Pass = 20 cycles

FIGURE 14 – Performance of Heat-Shrinkable Sleeves with Adhesives Having Different Cohesive Strength.

Figure 15 showed that a heat-shrinkable sleeve can perform extremely well when it is properly designed for the service environment.

FIGURE 15 – Heat-Shrinkable Sleeve with Hybrid Adhesive Tested at 60°C for over 150 Cycles.

CONCLUSIONS

1. Coatings with high cohesive and adhesive strengths such as FBE, 3LPE, Hot Melt based Heat Shrink Sleeves, etc showed excellent resistance to axial shearing forces due to thermal expansion and contraction.
2. Coatings with a smooth, continuous outer sheath such as 2LPE showed excellent resistance to axial shear forces even with the use of relatively soft mastic adhesives. The compressive hoop stress from the outer layer contributed to the better than expected performance.
3. Coatings having exposed edges or overlaps were more prone to soil penetration as a result of the axial pipe movements.
4. With exposed edges or overlaps, the cohesive strength of the adhesives will determine the coatings' resistance to axial shear forces.
5. With heat-shrinkable sleeves, the hoop stress of the cross-linked PE improved the resistance to axial shear forces.
6. Mastic adhesives are more sensitive to temperature.
7. Understanding the strength and weakness of each coating system will minimize unwanted surprises and help in the development of improved systems for the future.

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