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Failure Analysis of 14" JM Eagle PVC C-905 Buried Force Main Pipe

Executive Summary

Environmental Resources Management (ERM) contracted Plastic Expert Group & Plastic Failure Labs, Inc. (PEG) to conduct a 3rd party evaluation of a failed section of 14-inch diameter JM Eagle C905 DR32.5 PVC pipe (force main). The evaluation goal was to determine the failure mode and root cause of failure. The pipeline has experienced several other similar failures. Because of known quality issues with JM Eagle PVC pipes (http://legalnewsline.com/stories/510516546-federal-jury-finds-jm-eagle-liable-for-fraud-for-making-selling-faulty-pipes), we tested the pipe to determine if it was defective. Testing included AWWA and ASTM standard specifications for mechanical strength which included both tensile strength and impact strength. The pipe material strength exceeded the AWWA C905 minimum strength properties. Tests were also performed (ISO18373-1) to determine the temperature at which the pipe was extruded and the degree of fusion of the PVC powder (ISO18373-2). The results of these tests were in agreement with the mechanical strength tests indicating that the pipe was not defective.

Next, attention focused on inspection of the failed fitting for other causes of failure. No evidence of over-insertion (over-belling) was observed. Since the pipe broke circumferentially, the cause of failure is not likely to have resulted from operation (e.g., water hammer) as this would have led to longitudinal fracture. Circumferential fractures generally result from bending stress. Close inspection revealed abrasion and erosion damage caused by dirt and debris wedged between the spigot and the bell. Based upon the appearance, we believe the following scenario is most consistent with the observations:

1) The spigot of the pipe was dirty and coated with dirt/gravel (Figure 1).
2) As the dirty spigot was inserted into the bell, the gravel coating on the spigot likely wedged underneath and likely tore the gasket causing poor sealing (Figure 2).
3) A slow leak through the gasket increased in rate over time eventually reaching a velocity fast enough to cause erosion of the pipe (Figures 3 and 4).
4) The flow of leaking water eroded away the supporting earth underneath the bell allowing the bell to sag.
5) The bending moment on the sagging pipe joint caused the bell to fracture at its weakest point (Figure 5).
6) The weakest point in the bell is in the gasket trough where the material is the thinnest. Also, the change in direction at the gasket trough acted to concentrate stresses.
7) Once the bell fractured, the leak went from slow to catastrophic.

Conclusions

The root cause of failure was defective installation.

Sincerely,

Note: These opinions are provided in good faith with no warranty expressed or implied.

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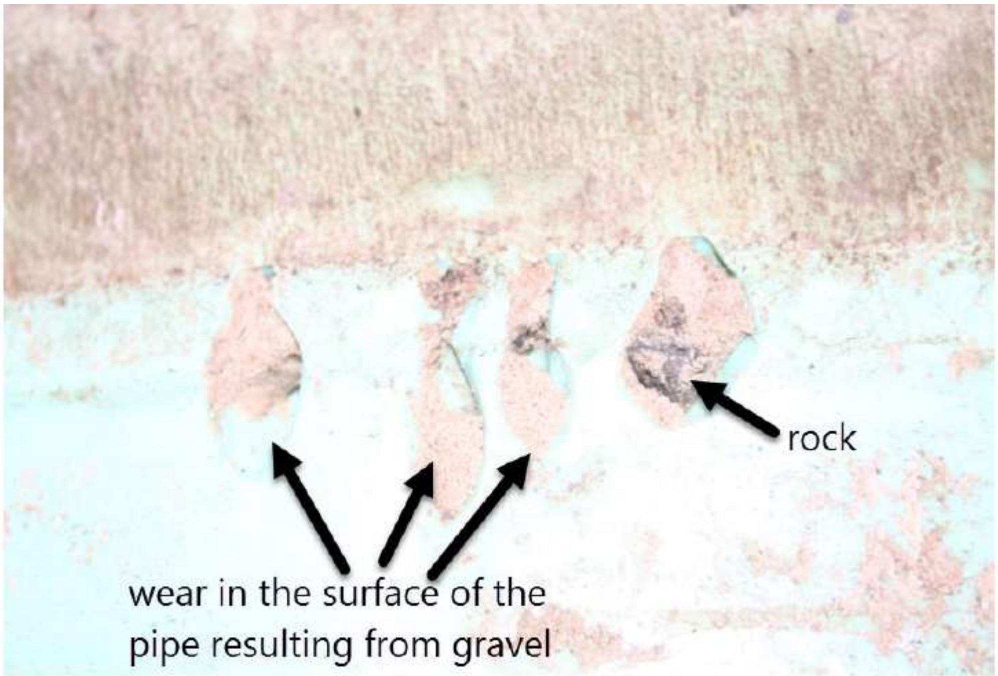

Figure 1. The spigot end of the pipe showed regions abraded away by gravel and pieces of rock which became embedded in the pipe surface.

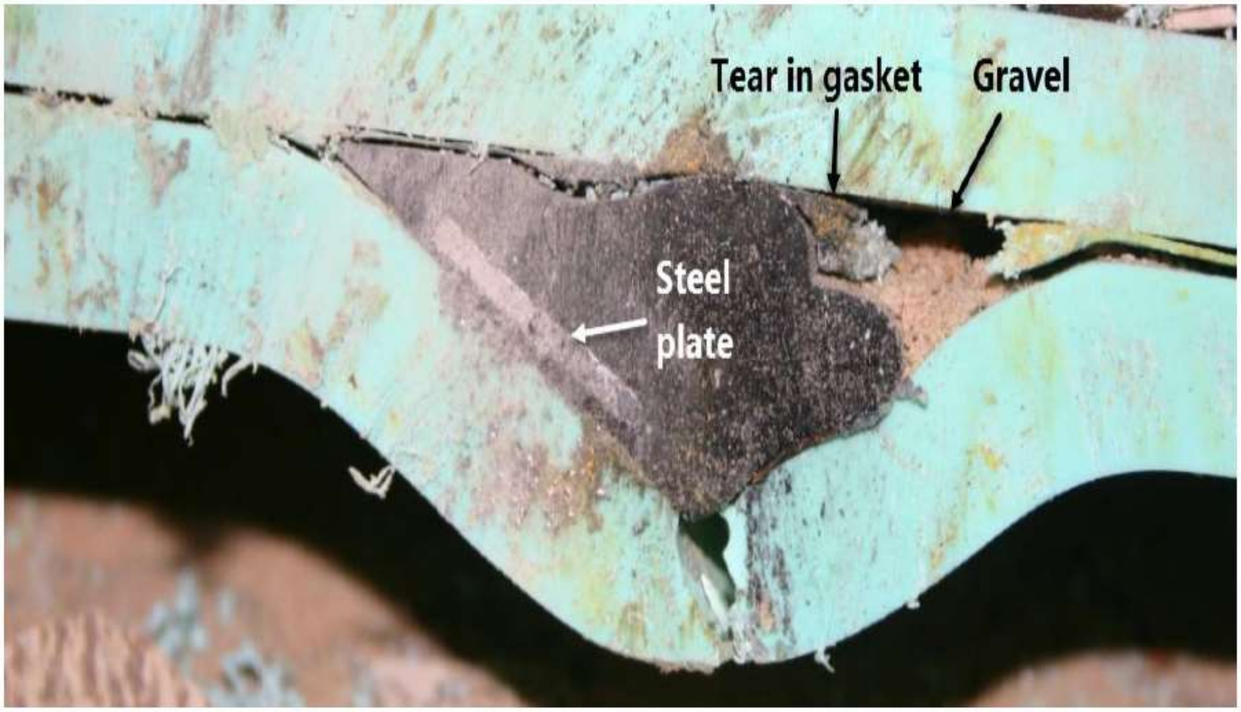

Figure 2. Cross-sectional view of the gasket reveals the torn gasket and gravel inside the seal/trough.

Figure 3. Black arrows indicate erosion caused by the exit of water from the joint before the circumferential crack formed in the gasket trough.

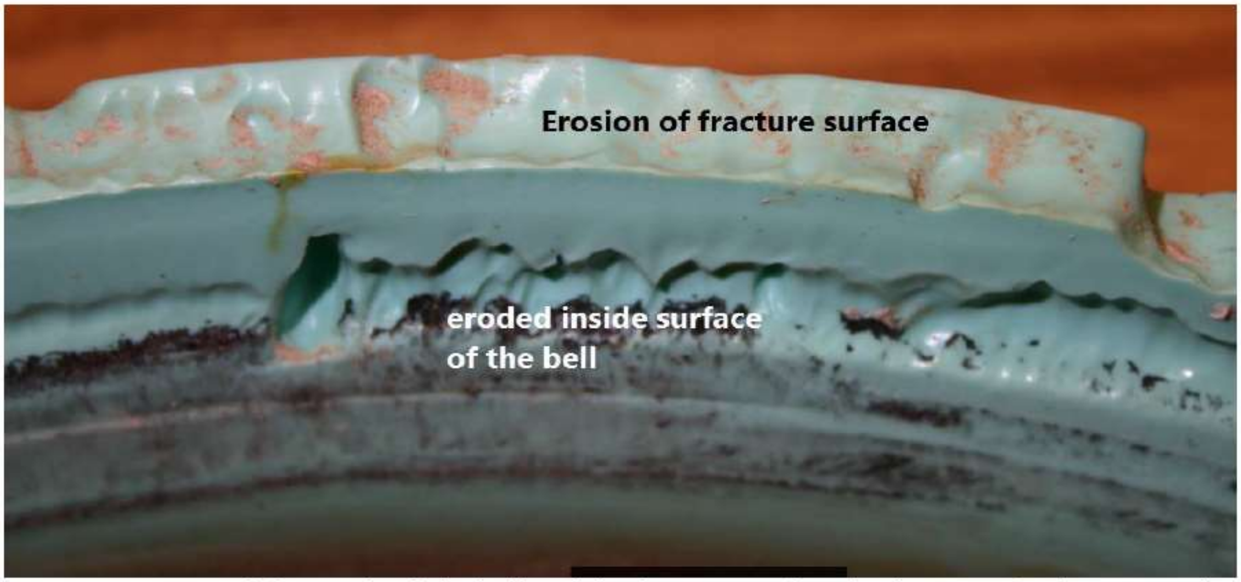

Figure 4. Erosion of the inside of the bell and the fracture surface by the water leaking passed the gasket.

Introduction

Environmental Resources Management (ERM) contracted Plastic Expert Group & Plastic Failure Labs, Inc. (PEG) to conduct a 3rd party evaluation of a failed section of 14-inch diameter JM Eagle C905 DR32.5 PVC pipe (force main). The evaluation goal was to determine the failure mode and root cause of failure. A section of failed pipe, including the bell and spigot, was shipped from El Dorado AR. The sample arrived at the machine shop (located in Sanford MI) on December 21, 2016.

The pipe sample was about 10 feet in length and contained a circumferential crack about 90% around its circumference in the seal trough in the bell (Figure 5). Reportedly there have been seven failures in the pipeline and all of the failures have been similar.

Figure 5. Photographs showing the top and bottom locations of the fracture in the bell of the pipe as received. Notice the extensive erosion of the fracture surface in the photo on the right. The erosion was caused by the rapid flow of water through the crack over an extended period of time. The gasket/seal is visible through the crack on the photograph on the right.

Background on PVC Pipe Failure

PVC piping is a preferred over steel piping because of its resistance to corrosion and relative ease of installation. PVC pipes and fittings are designed to last at least 50 years.[1] However, PVC pipes do occasionally undergo brittle failure.[2,3] PVC pipeline failures can occur because of: 1) manufacturing defects in the pipes,[4,5] 2) installation errors,[6] or 3) operational errors of the pipeline.[7] It has been our experience that the most common cause of failure is installation error. The most common installation error is over-insertion of the spigot end of one pipe into the bell end of the adjoining pipe (commonly called over-belling) and improper bedding preparation in the trench causing damage to the outside surface of the pipe. Indentation placed into the outside surface of the pipe by rock impingement act as stress concentrators and can initiate creep failure of the pipe. The most common manufacturing defects include weak extrusion knit-lines in pipes and either low or high fusion of the PVC particles during the extrusion process. These manufacturing defects lower pipe ductility making it more susceptible to failure. The most common operational error is pressure surging (water hammer). The most common cause of pressure surging is the sudden actuation of on/off valves.

The pipe manufacturer that has been plagued with significant quality issues in recent years is JM Eagle (http://legalnewsline.com/stories/510516546-federal-jury-finds-jm-eagle-liable-for-fraud-for-making-selling-faulty-pipes). Our lab has been involved in testing failed JM Eagle pipes and have found pipe quality issues are what caused the failure. We therefore initially focused our investigation on determination of the quality of the failed pipe.

Pipe Strength Testing

The AWWA C905 standard for PVC piping require that the pipes have certain strength properties including tensile strength and resistance to impact. The standard tests used to determine if the pipes meet these criteria include tensile strength testing (ASTM D638), IZOD impact testing (ASTM D256), and pipe ring compression test (ASTM D2412). The compression test is useful for exposing weak extrusion knit lines.

The pipes are required to meet the cell classification 12454 minimum requirements including:

IZOD impact >0.65 ft/lbs (Impact Resistance - ASTM D256)
Tensile strength >7000 psi (Strength - ASTM D638)

The test methods used to determine if a pipe meets this requirement involve machining three specific types of test specimens from the pipes. The test specimens have specific shapes and dimensions. The techniques used to cut these test specimens from the pipes is tedious and must be performed properly to insure that the PVC is not degraded during the machining process. A Machinist/Technician that is highly experienced in working with plastics should prepare the test specimens. If the machining process generates too much heat, the PVC will degrade and embrittle so that the test specimens will not pass the minimum strength requirements.

ASTM D2412 Compression Test

Three test rings were machined from the pipe near the bell. Two test rings passed the test demonstrating high ductility. However, one ring fractured during the test (Figure 6). Figure 7 shows the flattening test being run on a test ring of PVC pipe. Notice that the points of highest stress are on four locations in the ring. The test ring that fractured, broke where the top of the ring contacts the compression plate. Computer modeling reveals that the contact points of the ring with the parallel plates are the highest stress points and predicts that, if failure occurs, it would occur at these locations. Note that the test was only used for diagnostics purposes as the pipe is not required to pass the test once it has been installed. The main utility of the test is to expose weak extrusion knitlines in the wall of the pipe. The results reveal that the pipe DID NO have weak extrusion knitlines.

Figure 6. Photograph of the three test rings following completion of the ASTM D2412 compression test. One of the three rings (top) fractured with expulsion of a triangular shaped piece.

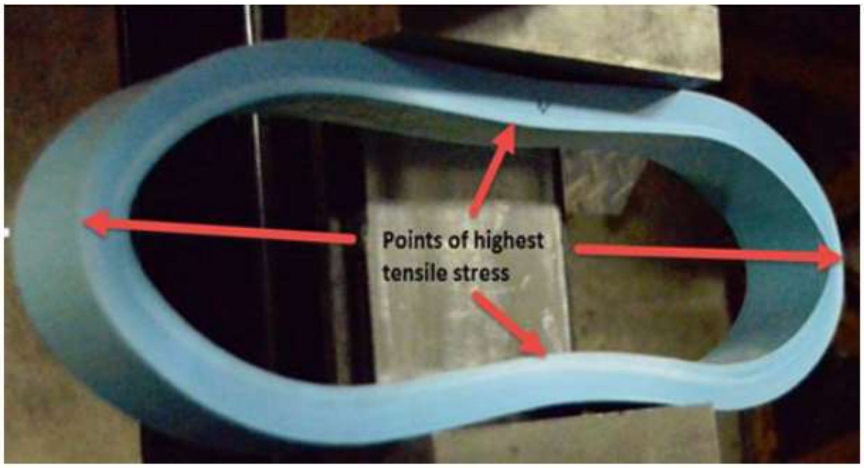

Figure 7. Photograph of a PVC test ring undergoing the ASTM D2412 ring compression test.

Tensile Testing (ASTM D638)

Tensile testing involves stretching dog bone shaped strips of the plastic machined from the pipes to measure the amount of force it takes to break the plastic (tensile strength). How far the plastic stretches before it breaks indicates the ductility or elongation of the plastic. The tensile and IZOD impact test specimens were machined from the pipe as shown in Figure 8. Three test specimens were cut from the pipe in the length direction and three in the circumferential direction.

A photograph showing the tensile test and IZOD impact test specimens before and after tensil testing is shown in Figure 9.

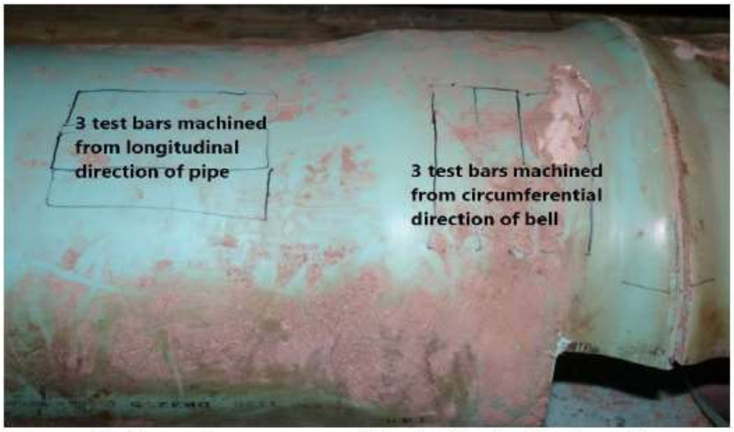

Figure 8. A marker was used to indicate the locations were test specimens were removed for mechanical strength testing.

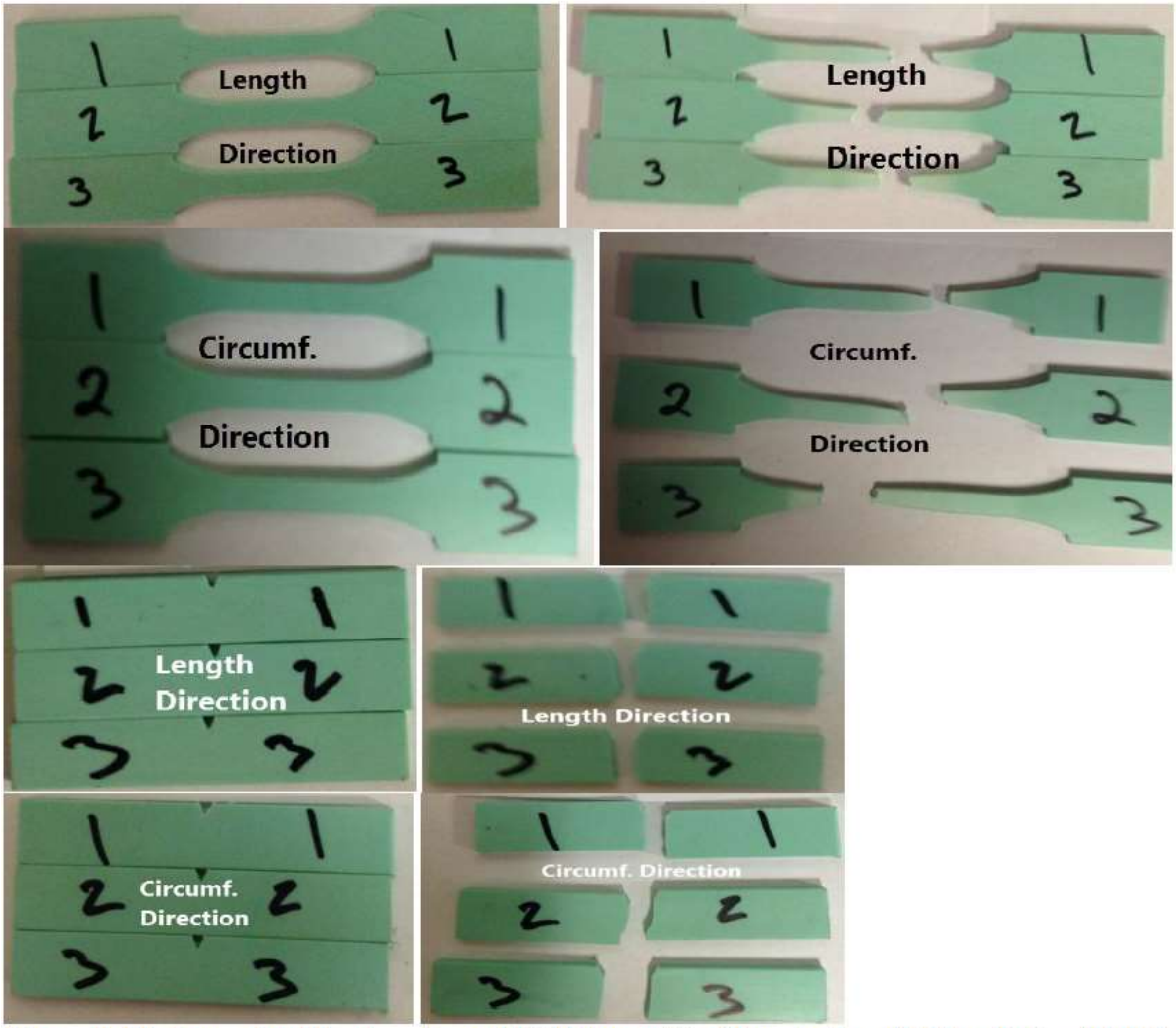

Figure 9. Photograph of the tensile and IZOD impact test bars before (left) and after (right) testing. Test results reveal that the pipe material is strong and exceeds minimum strength specifications.

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AWWA C905 requires that the PVC pipe material meet the 12454 PVC cell classification. This PVC cell classification requires a tensile strength >7000 psi and an IZOD impact strength of >0.65. The test data (Table 1) indicate that the pipe material has well above the minimum strength properties. The %Elongation at break of the test samples in both directions was >50% revealing that the pipe material is highly ductile and will undergo significant deformation before it breaks.

Table 1. Tensile and Impact Strength Data for the Samples Exceeds Minimum Requirements

Sample Direction	Tensile Strength (psi)	Elongation@Break	IZOD Impact (ft/lbs)
Lengthwise	7425	74%	1.1
Circumferential	8050	55%	1.2

Impact Strength Testing (ASTM D256)

Most of the time, pipes are exposed to constant water pressure which places a hoop stress on the pipe wall. However, the pipes also are occasionally exposed to sudden rapid pressure changes; e.g., when valves are opened and closed. Really fast changes in pressure (water hammer) can create high speed shock waves inside the pipe line. Therefore it is important that the pipe be able to tolerate both high speed stress (impact) as well as long term hoop stress. Some materials may respond in a very ductile manner to slow speed stress but fail catastrophically in when exposed to high speed stress. The IZOD impact test (ASTM D256) was used to assess the high speed impact strength of the pipe. Again, the IZOD impact test specimens were machined in the weakest (hoop) direction of the pipe. The standard calls for the test bars to be notched. A swinging pendulum is used to break the bars (Figure 10). The amount of energy absorbed by the test bar provides the impact strength of the material. All test specimens significantly exceeded the impact strength requirements as shown in Table 1.

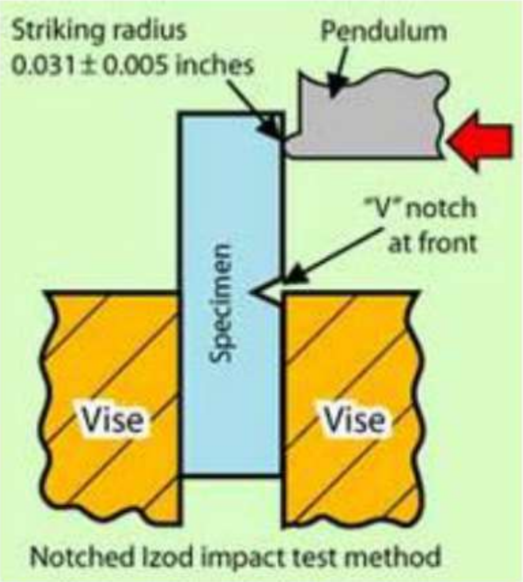

Figure 10. IZOD impact strength test.

Pipe Manufacturing Quality

PVC is a challenging resin to process due to its very narrow processing temperature range. If the temperature is too low (<170 °C), the PVC resin crystallites do not fuse. If the temperature is too high (>200 °C), the resin thermally degrades resulting in the liberation of hydrochloric acid gas (dehydrochlorination). During processing of PVC, as the material is heated, the smaller "grains" (crystallites) of the PVC, melt first. During melt extrusion processing, the grains fuse together forming a partially-fused or gel state. The degree of fusion or gelation is dependent upon the processing temperature and shear rate in the extrusion process, with higher temperatures and shear rates yielding a higher degree of fusion.[8-12] Benjamin measured both ductility and impact strength versus degree of fusion. The results of his work reveal that the best overall PVC strength is achieved a 45 – 70% fusion as shown in Figure 11.[13]

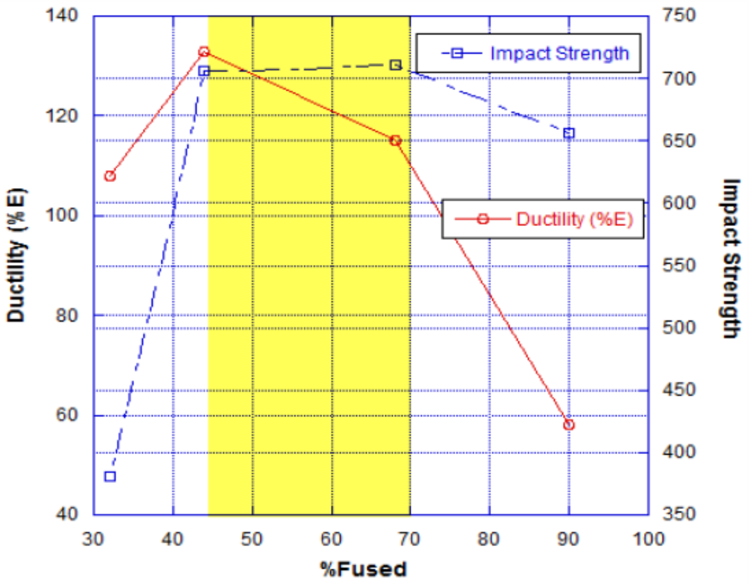

Figure 11. Data from Benjamin[13] was graphed. The data revealed that optimum balance of impact strength and ductility are achieved when the PVC is about half to two thirds fused.

When the degree of fusion is very low, the chemical and creep resistance of the pipe are poor. When the degree of fusion is very high, the ductility and impact strength of the pipe is poor. It is theorized that separation of incompletely fused PVC particles during a stress event is an energy absorption mechanism which explains why highly fused pipes have reduced strength.

PVC fusion is best measured using differential scanning calorimetry (DSC) following ISO18373-2. Only a few milligrams of sample are required for the test so the sample can be collected from a precise location in the wall of the pipe. The DSC thermogram for the pipe in the core of the pipe wall near the location of the fracture is shown below in Figure 12. The DSC thermogram has four regions of interest:

1) The glass transition temperature at around 82 °C (point where the PVC softens);
2) The region between 100 and 180 °C which reveals the level of fused PVC;
3) The region above 180 °C which reveals the level of unfused PVC;

4) The high point between the fused and unfused regions which reveals the extrusion temperature of the PVC pipe.

These four points of interest are seen in the DSC thermogram shown in Figure 12 which is a typical DSC thermogram for rigid PVC pipe. The ISO18373 data reveal that the extrusion temperature was 180 °C and the degree of fusion was 84%. As shown in Figure 11, the optimum balance of strength properties are achieved at a degree of fusion of between 45 and 70%. However, even though the degree of fusion is not optimal, the strength properties of the pipe are well above the minimum requirements for C905 pipe.

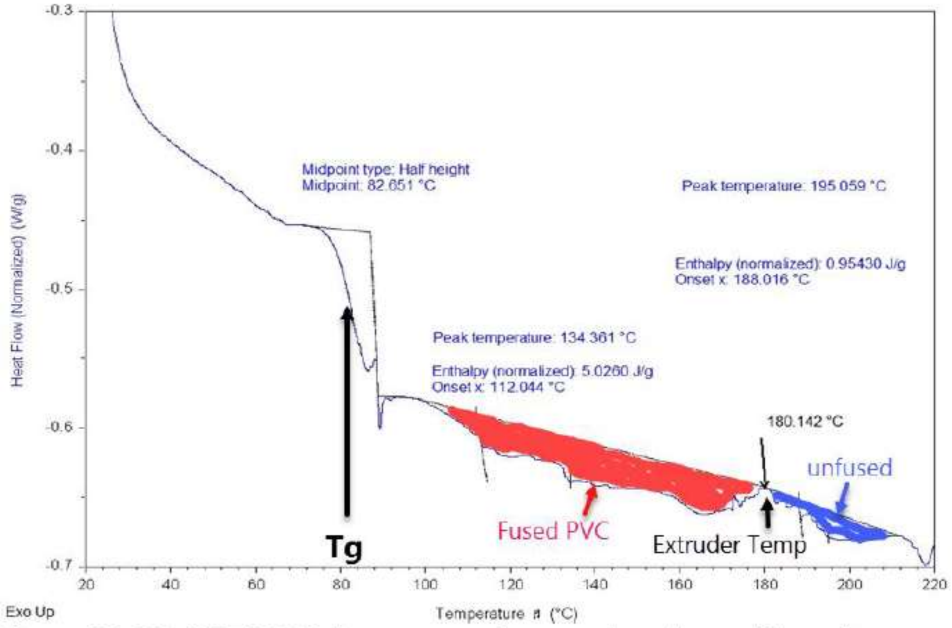

Figure 12. ISO18373 DSC thermogram for sample collected from the core of the pipe wall near failure point reveals pipe was extruded under proper conditions to achieve a high level of fusion (84%) at an extrusion temperature of 180 °C.

References

1) Janson, L.E., *"Plastic Pipes: How Long Can They Last?"*, Report No. 4 from the KP-Council, November 1996.
2)F. J. McGarry *et al.*, "*Brittle Fracture in PVC Piping Materials*", J. Polym. Sci.: Polymer Symp. Vol. 72, 83 – 110 (1985).
3) Truss, Ron; "*Understanding brittle failure of uPVC pipe*," Pure & Applied Chem., **57**, 993-1000, (1985).
4)"*Determining the quality of a failed PVC pipe*"; http://4spepro.org/view.php?article=000056-2009-06-22&category=Failure+Analysis
5)Y. Huang and P. Prentice, "*Experimental Study and Computer Simulation of the effect of Spider Shape on the Weld-Lines in Extruded Plastic Pipe*", Polymer Engineering and Science, September 1998, Vol. 38(9), 1506 – 1522.

6) http://c.ymcdn.com/sites/www.isawwa.org/resource/resmgr/handouts_for_seminars/05-09-12_presentation_fische.pdf
7) Bergant, A., Simpson, A.R., and Tijsseling, A.S., "*Water hammer with column separation: A historical review*"; Journal of Fluids and Structures, **22**, 135-171 (2006).
8) Comeaux, E.J., Chen, C.H., Collier, J.R., Wesson, R.D., "*Fusion Study of PVC: Relation of Processing Time and Temperature to the Degree of Fusion*", Polymer Bulletin **33**, 701-708 (1994).
9) J. W. Teh, A. A. Cooper, A. Rudin and J. L. H. Batiste *"Interpretation of DSC.Measurements of the Degree of Fusion of Rigid PVC"*; Journal of Vinyl Technology, **11**, 33–41 (1989)
10) Summers, J. W., "*The Melting Temperature (or not Melting) of PVC*", J. Vinyl & Additive Technology, **2008**, 105-109.
11) P. Vanspeybroeck and A. Dewilde, "*Determination of the Degree of Gelation of PVC-U Using a DSC,*" Becetel VZW, Belgium, 2004
12) Gramann, P., Cruz, J., and Ralston, B., *"Using Differential Scanning Calorimetry to Determine the Quality of a PVC Part"*, ANTEC Conference Proceedings, Chicago 2009.
13) P. Benjamin, "*Influence of the Extrusion Process on the Quality of PVC Pipes*", J. Vinyl Technology, **2**(4), 254 (1980).