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Brittle fracture in casing pipes

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ABSTRACT

Rapid Crack Propagation (RCP) is a brittle fracture mechanism that has been observed in the casing of large district heating pipes on several occasions. The phenomenon occurs mainly during installation work in cold weather. RCP cracks are driven by hoop stresses and a temperature decrease will cause a hoop stress build-up since the thermal contraction of the casing pipe is constrained by the steel pipe and the PUR foam. In addition, the casing pipe material is more brittle in low temperatures. Modern polyethylene materials are in general much more resistant to brittle fracture, since it is an important design property for the raw material producers.

The purpose of this project has been to determine critical temperatures with respect to RCP for polyethylene materials commonly used for casing pipes. Two polyethylene materials of classification PE80 were evaluated. One bimodal quality and one unimodal. Tests were done on casings with diameters ranging from 160 mm to 630 mm. Four types of tests were done in temperatures down to -40 °C: Charpy impact tests, impact tests according to EN 253, a “guillotine” test with a knife edge attached to a falling weight and finally a handling test similar to actual field work with power tools (drill, jigsaw and angle grinder).

The results show that the bimodal material is so resistant that there is no real risk for RCP in normal winter climate. For the older material type, however, special care should be taken already at temperatures a few degrees below zero.

Keywords: District heating pipe, casing, rapid crack propagation (RCP)

1. INTRODUCTION

The common district heating pipe of today has a casing of high-density polyethylene (HDPE). As most thermoplastics, HDPE has a high fracture toughness and mechanical damping and is well suited for applications where a good impact resistance is needed. At low temperatures, however, even thermoplastics may become brittle due to a decrease in mobility of the molecule segments. In Sweden, HDPE casings have on a number of occasions cracked by a mechanism known as Rapid Crack Propagation (RCP) during handling in cold weather. The driving potential for an RCP crack in a casing is a combination of tensile hoop stresses from the foaming process during pipe manufacture, and the temperature induced stresses from constrained thermal contraction as the temperature drops. There are extensive literature on RCP in HDPE pipes for gas distribution, but the problem has not been thoroughly treated for pre-insulated pipes, which, in a sense, is a more severe case. A pressurised fluid pipe will be almost instantly unloaded and the crack will arrest as the fluid leaks out. This will not happen in a district heating pipe casing, where the hoop stresses are supported by the rigid polyurethane (PUR) foam, and the crack may propagate a significant distance before it comes to a halt. The purpose of this project has been to determine critical temperatures with respect to RCP for polyethylene materials commonly used for casing pipes.

1.1 Rapid Crack Propagation (RCP)

RCP is the rapid propagation of a crack driven by strain energy stored in the material and usually initiated by some kind of impact. The risk for RCP increases with lower temperature, as the material becomes stiffer and more brittle. For given boundary conditions, there is a critical temperature below which RCP can occur. Analogously, there is a critical stress level for a given temperature. Common theories also suggest that the sensitivity increases with the thickness of the pipe wall. The research on RCP in polyethylene pipes was initiated by British Gas in 1973. The topic has been treated by the standardisation bodies for more than 25 years and two test methods for the determination of critical temperature/internal pressure have been issued as international standards: One laboratory test (the S4 test – Small Scale Steady-State test) and one full scale test (ISO 13477,1997 & ISO 13478, 1997). The two methods are both impact tests but do not yield completely comparable results due to differences in the loading situation. A correlation factor to handle this has been suggested by Vanspeybrock (2001). These methods are tedious and expensive and a simpler method, such as the Charpy impact testing (ASTM D6110, 1997), is desirable. Comparisons by Greenshields *et al* (2000) of results from both Charpy and S4 tests show that the Charpy method is well suited to rank different materials with respect to RCP sensitivity. Brown and Lu (2001) go further and suggest that the critical S4 temperature correlates with the Charpy impact energy and may be determined by one single Charpy test.

The particular case of RCP in district heating pipe casings has not been treated extensively in the literature. A theoretical study has been made by Bergström (1999). The phenomenon has, however, been observed on several occasions in practice. In Luleå, Sweden, RCP fractures have been seen twice (M. Johansson, 1995). In 1996, a 500 mm casing cracked along its whole section length at cutting with a drill or a jigsaw during preparations for jointing. The temperature at the time was -18 °C. A similar case was seen in 1999 at a temperature of -25 °C during work on seven year old excavated pipe with a diameter of 315 mm. In the mid 1990's, two failures was observed during installation of a 1000 mm pipe in cold weather in Germany (G. Johansson, 2005). In the first case, the casing cracked when the pipe was carelessly dropped on the ground from a crane. In the second case, a pipe cracked along its whole section length when laying in the pipe trench at night. The crack initiation was possibly caused by thermal movements.

1.2 Stresses in casing pipes

A casing pipe is usually subject to tensile hoop stresses as a consequence of the foaming pressure during manufacture. When the PUR components are injected into the space between the casing and the service pipe, they react under the formation of carbon dioxide and vaporisation of dissolved cyclopentane. This yields an overpressure and subsequent expansion of the casing. The wall thicknesses specified in the European product standard EN 253 (2005) are chosen so that the hoop stresses from the foaming are kept at a safe level. After the foam sets, the expansion of the casing is held constant and the hoop stresses relax with time due to the viscoelastic behaviour of the polyethylene.

Additional tensile hoop stresses will arise if the pipe is cooled down. This is from the thermal contraction of the casing, which is greater than that of the insulation foam. Hence, the casing is hindered from contracting as much as it tries to. Also the temperature stresses relax with time. Figure 1 shows a schematic hoop stress history for a district heating pipe casing manufactured and installed in winter time, and then excavated and repaired in cold weather ten years later. A large increase in stress level is expected if the pipe is excavated in cold weather, even if it has been in service for long time.

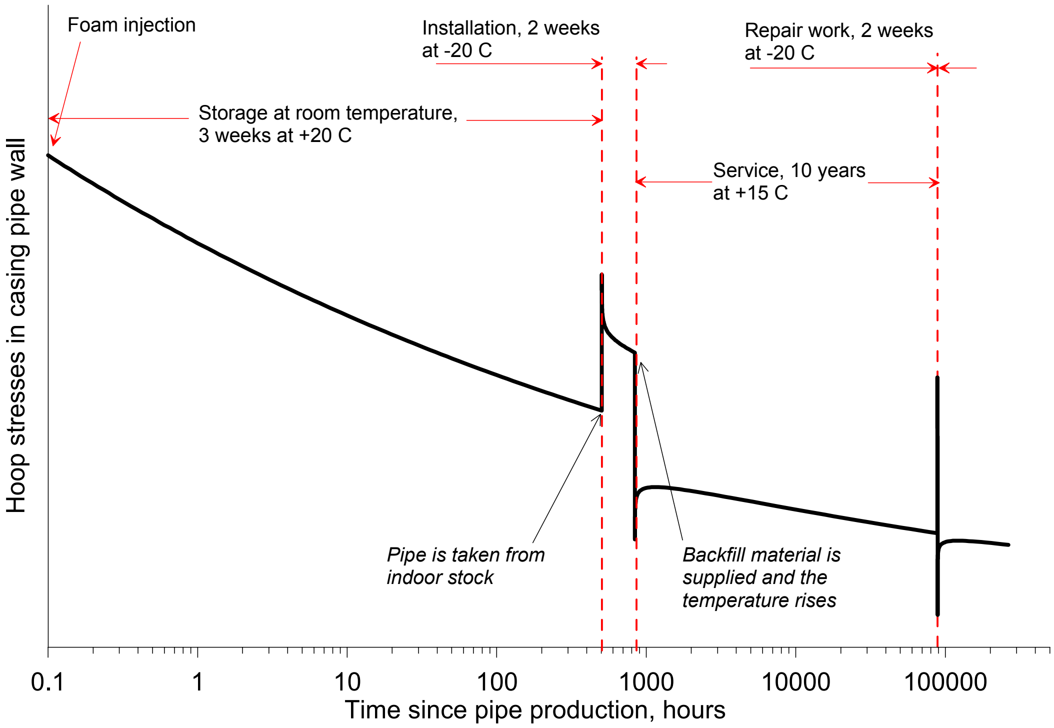

Figure 1. Schematic hoop stress history in district heating pipe casing. The stresses from the foaming pressure during manufacture will relax until the pipe is exposed to low temperatures—at installation or later repair. When the pipeline is backfilled, the temperature rises and compressive stresses may arise, since the tensile stresses from prior cooling are partly relaxed.

2. EXPERIMENTAL

Different kinds of impact tests were made on two HDPE materials at various temperatures in order to estimate critical temperatures and stress levels with respect to the risk for RCP.

2.1 Materials

The materials were chosen to cover both modern resins used today and older alternative frequently used previously.

1. A **unimodal**[1] PE80[2] resin. It fulfils the requirements in EN 253, and is used by some pipe producers.

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[1] Polyethylene is composed of molecules of various lengths, or weights. In *unimodal* materials, the molecular weight distribution is centred around one average. In *bimodal* materials, there are two sepa-

2. A **bimodal** PE80 material. It is the dominating alternative for casings today. The basic characteristics of the tested materials are summarised in table 1.

Table 1. Basic properties of the tested materials. The oxygen induction time is measured on the inside and the outside of the pipe wall.

Material	**Density (kg/m^3)**	**Melt Flow Rate (g/10 minutes)**	**Oxygen induction time (minutes)** *inside / outside*
Unimodal	945,9	0,417	42,3 / 44,3
Bimodal	953,2	0,433	45,1 / 44,7
EN 253 requirement	> 935	–	> 20

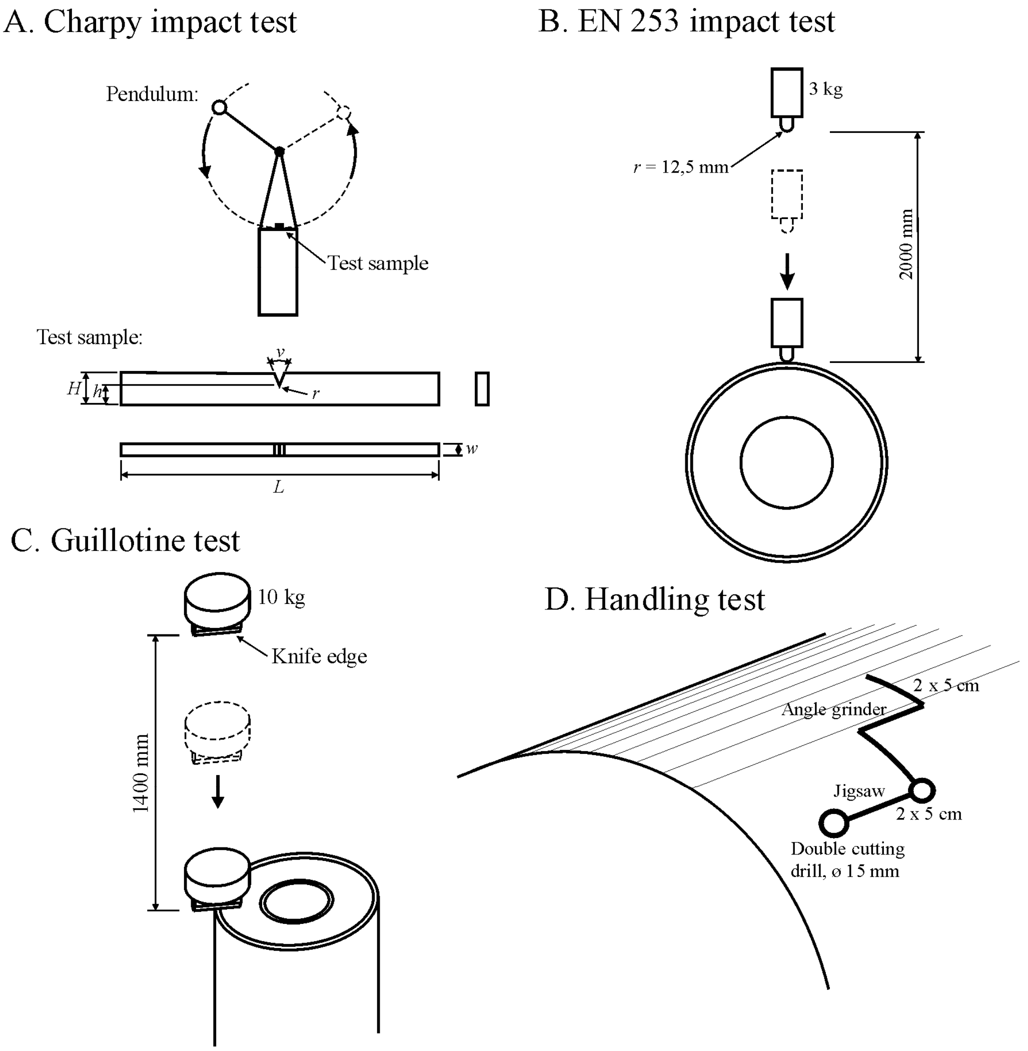

Figure 2. A) Test rig and specimen for Charpy impact test according to ASTM D 6110 (1997). The pendulum's striker head hits the test specimen with a velocity of 3.5 m/s and a kinetic energy of 15 J. B) Test rig for impact testing according to EN 253. The falling weight with its spherical tip hits the casing pipe surface with a velocity of 6.3 m/s and a kinetic energy of 59 J. C) Test rig for guillotine tests. The falling weight and knife edge hits the edge of the casing pipe at a velocity of 5.2 m/s and a kinetic energy of 137 J. D) Handling test. First, a hole is drilled through the casing pipe with a double cutting drill. Secondly, two slits are cut with a jigsaw. Then a new hole is drilled and finally two slits are cut with an angle grinder.

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rate peaks in the molecular weight distribution. Bimodal materials are usually more resistant to brittle fracture mechanisms.

[2] Polyethylenes for pressure pipes are classified with respect to their estimated long-term strength. Pipes of PE63, PE80 and PE100 shall withstand an internal pressure of 6.3, 8 and 10 MPa respectively for 50 years evaluated in accordance with ISO/TR 9080 (1994).

2.2 Charpy impact test

Charpy impact tests were made in accordance with ASTM D 6110. The test samples were conditioned to temperatures ranging from -40 °C to +80 °C prior to impact.

With the Charpy test, a pendulum is used to break a notched test sample. The fracture toughness is determined as the impact energy absorbed by the sample as the pendulum strikes. The impact energy equals the difference in potential energy of the pendulum at its highest positions before and after passing the sample, and this is readily measured with the angle swept by the pendulum arm, figure 2A.

2.3 EN 253 impact test

Small pipes of dimension DN 65/160 were tested along with large pipes, with casing diameters ranging from 450 to 630 mm, of one and each of the materials. Standard tests are usually done on small pipes only due to practical reasons.

The test method is described in EN 253, §5.4.6 and is schematically shown in figure 2B.

2.4 Guillotine test

The S4 and Full-Scale tests mentioned above are tedious and expensive, therefore an alternative test method was developed. The guillotine test comprises a knife edge attached to a falling weight (figure 2C), and this was done on casing pipes of the unimodal material and on concrete filled[3] pressure pipes with various wall thicknesses of the bimodal material. All tests were done on pipes with a diameter of 160 mm and a length of 500 mm. The pipes were cooled down to temperatures ranging from -10 °C to -48 °C prior to impact in order to obtain tensile hoop stresses in the pipe wall. The tensile stresses were calculated according to the following:

The radial expansion Δr_C of a casing pipe due to a temperature change ΔT and an internal pressure P_i can be expressed

$$\Delta r_C = \alpha_{PE} r_C \Delta T + \frac{P_i r_C^2}{E_{PE} s_C} \qquad (1)$$

Where α_{PE} and E_{PE} are the coefficient of thermal expansion and Young's modulus of elasticity for the polyethylene material and r_C and s_C are the mean radius and wall thickness of the pipe. If the PUR foam is treated as a one dimensional elastic foundation, the corresponding expansion of the foam layer Δs_F is

$$\Delta s_F = \alpha_{PUR} s_F \Delta T - \frac{P_i}{E_{PUR}} s_F \qquad (2)$$

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[3] The reason for using pressure pipes with concrete filling was to enable measurements on thick-walled specimens without having to use pipes of very large diameter. For example, a casing according to EN 253 of wall thickness 14,6 mm has a diameter of 1200 mm.

Where α_{PUR} and E_{PUR} are the coefficient of thermal expansion and Young's modulus of elasticity for the PUR foam[4] and s_F is the thickness of the foam layer. When the pipe is subject to a temperature decrease, the compressive stress between the casing and the foam adjusts so that the decrease in pipe radius Δr_C equals the decrease in foam thickness Δs_F. By equating (1) and (2), the equilibrium pressure can be obtained:

$$P_i = \Delta T(\alpha_{PUR} s_F - \alpha_{PE} r_C)\left(\frac{r_C^2}{E_{PE} s_C} + \frac{s_F}{E_{PUR}}\right)^{-1} \tag{3}$$

The tensile hoop stress σ in the pipe wall is then determined from

$$\sigma = \frac{P_i r_C}{s_C} \tag{4}$$

After impact, it was recorded whether the pipe cracked or not, and how far the crack extended.

2.5 Handling test

A handling test was designed to simulate the actual conditions at which pipes may crack during actual work. Tests were made on large pipes of one and each of the materials at temperatures down to -30 °C. All test pipes were subjected to the same sequential treatment (figure 2D):

1. An initial hole through the casing was drilled with a ∅16 mm double cutting drill.
2. A 50 mm long slit was cut with a jigsaw in the axial direction.
3. A second hole was drilled at the end of the slit.
4. A 50 mm long slit was cut with a jigsaw in the tangential direction.
5. A second axial slit was cut with an angle grinder.
6. Finally, the angle grinder was used to cut a second tangential slit.

3. RESULTS

The Charpy tests showed distinct transition temperatures between ductile and brittle behaviour at -5 °C and -15 °C for the unimodal and bimodal materials respectively, figure 3.

Figure 4 shows the results from the guillotine tests. The tests are made on cooled pipes, and the cracking behaviour is related to both the temperature in itself and the hoop stress caused by the temperature decrease. Under the assumption that a non-arresting crack (i.e., 100 % crack length in figure 4) occurs if the temperature is sufficiently low, the required stress levels for RCP are approximately 2 MPa for the unimodal material and 3.5 MPa for the bimodal material.

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[4] For concrete filled pipes, the corresponding material properties for concrete is inserted instead of those for polyurethane.

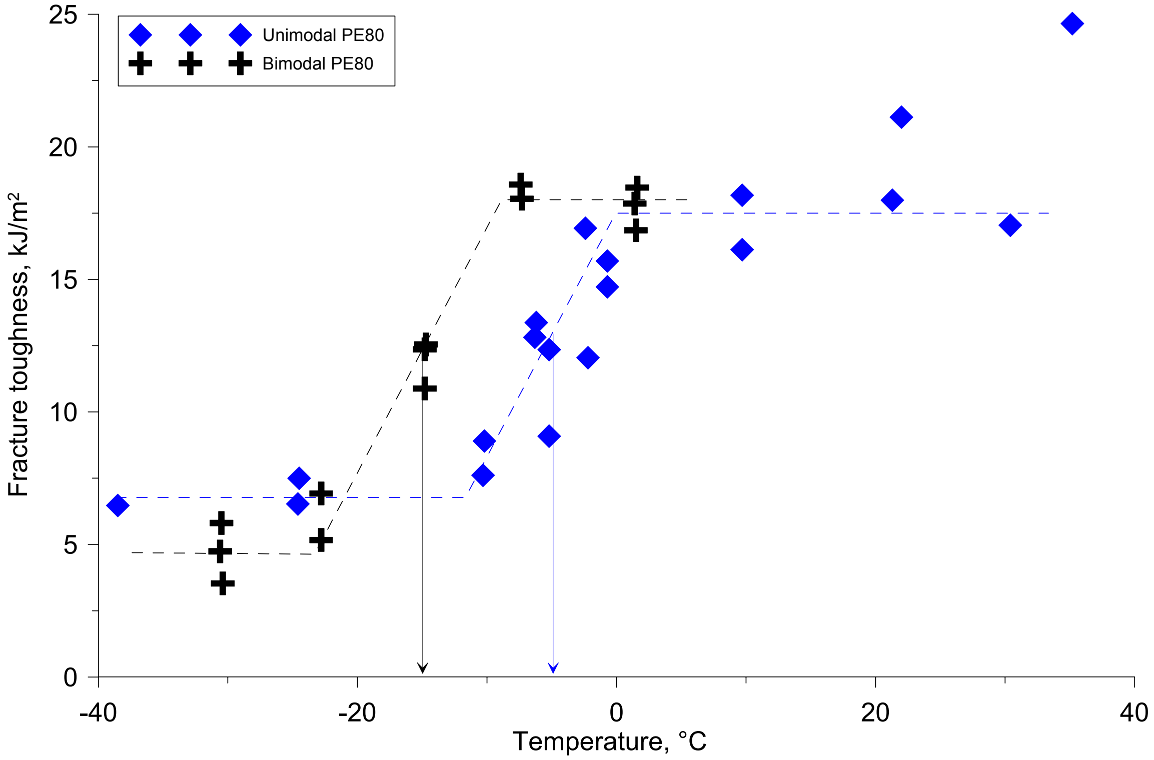

Figure 3. Measured impact resistance vs. temperature for the tested materials. Both materials show clear transition temperatures between ductile and brittle behaviour at –15 °C and –5 °C respectively.

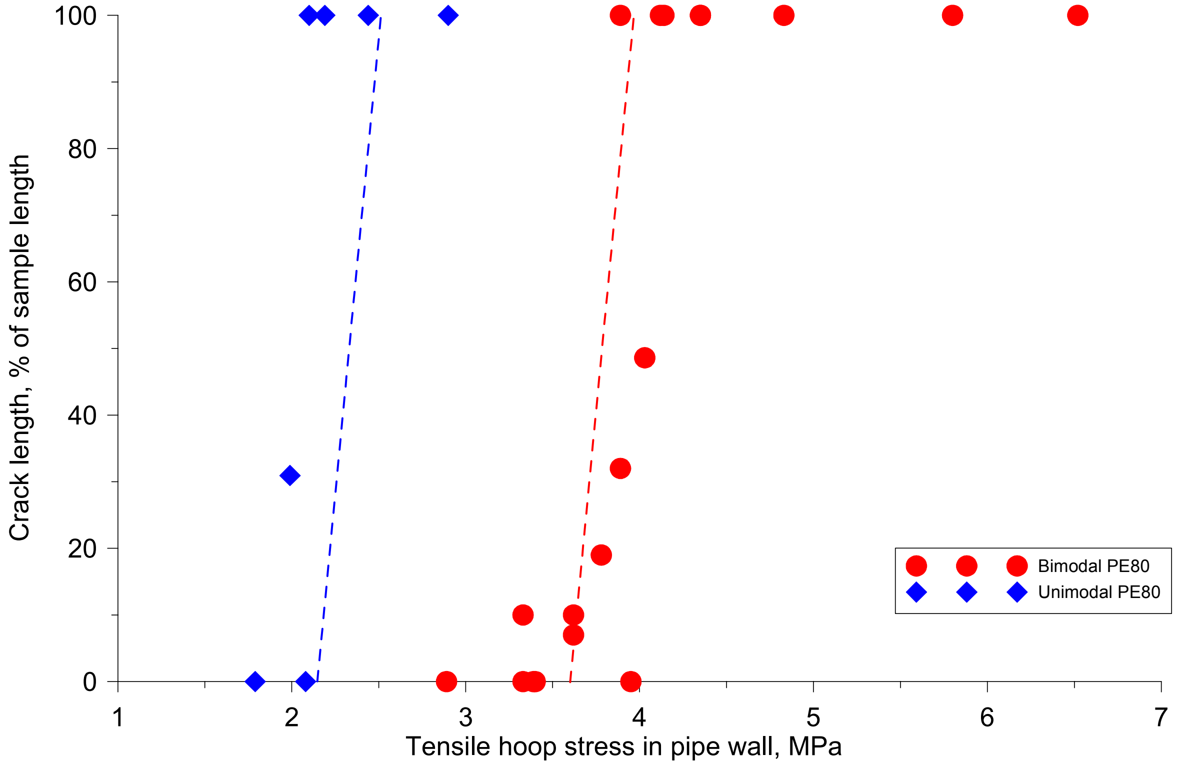

Figure 4. Crack propagation in % of sample length as function of temperature induced hoop stress calculated according to equations (1) to (4) for samples cooled to between -10 °C and -48 °C.

It is fairly unusual that small pipes crack during the EN 253 impact test. Here, however, one small as well as one large pipe of the unimodal material failed the test, table 2. The results are in agreement with the guillotine test, in the sense that the calculated hoop stress is greater than or close to the critical value for the unimodal material and well below for the bimodal material

Table 2. Results from impact testing according to EN 253 at –20 °C. Only the unimodal material cracked at the test. The stress is the calculated temperature stress in accordance with equations (1) to (4) with the reference temperature +20 °C.

Material	Dimension	Sample length mm	Crack	Stress MPa
Unimodal	DN 65/160	1010	**Yes**	1,8
	DN 65/160	1010	—	1,8
	DN 300/500	3150	**Yes**	2,4
Bimodal	DN 65/160	820	—	1,8
	DN 65/160	820	—	1,8
	2×DN 150/450	2350	—	2,3

The large pipe of unimodal material cracked at -25 °C during the handling test, figure 5. All other samples remained intact. Comparisons indicate that a higher stress level, and hence a lower temperature, is required for RCP to occur during the handling test than during the EN 253 and guillotine tests. This may be a consequence of the less violent initiation at the handling test.

Figure 5. After handling test at –25 °C with fracture on material B.

4. DISCUSSION

The tests clearly show that RCP do occur at regular handling of district heating pipe casings, figure 5. Furthermore, there are significant differences with respect to critical temperature between different polyethylene materials. Bimodal materials are significantly safer with respect to brittle fractures.

Figure 6 summarises the impact tests. The theoretical curves are limiting temperatures for significant risk for brittle fracture for different pipe dimensions. They are calculated under the assumption that the limiting stresses observed at the guillotine test are decisive. The dots in the diagram show the results from the other tests. They agree with the theoretical curves, but unfortunately test data are missing at temperatures low enough to promote fracture in the bimodal material.

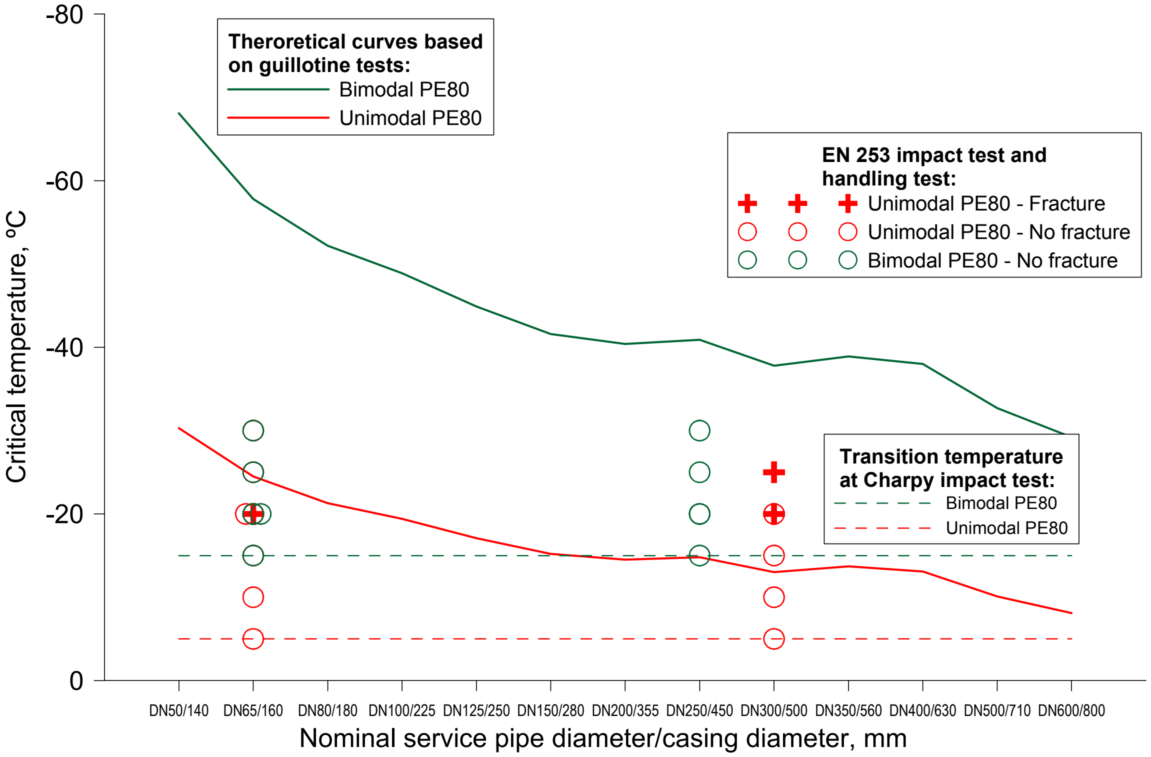

Figure 6. Critical temperature vs. risk for brittle fracture. The curves are calculated assuming that the hoop stress needed for brittle fracture to occur is 2 MPa for the unimodal material and 3.5 MPa for the bimodal material, cf. figure 4. The temperature decrease is calculated from a reference temperature of +20 °C.

With a large pipe and a unimodal polyethylene material, there is a risk for brittle fracture already a few degrees below zero. For smaller pipes, a lower temperature is necessary. For small pipes with bimodal casing material, the temperatures required to promote an RCP crack are so low that they are unlikely to occur in an actual case.

The theoretical limits indicated by the curves are conservative for two reasons. At actual installation work, the pipes are normally stored outdoors for some time prior to installation and the hoop stresses caused by the cooling will to some extent relax. The crack initiation is also important. The curves are based on the guillotine test which is quite extreme—it may be compared to a heavy blow with a sharp axe.

Since only one actual fracture was seen at the handling tests, it is hard to evaluate the correlation between critical handling temperature and the transition temperature at a Charpy impact test. It is obvious that the Charpy test can be used to rank materials with respect to their sensitivity to brittle fracture, cf. the dashed lines in figure 6. With more empiric data, the method could probably also be used to set requirements on toughness properties and material qualification.

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6. ACKNOWLEDGEMENTS

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