Mechanical behaviour of adhesively bonded polyethylene tapping tees

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Abstract

The mechanical properties of adhesively bonded MDPE joints were studied. The lap-shear joints were prepared using PE80 polyethylene gas pipe and four adhesive types; two acrylic and two epoxy resins. The key mechanical properties of lap shear strength and impact resistance were investigated as a function of adhesive type and surface preparation technique. Mechanical abrasion of the PE80 surface increased the strength of the bonds from 40 to 460% for the four adhesives, with the best performing acrylic adhesive having a lap-shear strength of 1.76 MPa and impact strength of 2.5 kJ/m^2. When used to bond PE80 tapping tees to PE80 gas pipe, the acrylic adhesive produced a gas tight seal at both the standard test pressure of 0.4 MPa and at an increased pressure of 0.8 MPa, and outperformed the PE80 tapping tee during shear testing and withstood a maximum of 10 cycles of 175 J during impact testing. These results highlight the potential of adhesive bonding as a method of joining PE80 tapping tees to PE80 gas pipe.

Keywords: Adhesively bonded joint, mechanical properties, PE80 pipe, electrofusion welding

1. Introduction

Polyethylene (PE) has been applied as an effective pipeline material since its introduction in the 1960s [1] and has played an important role in the rebuilding and modernisation of mains gas and water supply networks as well as sewage systems [2]. PE pipes in the form of medium-density polyethylene (MDPE), which has a minimum required strength of 8 MPa and is designated PE80 and high-pressure polyethylene (HPPE) which has a minimum required strength of 10 MPa and is designated PE100, both offer a low cost, fast way to repair or replace old networks with many advantages over metal pipes, such as higher strength-to-weight ratio, ease of jointing, higher impact strength, higher flexibility and higher chemical and corrosion resistance [3-7]. MDPE is considerably more flexible than HPPE, further increasing suitability to site applications and resulting in new and faster ways of installation. When replacing old pipelines, especially iron mains, the new PE pipeline can be inserted (slip lined) inside the old decommissioned pipe, eliminating any need for extensive digging [8-9]. Where services need to be connected, or any fittings need to be installed, a section is removed from the old iron pipe exposing the new PE pipeline inside [10].

Within the gas distribution network, each user is connected to the mains supply using a PE tapping tee fitting which is welded to the PE main pipeline. These fittings were initially affixed using the hot iron technique, where a hot plate is applied to melt the two surfaces before pushing them together to fuse them. This technique was fairly basic and did not guarantee a good quality joint due to the lack of standard practices and material mismatching. Since the 1980s electrofusion welding has become the most widely recognised way of joining PE pipes and fittings [11-13]. The electrofusion process induces a high current through a high resistance wire contained within the moulded PE fitting, which, when energised, becomes hot, melting the surrounding polymer, see Fig 1. The melts are then pressed into contact, creating a fused joint [13]. Electrofusion, however, does not guarantee a perfect joint; where mixing of the two molten parts contained within the fitting does not occur properly, either by surface contamination, part mismatching or a short circuit, only a partial bond will be achieved [14]. Where defects occur in the fusion zone, these can act as stress initiation sites for slow crack growth (SCG) which will propagate through the fused joint, eventually leading to failure [1,3]

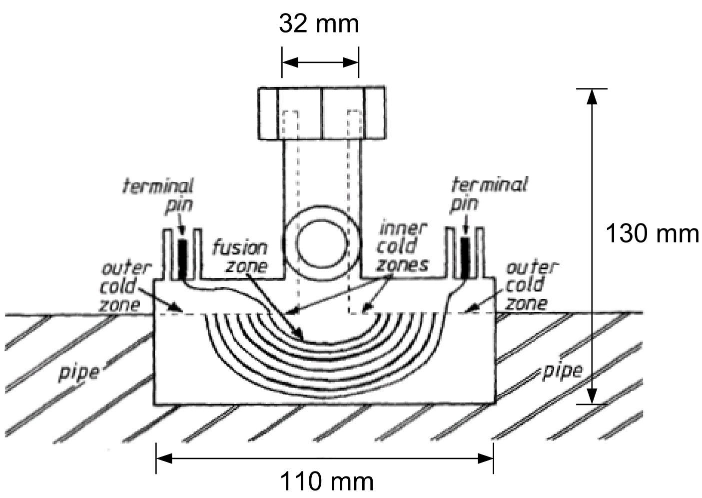


Fig 1 – Schematic illustration of an electrofusion welded tapping tee [13].

The current alternative solution to an electrofused tapping tee is to use a mechanically fixed device which simply bolts around the PE pipe to clamp it into place. Although these alternative fittings can overcome the problems associated with their electrofused counterparts, they are inherently more expensive to fit, restricting their use to small scale installations and repair work.

The possibility of using adhesives as an alternative solution to electrofusion and mechanical fixing of tapping tees has received little consideration due to the difficult nature of bonding PE. Previous attempts to bond PE to PE have resulted in poor mechanical and physical adhesion properties due to its low surface energy [15] and the presence of antistatic agents which can lead to an oily surface, further hindering the effectiveness of the bond [16]. There are a number of methods available to modify the surface of PE and increase its surface energy such as plasma treatment [5, 7, 17-20], UV grafting [6, 21], chemical treatment [22-25] and flame treatment [26]. Although these techniques have been shown to improve the strength of PE to PE adhesive bonds, they are largely impractical for use in the field.

However, with recent developments in adhesive technology, the structural bonding of PE to PE bond may now be a realistic possibility. In recent years, the ability of adhesives to successfully bond to contaminated surfaces has significantly improved, for example heat cured epoxies have good solubility of oil contaminated surfaces when compared to water based adhesives, which simply form a hardened film that slips on top of the oily surface. Scavengers can also be added to most epoxy adhesives to help further disperse surface contamination. These advances in technology mean that there is now the potential of using adhesively bonded PE tapping tees as a replaced for electrofusion welded parts.

This current study will focus specifically on the mechanical behaviour of PE80 tapping tees bonded to PE80 pipe using various commercially available adhesives. In particular the influence of surface preparation and adhesive type on the shear strength, impact resistance and pressure tightness of the bond are investigated.

2. Materials and Methods

2.1 Materials

All substrates used in this investigation were machined from 250 mm diameter, 15 mm thick PE80 yellow gas pipe, manufactured by GPS PE Pipe Systems. The key characterisitcs of this PE80 polymer are given in Table 1. Of the available adhesive types, acrylics and epoxies have both been shown to give the highest bond strength with PE [5, 27]. In this experiment four types of commercial adhesives were selected to bond the PE80 substrates; two acrylic based (WEICON Easy-mix PE-PP 45 and Loctite AA 3038) and two epoxy resins (Polywater BonDuit and Polywater PowerPatch), see Table 2. All four types are liquid, cointaining 100% adhesive components which can be applied or used at room temperature and have been designed for fast structural, high strength bonding of low energy plastics such as PE and present no potential problems regarding solvent fumes.

Table 1 – Physical and mechanical properties of the PE80 polymer supplied by GPS PE Pipe Systems

Material	Thickness (mm)	Density (g/cm^3)	Tensile strength (MPa)	Heat distortion temperature at 0.46 MPa (°C)
PE80	15	0.93-0.95	14-22.8	47-77.8

Table 2 – Adhesives selected for the study (Manufacturer's data)

ID	Adhesive type	Details	Brand	Indicative properties	
				Density (g/cm^3)	Tensile strength (MPa)
A	Acrylic	Two-component construction adhesive. Bonds low energy plastics without pre-treatment	WEICON Easy-Mix PE-PP 45	1.07	13
B			Loctite AA 3038	1-1.2	13
C	Epoxy	Two-part adhesive for joining HDPE conduit	Polywater BonDuit	<2	7-10
D		Two-part adhesive for sealing and repairing PE insulated electrical equipment	Polywater PowerPatch	1.4-1.7	7-10

2.2 Tensile lap-shear testing

Tensile lap-shear joint specimens were prepared in accordance with ASTM D1002-99 standard using strips of PE80 pipe (140 x 25 x 15 mm thick) bonded with adhesive types A to D. Prior to bonding, the specimens were divided into two sample sets; one set was degreased with acetone and wiped with a dry cloth, the second set was abraded with 120-grade emery paper of grit size 125 μm until no evidence of surface gloss was visable and then wiped with a dry cloth. The specimens were then bonded in a single lap-shear joint geometry with a nominal adhesion area of 25 x 50 mm, see Fig 2 [28] . Any excess adhesive at the interface was expelled out by rolling the joint at a load of 0.5 kg which resulted in a joint thickness of around 0.5 mm [5]. The specimens were then cured at room temperature and ambient humidity for 24 h. The bonded area of each specimen was then measured and recorded prior to testing. In total 10 lap-shear joints were prepared using this method for each adhesive type; 5 samples with abraded contact surfaces and the other 5 without. In additon to the lap shear joints, 5 tensile test dog bone specimens of gauge width 10 mm were machined from the 140 x 25 x 15 mm thick PE80 pipe strips to allow comparison between the adhesive joints and an electrofusion joint, which should be as strong as the substrate material it has bonded [13].

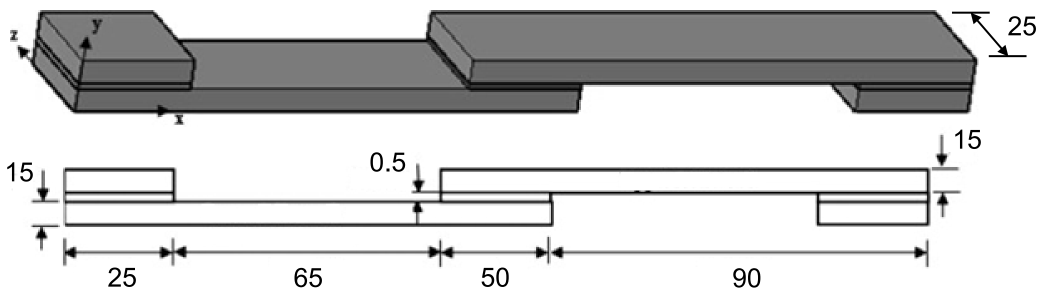


Fig 2 – Specimen geometry for single lap-shear adhesive joint (dimensions in mm) [28]

All tensile tests were carried out at 23 °C in accordance with ASTM 1002-99 standard, using an Instron 3382 tensile testing machine with a 100 kN load cell under a crosshead speed of 2.0 mm/min. The lap-shear strength in Pascals (Pa) was calculated as the measured peak load divided by the true surface area of the bond. The tensile strength of the PE80 sample was calculated as the measured peak load divided by the cross-sectional area of the dog bone specimen.

2.3 Impact testing

Impact testing was conducted with the best perfoming acrylic and epoxy adhesives and surface finish configurations from the initial tensile lap-shear tests. The test specimens were prepared in a lap-shear configuration in accordance with BS EN ISO 9653:2000 standard, with a bond area of 25 x 25 mm, see Fig 3 [29].

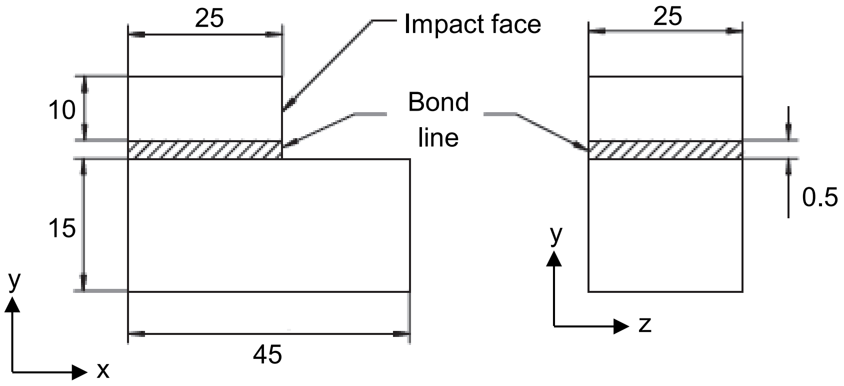


Fig 3 – Specimen geometry for impact testing

(dimensions in mm) [29]

Testing was carried out at 23 °C using an Instron Dynatup MiniTower with a hemispherical striker of nose radius of 20 mm and mass of 1.175 kg. The specimens were mounted by placing them in a machined recess in the fixture jig and securing with the clamping screw as shown in Fig 4 [29]. The striker was dropped on the centre of the impact face at an initial velocity of 1 m/s and then the drop height was increased in 5 mm increments until the test sample fractured. The impact strength was then calculated as the impact energy, which was in the range 0.61 to 1.58 J, divided by the surface area of the bond. The results for 5 samples of each adhesive tested are presented.

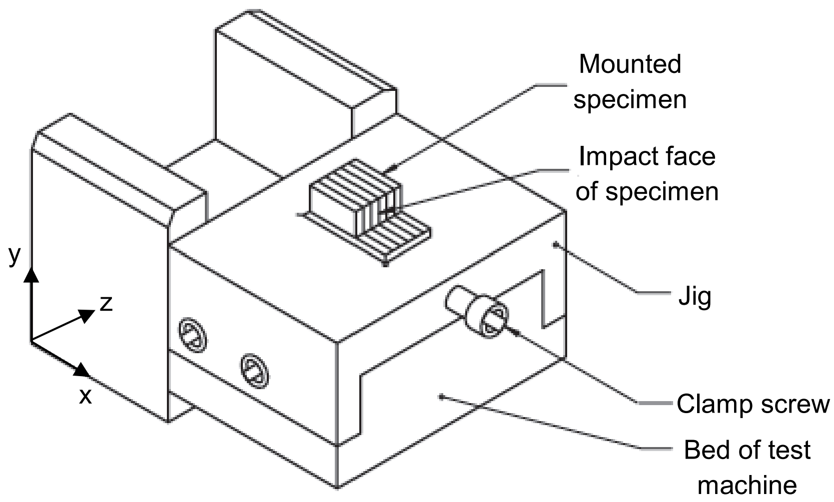


Fig 4 – Test fixture for impact testing

(dimensions in mm) [28]

2.4 Tapping tee adhesion testing

The adhesion strength of gas pipeline tapping tees was conducted using the best perfoming acrylic and epoxy adhesives and surface finish configurations from the initial tensile lap-shear and impact tests. The tapping tees were standard DuraFuse, electrofusion type with integrated cutter, having a 90 mm saddle fitting and 32 mm offtake with an overall bond area of 0.01 m^2, see Fig 5. Seven of these tees were bonded with each adhesive type to 90 mm diameter, 15 mm thick PE80 yellow pipe at room temperature and ambient humidity, under a clamping force of 10 N which was applied via two adjustable steel straps around the circumference of the tee to pipe assembly, see Fig 5. After 15 min the clamping force was removed and the specimens were then cured at room temperature and ambient humitiy for a further 24 h. Once cured the assemblies were subjected to a series of test procedures.

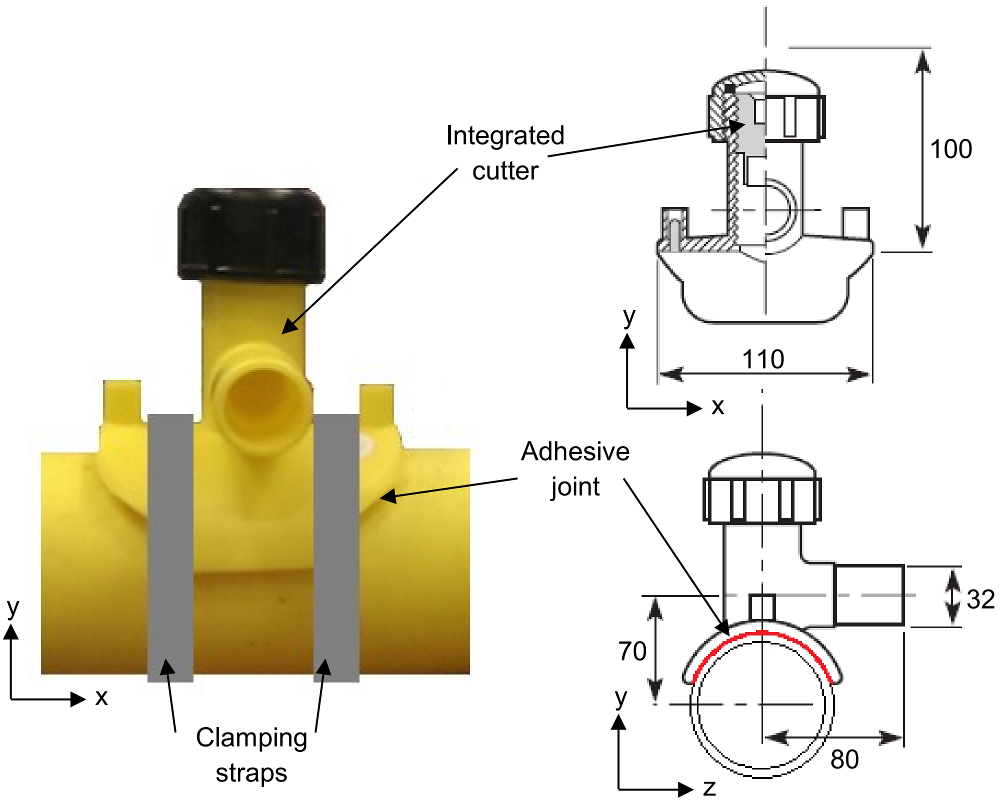


Fig 5 – Tapping tee and PE80 pipe test assembly

(dimensions in mm)

Integral cutter test

This test involved using the tapping tees integrated cutter to bore a hole through the PE80 pipe on to which it had been previously bonded, whilst monitoring the adhesive joint for any signs of failure. To replicate conditions in a pipeline trench, the pipe was fully supported along its base to prevent downward movement and clamped down at both ends to avoid rotation. The cutter was then driven via its own 3/4" BSP screwthread until a 21 mm diameter blank had been removed from the pipe. No additional support was applied to the tapping tee during the test.

Shear test

This test involved shearing the tapping tee from the pipeline by driving a flat-plate tool into the edge of the saddle at a contant velocity of 2.0 mm/min, see Fig 6. Tests were carried out at 23 °C using an Instron 3382 tensile testing machine with a 100 kN load cell. Prior to testing, the pipes were filled with concrete to improve rigidity and aid clamping to the machine bed via a screw thread and bar which were passed through a central tube in the concrete

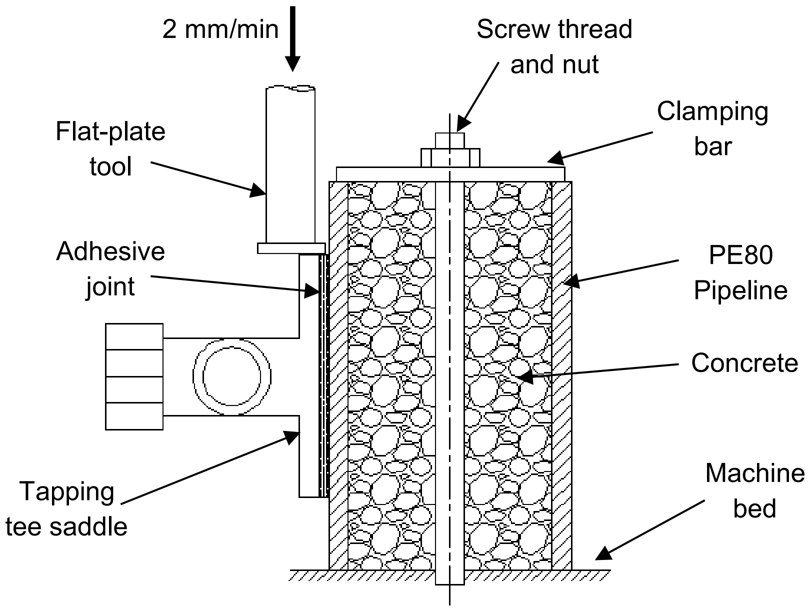


Fig 6 – Tapping tee and PE80 pipe shear test experimental setup

Impact test

Impact tests were performed on the tapping tee to pipeline joint, using a 10.5 kg, custom made steel impact ring which was dropped around the outer circumference of the pipe, striking the edge of the saddle, see Fig 7. The impact energy was set at 175 J and the impact ring was repeatedly dropped for a maximum of 10 cycles or until the test sample failed.

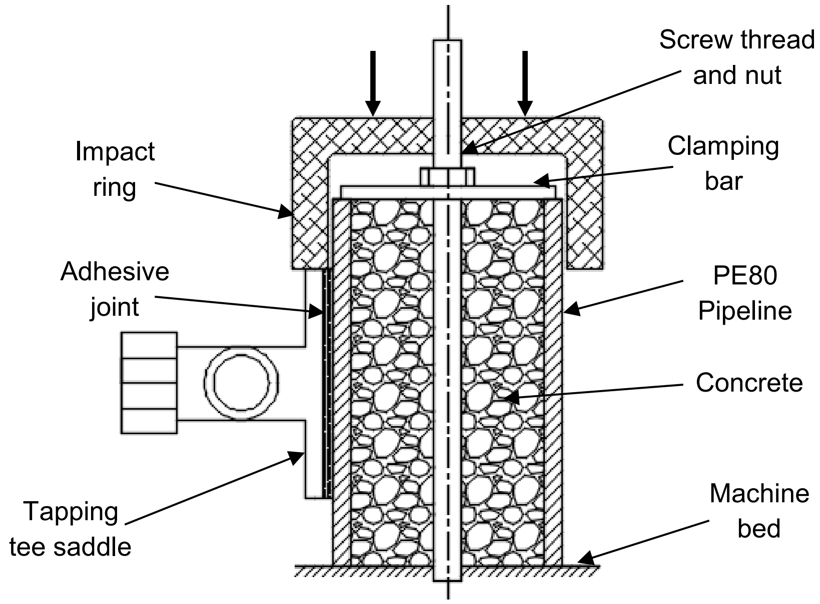


Fig 7 – Tapping tee and PE80 pipe impact test experimental setup

Pressure test

Pressure testing of the adhesively bonded tapping tees was performed in accordance with BS EN 12117 standard. The tee was fitted with a pressure valve cap and then pressurised with air to 0.4 MPa and then 0.8 MPa using a Ring RFP1 pump. The full assembly was then submerged in a water tank for 24 h after which the pressure drop was measured.

2.5 Fractography

All samples were closely observed during testing and the fractured surfaces of the joints were examined afterwards using a Nikon LV-100 upright microscopy system. Surface roughness measurements were performed in accordance with ISO 4287 standard using an Alicona InfiniteFocus microscope at x5 magnification. Results presented are based on 10 roughness average (Ra) measurements per sample.

3. Results and Discussion

3.1 Tensile lap-shear testing

Results of mean and range of lap shear strength for the four adhesive types, bonded to the PE80 pipe with both cleaned as-received and abraded surfaces, are shown in Table 3, along with results for the tensile strength of the raw PE80 pipeline. Typical lap shear stress-strain curves are presented in Fig 8a and 8b respectively.

Table 3 – Shear strength values for the four adhesives bonding the PE80 pipe

ID	Surface preparation	Shear strength (MPa)	
		Mean	Range
A	Cleaned	1.27	+0.3 -0.15
	Abraded	1.76	+0.29 -0.27
B	Cleaned	0.69	+0.37 -0.38
	Abraded	1.27	+0.12 -0.07
C	Cleaned	0.21	+0.04 -0.06
	Abraded	1.18	+0.32 -0.21
D	Cleaned	0.26	+0.04 -0.04
	Abraded	0.88	+0.11 -0.13
PE80 pipe	N/A	19.95 (tensile)	+1.43 -0.84

As can be seen from Table 3, the mean tensile strength of the PE80 pipe is 19.95 MPa, which is over ten times higher than the shear strength results recorded for the various adhesive lap joints, which were in the range 0.15 to 2.05 MPa. Of the four adhesives, the acrylic, types A and B, performed better than the epoxy resin, types C and D, for both surface preparation techniques.

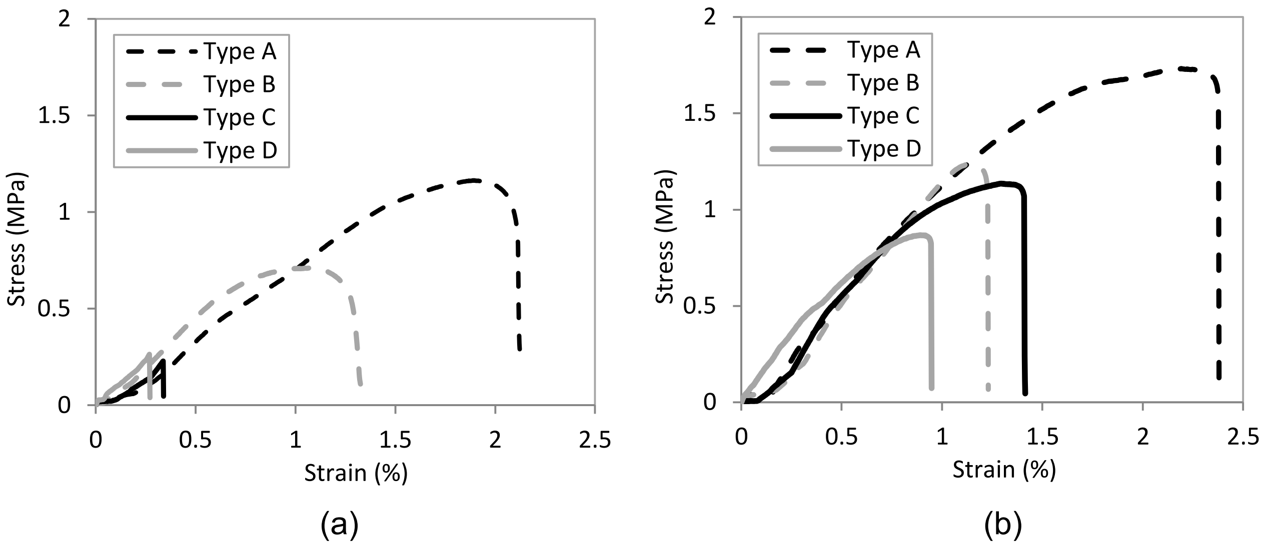


Fig 8 – Typical lap shear stress-strain curves for the four adhesive types (a) cleaned as-received, (b) abraded.

The strongest adhesive was type A, which achieved mean results of 1.27 and 1.76 MPa for cleaned as-received and abraded samples respectively. Abrading the PE80 surface prior to bonding gave a significant increase in shear strength for all four adhesive types but was most notable for the epoxy resins, particularly type C where the mean shear strength was improved from 0.21 to 1.18 MPa. These increases can be related to changes in the topography of the cleaned and abraded surfaces of the test specimens, as shown in Fig 9. The micrographs reveal a high level of surface roughness in the range 5.05 to 6.83 μm Ra for the 10 abraded specimens when compared to that of the 10 cleaned as-received samples which were in the range 1.35 to 1.79 µm Ra. These surface imperfections serve as locations where the adhesive can enter and mechanically bond with the adherent thus significantly increasing the lap-shear strength [30].

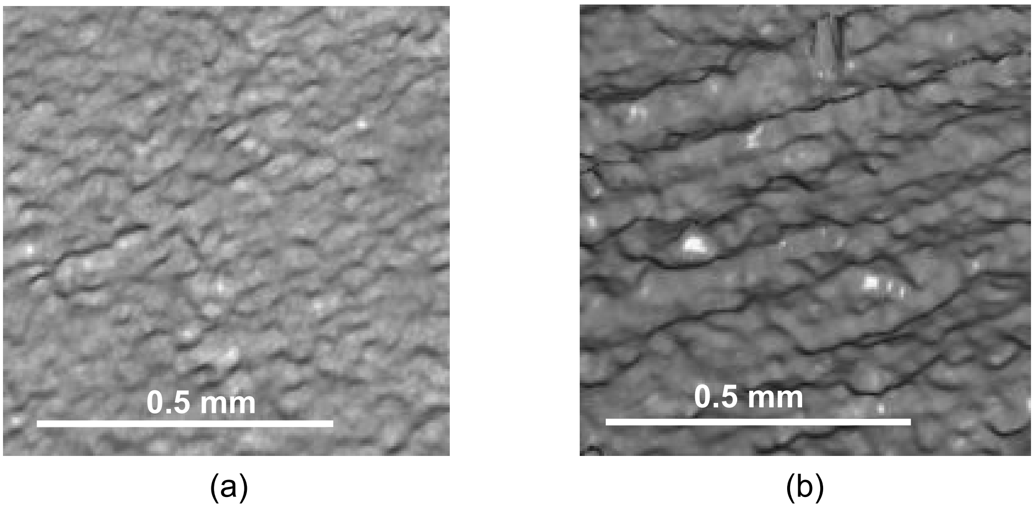


Fig 9 – 3D Optical micrographs of surface topography for
(a) cleaned as-received, (b) abraded.

As shown in Fig 10 there are four main failure modes associated with lap shear tests [31]. To allow for a true comparison of bond strength, the overlap bond area was pre-calculated using ASTM D1002 standard to ensure that the adhesive joint always failed before the PE80 substrate.

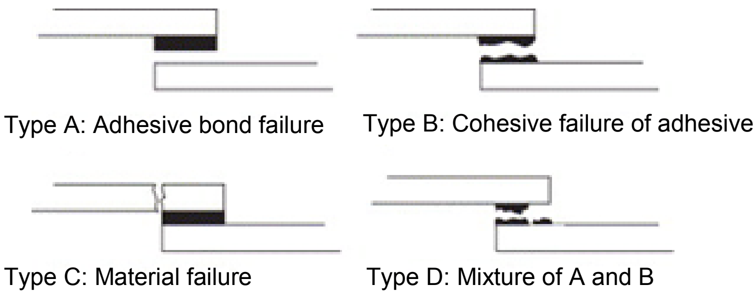


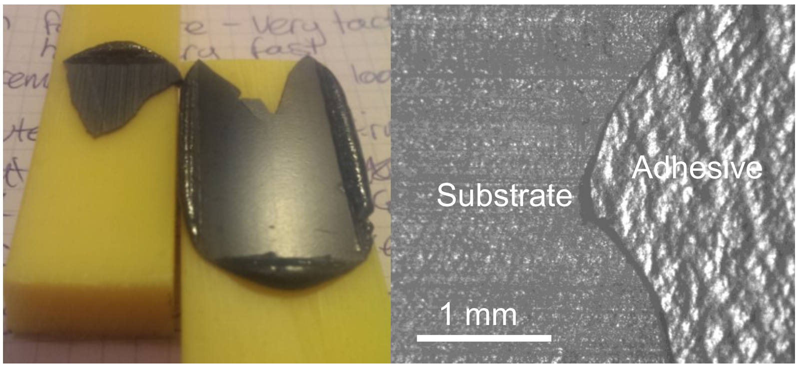
Fig 10 – Typical failure modes during lap-shear adhesion tests [31]

Table 4 shows that the two main failure modes observed were type A: adhesive bond failure and type D: mixture of adhesive bond and cohesive failure of the adhesive, with the exception of the raw PE80 pipe sample which failed in mode type C: material failure. The failure mode varied between acrylic and epoxy resin adhesive types. The acrylic types A and B failed gradually in a peeling nature (Type D failure) whereas the epoxy resin types C and D failed suddenly with an audible fracture (Type A failure).

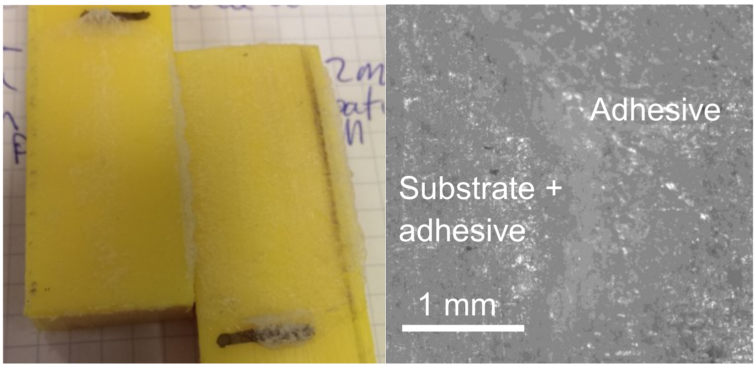
Table 4 – Lap shear test failure modes for the four adhesives bonding the PE80 pipe (Refer to Fig 10 for details of failure mode types)

ID	Surface preparation	Failure Mode	Failure Mode Ratio (Type A:B)
A	Cleaned	Type D	0.90 : 0.10
	Abraded	Type D	0.85 : 0.15
B	Cleaned	Type D	0.95 : 0.05
	Abraded	Type D	0.85 : 0.15
C	Cleaned	Type A	1 : 0
	Abraded	Type A	1 : 0
D	Cleaned	Type A	1 : 0
	Abraded	Type A	1 : 0
PE80 pipe	N/A	Type C	N/A

The morphology of the failure area for the epoxy resin types consisted of large areas of bare substrate where the adhesive to substrate interface had failed (Fig 11a). Whereas the morphology of the failure area for the acrylic types consisted of a mixture of large areas of bare substrate, interspersed with smaller areas of cohesive failure (Fig 11b). As discussed in Section 1, this low ratio of apparent adhesive bond to cohesive strength is typical when trying to bond PE to PE due to its inherent low surface energy [15]. Although it would be desirable to further improve the interface strength to achieve a fully cohesive failure (Type B failure), the shear strength results obtained are already higher than those previously reported for bonding of PE using acrylic and epoxy resin adhesives [27]. Based on these results, a decision was made to take the best performing acrylic adhesive type A and epoxy resin adhesive type C forward to the impact and tapping tee adhesion testing stage.



(a)



(b)

Fig 11 – Failure modes of (a) Type A: adhesive bond failure
(b) Type D: Mixture of adhesive bond and cohesive failure of the adhesive

3.2 Impact testing

Drop weight impact strength results for adhesive types A and C are presented in Table 5. The results of all 5 test samples for both adhesives are consistent, with type A giving the highest impact strength in the range 2.34 to 2.51 kJ/m^2 and type C being 1.83 to 1.96 kJ/m^2. The failure mode for both adhesive types was consistent with those reported for the tensile lap-shear tests in section 3.1.

Table 5 – Drop weight impact strength for adhesive types A and C.

ID	Impact strength (kJ/m^2)	
	Mean	Range
A	2.45	+0.07 -0.11
C	1.91	+0.05 -0.08

3.3 Tapping tee adhesion testing

The first stage of this procedure was to test the performance of the tapping tee integral cutter, which is used to cut a hole in the main PE80 pipeline to permit gas flow through the tee and to the end user. A total of 12 samples, 6 for adhesive types A and C, were cut through with no signs of peeling or movement in the bonded joints. In all cases the removed coupon was retained in the cutter and the holes produced were clean and of the correct shape and dimensions [32]. However, adhesive type C was observed to produce a significant level of swarf debris during cutting, which remained in the PE80 pipeline and could hence cause problems with the quality of gas delivery.

The next stage was shear testing. Results of mean and range of shear strength for the 3 tapping tee assemblies bonded with adhesive types A and C are shown in Table 6.

Table 6 – Shear strength of tapping tees bonded with adhesive types A and C.

ID	Shear strength (MPa)	
	Mean	Range
A	1.08	+0.05 -0.05
C	0.87	+0.02 -0.03

The mean shear strengths were 1.08 and 0.87 MPa for tapping tees bonded with adhesive types A and C respectively, which are similar to values reported for the lap shear tests in Table 3. However, the failure modes for the two sample types were very different. All 3 type C samples failed catastrophically in an adhesive manner (see failure Type A, Fig 10), with failure occuring at the adhesive to substrate interface, see Fig 13b. This failure is depicted by the sharp decrease in load at 10 mm displacement on the load-displacment curve in Fig 12. For type A, the PE80 tapping tee failed before the adhesive bond for all 3 samples. This mechanism is clearly understood by comparing the load-displacement plot in Fig 12 with the image of the tapping tee failure in Fig 13a. After the ram makes initial contact with the PE80 tapping tee, the load rapidly increases to 10 kN at 10 mm displacement, at which point the tapping tee saddle yields and fails in shear and the ram tears the material downwards until it makes initial and then permananent contact with the oulet pipe of the tapping tee at around 28 and 33 mm respectively. After this point the force rapidly increases again until the PE80 oulet pipe begins to yield before, finally, the test is stopped at 50 mm displacement.

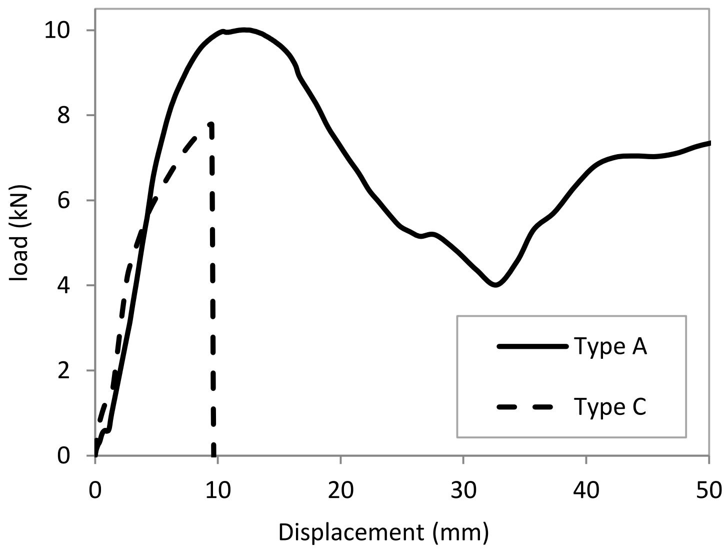
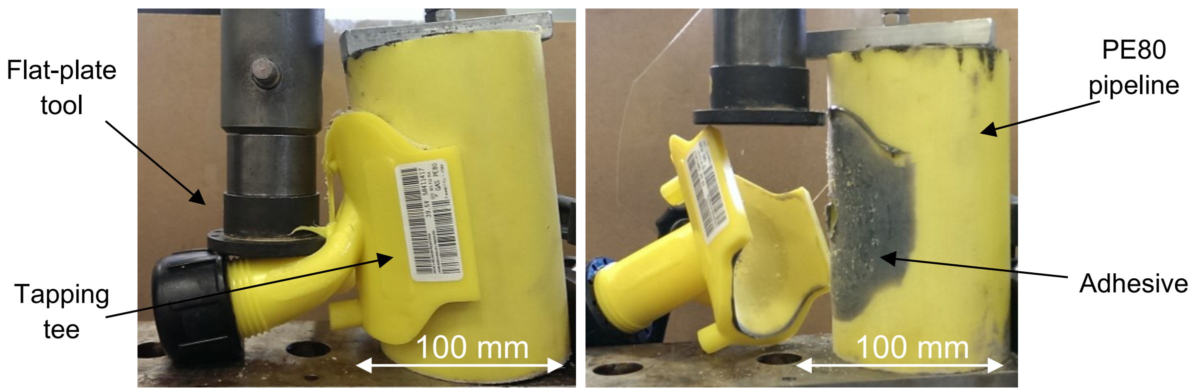


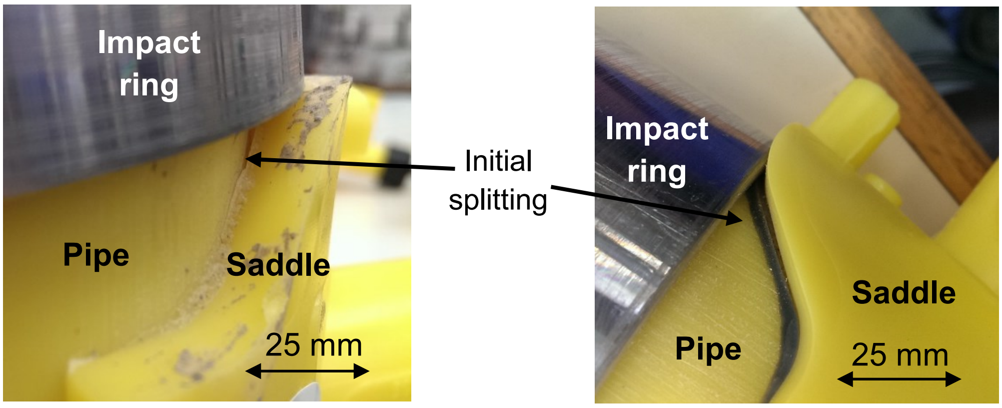
Fig 12 – Typical load-displacement curves for tapping tee assemblies bonded with adhesive types A and C.



(a) (b)

Fig 13 – Shear test failure modes of tapping tee assemblies bonded with (a) adhesive type A, and (b) adhesive type C.

Following shear testing, a further 3 tapping tee assemblies, adhesively bonded with adhesive types A and C, were subjected to impact testing. The tapping tees assembled using adhesive type A all withstood the maximum number of 10 cycles at 175 J without complete failure. An initial split was observed on all 3 samples after 3 cycles (Fig 14a), but this remained stable and did not propagate further during the remaining 7 cycles. Conversely, the 3 tapping tees assembled using adhesive type C also all split after 3 cycles (Fig 14b) but then went on to fail catastrophically after 5-6 cycles. The failure mechanism was again adhesive, the same as that observed during the shear testing, see Fig 13b.



(a) (b)

Fig 14 – Initial splitting of tapping tee assemblies during impact testing, bonded with (a) adhesive type A, and (b) adhesive type C.

The final stage of the tapping tee testing programme was a pressure check in water to ensure that the adhesively bonded joints were gas tight. No visual leaks or decrease in gauge pressure, from its initial set point of 0.4 MPa, were observed for the tapping tee assemblies bonded with both adhesive types A and C. A further test was then conducted in which the standard pressure was doubled to 0.8 MPa. Again there was no decrease in pressure.

4. Conclusions

This work has highlighted the potential of adhesive bonding as a method of joining PE80 tapping tees to PE80 gas pipelines. Four adhesive types, two acrylics and two epoxy resins, were used to bond samples of PE80 pipe with both cleaned as-received and abraded surfaces. The specimens were then subjected to a series of lap-shear strength and impact tests which highlighted two adhesives, WEICON Easy-Mix PE-PP 45 and Polywater BonDuit, as having the highest bond strengths of 1.76 and 1.18 MPa and impact strengths of 2 and 2.5 kJ/m^2 respectively, when bonded to abraded PE80 surfaces.

These two combinations were then used to bond PE80 tapping tees to PE80 pipe for further shear, impact and pressure testing. Results showed that both adhesives were able to produce a pressure tight seal at both the standard test pressure of 0.4 MPa and at an increased pressure of 0.8 MPa. However, the WEICON acrylic adhesive performed best on the mechanical tests, where it withstood a force of 10 kN and outlasted the PE80 tapping tee in the shear test and endured the maximum of 10 cycles of 175 J during the impact test. The performance of the Polywater epoxy resin was inferior and failed adhesively during the shear test at a force of 8 kN and during the impact test after 5-6 cycles of 175 J.

Although this work has highlighted the potential use of adhesives to bond PE80 pipeline, all tests were performed at room temperature (23°C) and do not consider potential changes in temperature in the field. Future work will therefore focus on testing adhesive joint performance across an extended operating temperature range of −20 to +40 °C.

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