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Acoustic Properties of the Elastomeric Materials Aqualene™ and ACE™

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Abstract
An important aspect of coupling ultrasound into a component is the ability to maximise transmission by matching acoustic impedance. Another consideration in ultrasonic testing is the relative velocities of the coupling and tested materials so as to provide effective angles of refraction. The most widely used materials for coupling in industrial applications are water, poly-methyl-methacrylate (PMMA, trade-names Lucite™, Acrylite™, Perspex™) and cross-linked polystyrene (trade-name Rexolite™). However, under some circumstances, the characteristics of the standard coupling materials may not be suitable and it may be desirable to adjust the acoustic parameters to meet the needs of the application. Work has been carried out to produce polymers that can have their acoustic properties adjusted over a range of velocities similar to that of water. Relevant acoustic properties of the materials have been measured and comparison is made to other polymers commonly encountered in NDT applications.

Keywords: Polymer, acoustic impedance, velocity, attenuation

1. Introduction

Acoustic properties of polymers are rarely considered by bulk plastics manufacturers. Yet these properties can have significant effects on ultrasonic tests of the materials or when ultrasonic equipment is made using these materials. A review of the literature often finds a wide range of variation for the acoustic velocities published for even the same polymer. A good example is polyethylene (PE). PE can be obtained in several forms based on density; high-density polyethylene (HDPE), medium-density polyethylene (MDPE) and low-density polyethylene (LDPE). There is also a variety called ultrahigh molecular weight polyethylene (UHMWPE). The source of the different densities is the number of branched carbon chains. However, molecular length, branching of the molecular chains, processing temperatures, extrusion effects in aligning the chains, additives, etc. are all factors in the variations that researchers have reported for acoustic velocity.

Table 1 indicates the range of velocity reported from several on-line sources for PE.

Table 1 Range of velocities reported for Polyethylene

Source	Velocity quoted (m/s)
www.KayeLaby.NPL.co.uk	2100-2400
www.therm-a-guard.com	2210
www.ONDT.com (materials properties)	2460
www.nde-ed.org/GeneralResources/MaterialProperties/UT/ut_matlprop_plastics.htm	2670

Unless they are aware of these potential variations, the user of polymers for ultrasonic applications may not obtain consistent results.

In this paper, polymer materials developed by Innovation Polymers, (Kitchener, Ontario, Canada) are considered for use in industrial ultrasonic imaging. These are based on two classes of polymers. One is a thermoset polymer called Aqualene™ . The other is a thermoplastic polymer referred to as ACE™ (Acoustic Coupling Elastomer).

These two materials were previously introduced [1, 2] as single entities. However, Innovation Polymers' development of the materials over the past few years has provided each with a range of properties that can be used to optimise their use for selected applications.

In addition to the acoustic properties, selected mechanical properties are provided in this paper.

Aqualene™ and ACE™ are based on divinyl olefins with variations in the curing processes and additives to adjust hardness, attenuation and acoustic velocities. Property variations can also occur due to differences in the forming processes used. The forming process can be by injection moulding or compression or transfer moulding. The forming process and variations in injection pressures and injection-head temperatures are also factors that can change acoustic and mechanical properties.

In this paper, several formulations of these materials are evaluated with respect to their compression wave phase velocities and attenuation coefficients determined as functions of frequency. The shear mode in these materials is extremely attenuated and as a result no reliable measurements were made using the shear mode.

Properties as they apply to medical phantom applications as a tissue-mimicking material have been discussed [3, 4]. Saletes' paper [3] reports in detail, the equipment and steps used to characterise the acoustic properties.

This paper extends the property analysis started by Saletes *et al* [3] by examining a variety of variations on the formulations with a view to address the concerns for industrial applications.

2. Measurement set-up and procedure for phase velocity and attenuation

A standard through-transmission immersion setup as illustrated in Figure 1 was used to determine both the attenuation and acoustic velocities of the compression mode.

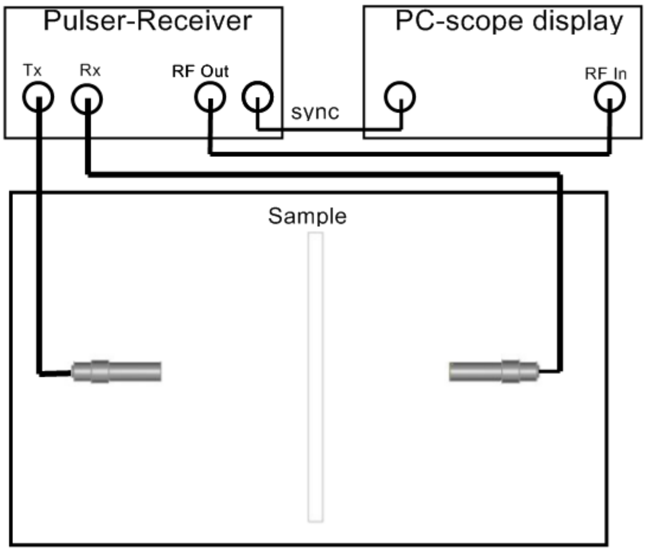

Figure 1 Measurement setup

Measurements were made at 23°C. Material samples were uniform flat sheets with variability in thickness on the order of 0.1mm. Matched pairs of transducers were used, with resonant frequencies ranging from 5MHz to 50MHz.

For each pair of transducers, a time-of-flight measurement was made for ultrasound travelling from the transmitter to the receiver. A second time-of-flight measurement was then made using the identical transducer geometry and instrument settings, but with the sample now absent. Time-averaging was used to minimize random noise. The digitized signals were then converted to the frequency domain using a commercial signal processing package.

The compression wave phase velocity of each sample was determined as a function of frequency using the phase-slope technique. Figure 2 shows the two received pulses corresponding to the pair of 10 MHz transducers. The blue trace indicates the response in water alone and the red trace indicates the response with the Aqualene sample inserted in the sound path.

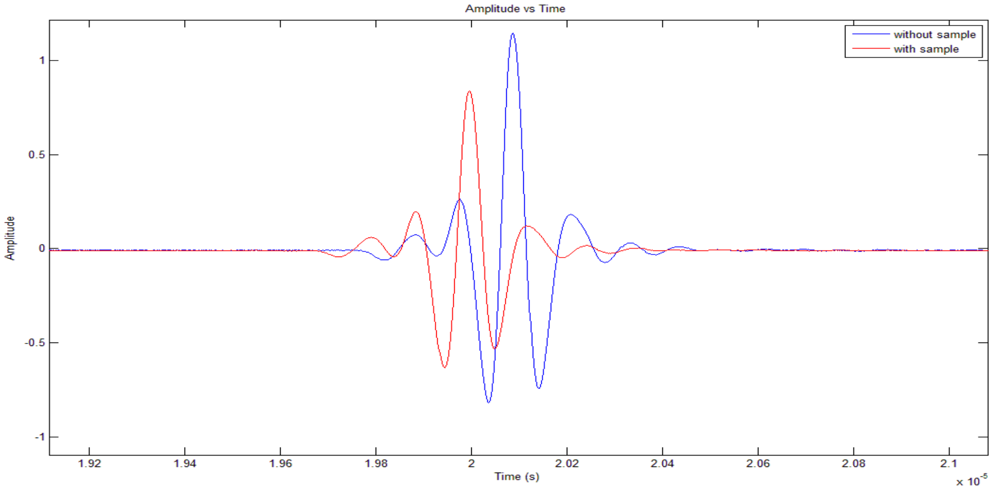

Figure 2 Amplitude vs. time plots acquired with a pair of 10MHz probes through water alone (blue solid line) and Aqualene inserted into the water path (red solid line)

Direct experimental measurement of signal amplitude, with appropriate corrections for diffraction and interfacial reflection coefficients, was used to calculate the attenuation coefficient α(ω) of the samples, summarized as follows:
The Fast Fourier Transforms were calculated corresponding to each pulse captured for the velocity calculations described above. Figure 3 illustrates the magnitude spectra calculated for the signals seen in Figure 2. The spectrum magnitudes were then compared as a function of frequency within the usable bandwidth of each transducer pair.

Wave amplitude is also affected by the divergent ("spreading out") nature of the beam caused by the finite diameter of the transducers. This wave diffraction effect will be slightly different when a polymer sample is in the wave path, as opposed to the case when the sample is absent. For this project, the influence on the calculated value of wave attenuation is very small such that this correction factor may be omitted [5].

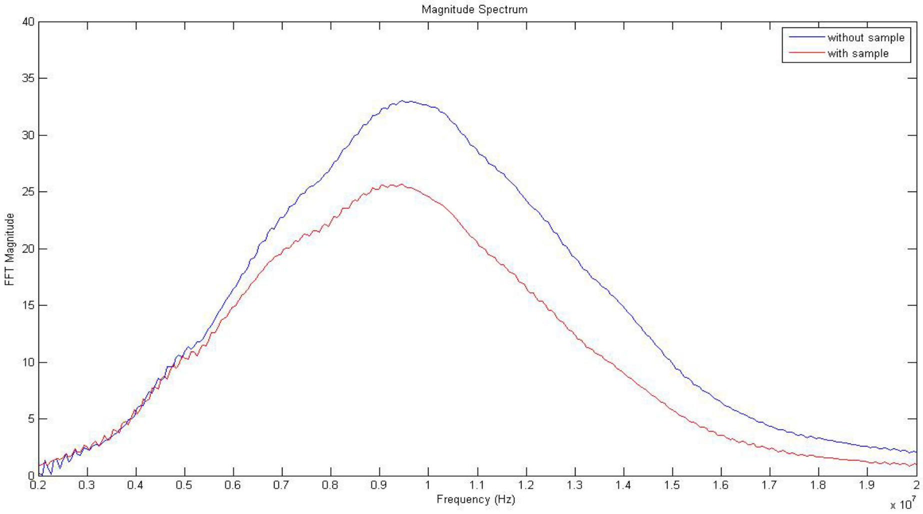

Figure 3 Magnitude spectra of water and Aqualene acquired with a pair of 10MHz probes. Spectrum with the sample present (red solid line) and spectrum with the sample absent (blue solid line)

3. Observations and Results

3.1 Acoustic Velocities

Compression wave phase velocities were calculated for the ACE and Aqualene samples materials at a water temperature of 23°C. The measurements were made multiple times with each set of transducers, each at a separate location on the material. The mean values of the velocity measurements are shown in Figure 4; the vertical error bars represent the standard deviation of the separate trials. The acoustic velocity of ACE rose from 1537m/s at 2.5MHz to 1557m/s at 44MHz, and for Aqualene the acoustic velocity rose from 1574m/s at 2.5MHz to 1578m/s at 47MHz. At frequencies less than 10MHz, the error bars in both materials are less than 0.1%. However, the error values at higher frequencies reach up to 0.8% due to a relatively low signal-to-noise ratio.

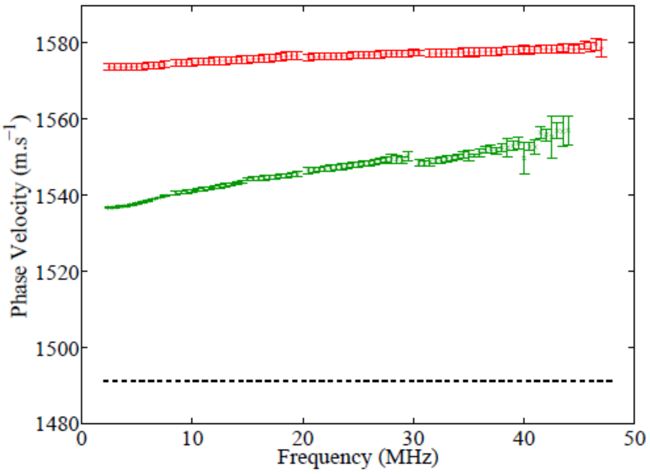

Figure 4 Measured compression wave phase velocity for Aqualene (uppermost curve, red circles) and ACE (middle curve, green crosses) compared to water (black dashed line) at 23°C. Water data is taken from (Bilaniuk & Wong [6]), (original graph from I. Saletes)

3.2. Attenuation

The magnitude spectra were used for the attenuation coefficient calculations. Figure 5 shows the values for the attenuation coefficient as determined by this method of direct measurement of signal amplitude, for both materials.

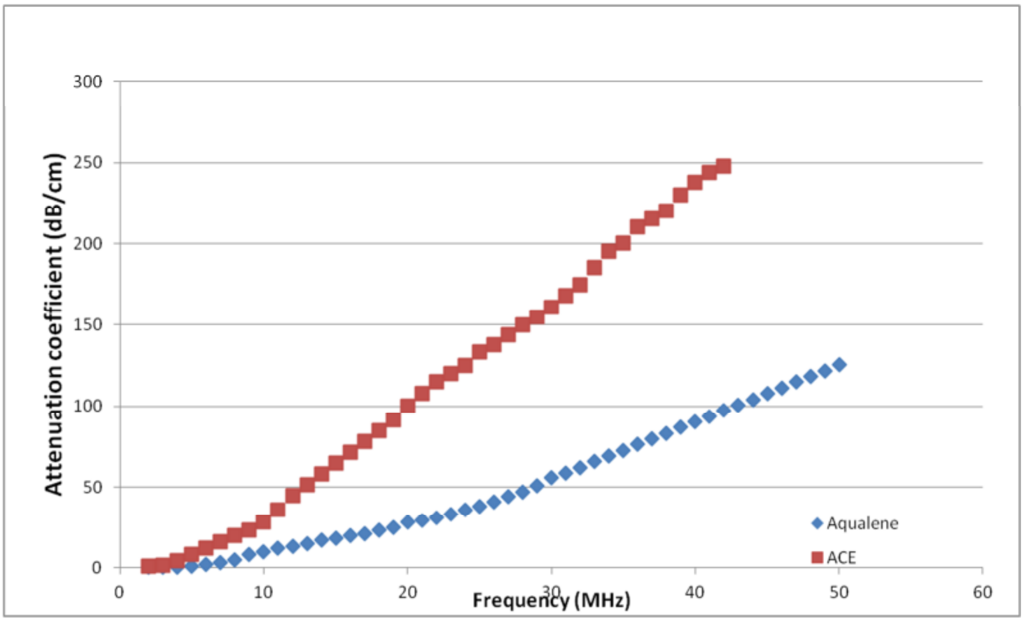

Figure 5 Comparison of attenuation coefficient values for ACE – EPM 400 (upper curve) and Aqualene EPR-320 (lower curve) obtained with the signal amplitude method

It was noted in the Introduction that several formulations of the initial materials have been developed. Velocity and attenuation analyses of the other formulations have been carried out and assembled in tabular form for comparison.

4. Comparison with water and other polymers

From the calculations made using the through-transmission tests, acoustic properties were determined and are tabulated in Table 2. Relative hardness of the various formulations is indicated using the Shore A hardness scale.

Table 2 Comparison of acoustic properties

Material	Velocity (m/s)				Atten @ (dB/mm)				Durometer (Shore A)
	2MHz	5MHz	10MHz	20MHz	2MHz	5MHz	10MHz	20MHz	
Aqualene EPR-M100	1565	1576	1580	1583	0.12	0.483	1.586	3.976	46
Aqualene EPR-M150	1563	1568	1572	1576	0.097	0.396	1.145	3.313	48
Aqualene EPR-M300	1555	1567	1572	1575	0.065	0.295	0.929	2.924	50
Aqualene EPR-M320	1565	1566	1567	1568	0.122	0.369	0.852	1.966	35
Aqualene EPR-M310	1548	1559	1563	1566	0.06	0.264	0.809	2.483	30
Aqualene EPR-M3CB.01	1576	1580	1582	1583	0.086	0.367	1.105	3.324	54
Aqualene EPR-M3CB.1	1561	1570	1573	1575	0.076	0.333	1.019	3.112	52
Aqualene EPR-M3W.05	1551	1564	1568	1571	0.071	0.305	0.914	2.742	45
Aqualene EPR-M3W.5	1565	1567	1568	1568	0.075	0.33	1.016	3.126	50
ACE-EPM M400	1529	1541	1547	1552	0.242	0.992	2.881	8.372	42
ACE-EPM M410	1528	1530	1532	1532	0.274	1.115	3.223	9.316	45
ACE-EPM M420	1586	1604	1615	1624	0.286	1.146	3.273	9.347	80
ACE-EPM M425	1578	1600	1609	1615	1.473	4.453	10.285	23.755	38
ACE-EPM M430	1580	1599	1607	1611	0.292	1.171	3.353	9.599	83
ACE-EPM M435	1557	1575	1584	1591	1.189	3.867	9.437	23.028	30
ACE-EPM M440	1577	1593	1598	1601	1.66	4.709	10.364	22.81	50
ACE-EPM M445	1559	1590	1606	1618	1.072	3.528	8.684	21.377	57
ACE-EPM M450	1577	1588	1597	1605	0.302	1.241	3.614	10.531	68

Some mechanical properties of the polymers developed by Innovation Polymers are provided in Table 3.

Table 3 Comparison of mechanical properties

Polymer	Product Name	Hardness (Shore A)	Sp. Gr.	Elongation %	Tensile (MPA)	Relative texture comparison to Reference polymer
Aqualene	EPR-M100	50	0.94	510	3.3	Aqualene Ref
Aqualene	EPR-M150	52	0.94	NA	NA	Slightly stickier
Aqualene	EPR-M300	52	0.94	NA	NA	Not sticky, easier to tear
Aqualene	EPR-M320	35	0.92	NA	NA	Soft, not sticky
Aqualene	EPR-M310	30	0.93	NA	NA	Soft, not sticky
Aqualene	EPR-M3CB.01	54	0.94	NA	NA	Not sticky, slightly harder
Aqualene	EPR-M3CB.1	52	0.93	740	5.1	Same
Aqualene	EPR-M3W.05	45	0.94	NA	NA	Dry, no tack
Aqualene	EPR-M3W.5	50	0.92	NA	NA	Silicone-feel
ACE	EPM-M400	35	0.92	1200	10	ACE Reference
ACE	EPM M410	45	0.93	550	5	same
ACE	EPM M420	74	0.94	600	2	very stiff and hard
ACE	EPM M425	30	0.93	1000	2.5	Softer and sticky
ACE	EPM M430	74	0.94	800	21	extremely stiff
ACE	EPM M435	30	0.92	1300	28	much softer and pliable
ACE	EPM M440	39		1400	8	slightly less stiff
ACE	EPM M445	57	0.89	800	6	slightly stiffer
ACE	EPM M450	63	0.94	900	32	stiffer, duller & harder

Plotting velocity values for Aqualene and ACE varieties listed in Table 2 indicates a range spanning from about 1525m/s to about 1625m/s at frequencies from 2 to 20 MHz (Figure 6)

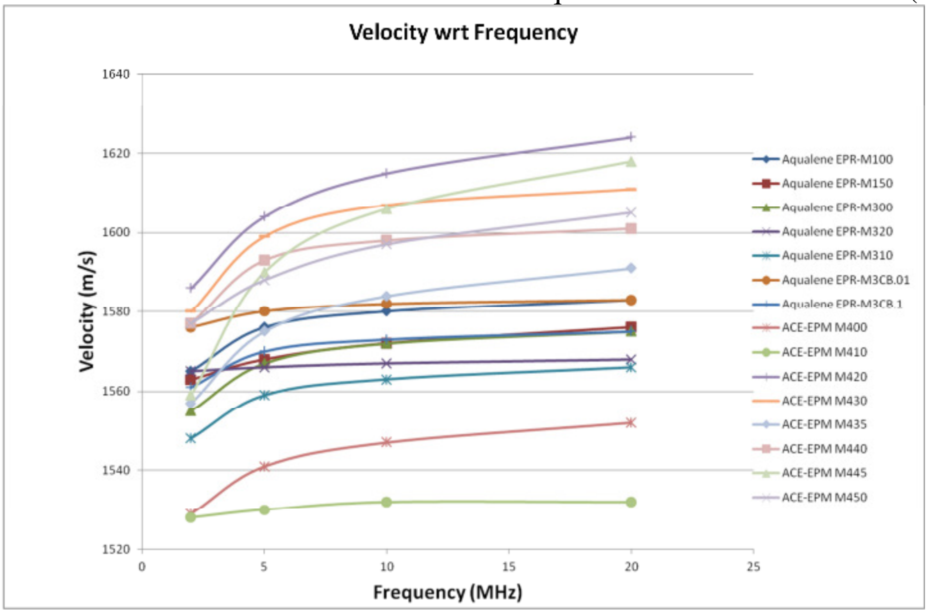

Figure 6 Aqualene and ACE velocities between 2MHz and 20MHz

Plotting the attenuation of the Aqualene and ACE materials against frequency indicates three distinct groups. Figure 7 illustrates how Aqualene attenuation is notably less than ACE, and the ACE data indicate a split into two groups based on attenuation.

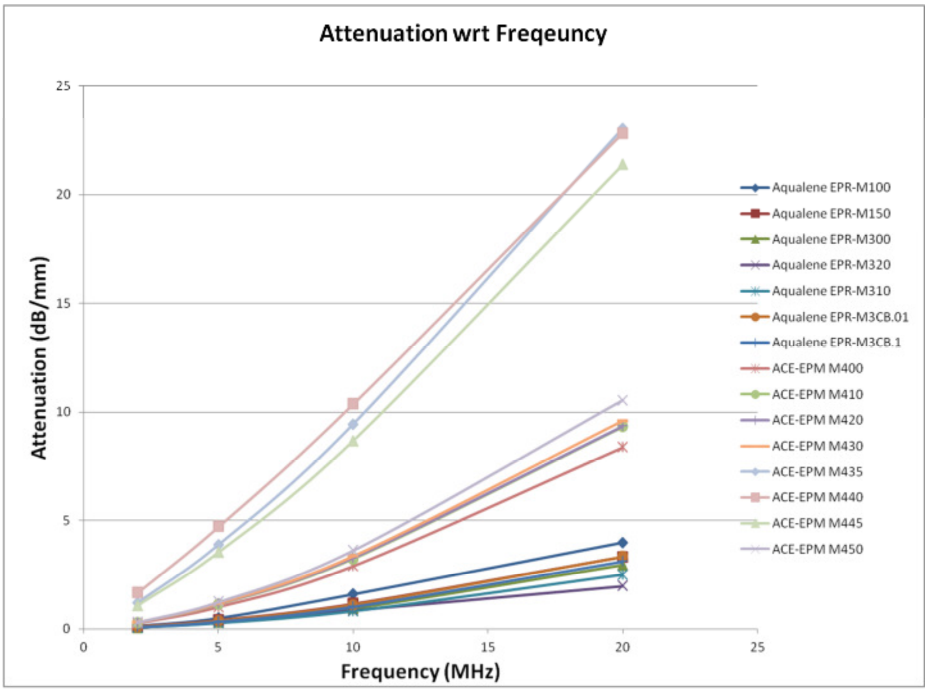

Figure 7 Aqualene and ACE attenuation between 2MHz and 20MHz

To provide a comparison of the attenuation characteristics of Aqualene and ACE to other polymer materials commonly encountered in NDT, Figure 8 shows the Aqualene EPR-320 and the ACE EPM-400 attenuation spectra together with those of a selection of common polymers.

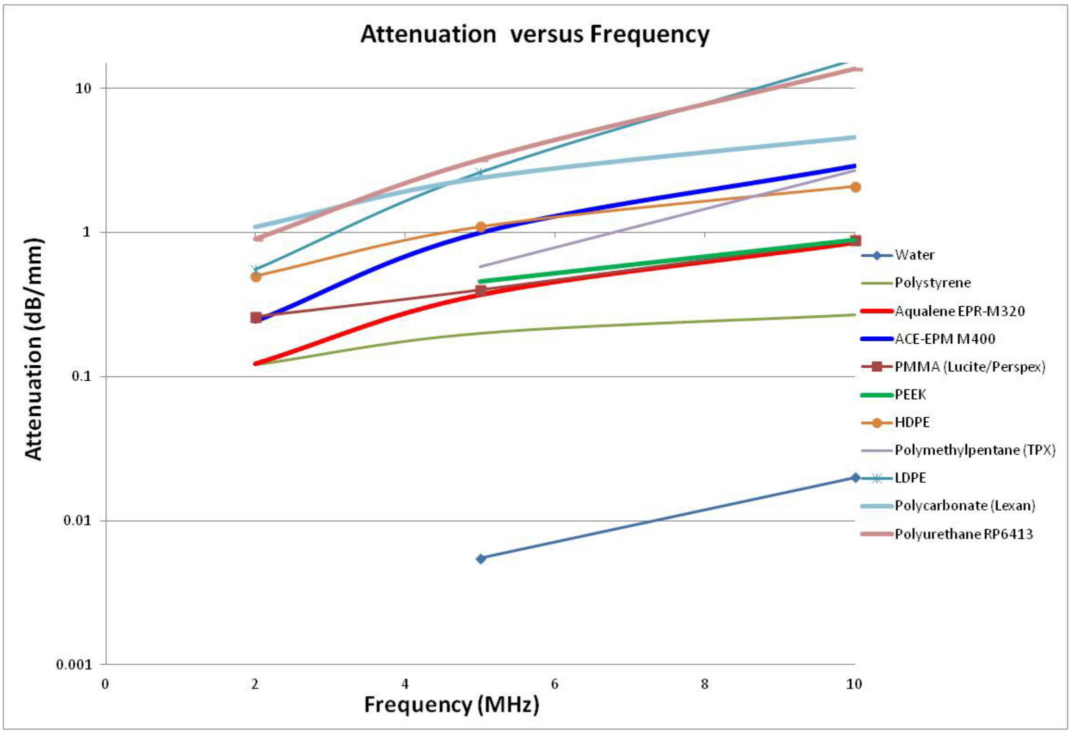

Figure 8 Comparing common polymer attenuations

References for values used in Figure 8:

- Water: Handbook of Reference Data for Nondestructive Testing, ASTM 2002
- Polystyrene & PMMA: Nondestructive Testing Handbook, Vol. 7, ASNT, 1991
- LDPE, Polyurethane & TPX: Laust Pedersen acoustic tables, Onda Corp. http://www.ondacorp.com/tecref_acoustictable.shtml
- PEEK: Carlson et al; Frequency and Temper. Dependence of acoustic properties of polymers. 2003 IEEE Ultrasonics Symposium,
- HDPE & polycarbonate: Szabo & Wu, J. Acoust. Soc. Am., Vol. 107, No. 5, Pt. 1, May 2000

Figure 8 indicates that Aqualene and ACE materials have attenuation values comparable to those of some polymers typically used for refracting wedges in NDT applications. Only polystyrene (Rexolite) has lower attenuation than the Aqualene M320. ACE EPM400 has slightly higher attenuation but is similar to some versions of HDPE and lower than polyurethane, LDPE and polycarbonate (Lexan). Water has been added to the plot in Figure 8 to indicate the large difference (over an order of magnitude) between attenuation values of water and those of the common polymers.

A separate assessment was made of Aqualene (EPR-M300 formula) to determine the change of velocity with change in temperature (dV/dT). For this single assessment, the peak amplitude signal of the bulk waveform was used. The graph in Figure 6 compares this with water and illustrates the typical decrease in velocity with increasing temperature seen in most solids whereas water shows its anomalous trait of a positive dV/dT.

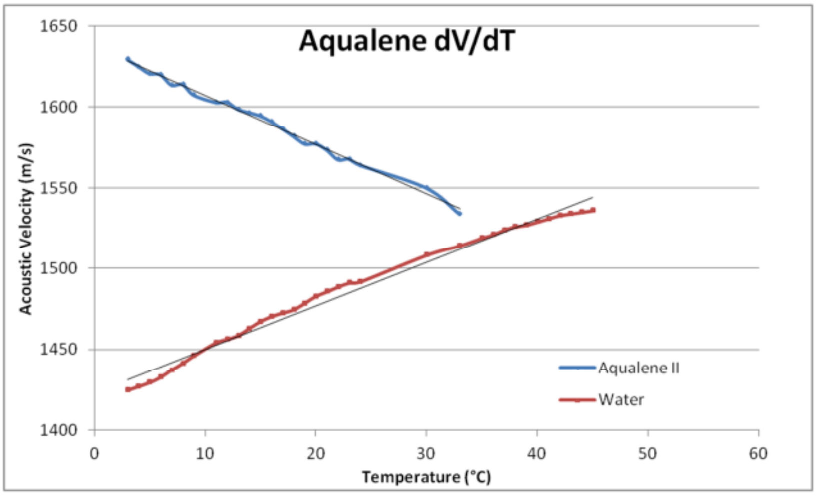

Figure 6 dV/dT of Aqualene in region where water dV/dT is approximately linear

In the region of approximate linear dV/dT of water (between about 5°C and 35°C), dV/dT for Aqualene is approximately -3m/s/°C.

6. Conclusions and Comments

Elastomeric materials have been developed that can be formulated to fine-tune values of acoustic velocity and attenuation. Acoustic impedances of the formulations are near that of water. Compared to water, the attenuation of the materials is higher; however, compared to other elastomeric polymers used in non-destructive testing the attenuation values are relatively low.

Since acoustic parameters are closely linked to mechanical parameters, adjustment of one parameter is rarely possible without changes detected in another parameter. Therefore, selecting a formulation to optimise performance based on one property will unavoidably be a compromise of other properties.

The developers have managed to assemble a range of materials with acoustic velocities near that of water and having a range of hardness from approximately 30 to 70[1] Shore A Durometer. This provides users with material options for acoustic matching to the test piece or to eliminate or reduce the interface signal with water when used as a wheel-probe. Alternatively, mechanical considerations may be important. Then wear, conformability and ability to produce a positive refracting angle when testing joints in low-velocity plastics such as HDPE, might be considered priorities.

Acknowledgements

We would like to thank Dr. I. Saletes and Jill Bond at the University of Toronto for their original work on these materials and allowing us to review the notes relating to their analysis techniques. Their ongoing assistance has been very helpful and is greatly appreciated.

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3. Saletes, I., Bond, J.V., Luo. M., MacNeil, R, Ginzel, E, Sinclair, A.N., Aqualene: a new material for high frequency ultrasonic phantom and equipment calibration, submitted to Ultrasonics for publication June, 2015

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[1] Shore A hardness 30 is approximated by a soft pencil eraser and Shore A Hardness 70 is like an automotive tyre tread