Chapter 2

Mechanical Properties Of Interlayer Materials

For the production of a successful interlayer toughening agent for composite materials, a full understanding of the material and its fracture behaviour should be available. Also, by establishing some basic chemical and mechanical relationships between the material’s constituents before being formed into a composite, important references can be established for any future experimental or numerical modelling study of the material. Accordingly, a primary part of this study was the assessment of fracture and tensile properties of the materials chosen for the interlayer toughening study. In order to obtain a full explanation of the experimental results fracture toughness testing, scanning electron and optical microscopy, Raman spectroscopy techniques and finite element analysis were used. This study served to estimate the toughening potential of the blends, together with establishing basic fracture behaviour and toughening mechanisms as a function of toughening agent content.
2.1 Materials and preparation

The materials used in this study were Dow Chemicals Derakane 8084 vinyl-ester (VE) resin mixed with poly(acrylonitrile-butadiene-styrene) particles (ABS) provided by DENKA Co. of Japan. Four different particle weight concentrations were used: 3.5%, 7%, 11% and 15%. The ABS powder was dried in a vacuum oven for 5 hours at 50°C and mixed with the resin using a high-speed shear blender (SILVERSON L4RT). A satisfactory mixing procedure was achieved by using three different mixing heads using mixing speeds in the range of 7000 and 7500 cycles/min. The blended vinyl-ester resin was then further mixed with additives which serve to control the speed of the resin solidification process. For this purpose 1.5% methyl-ethyl-ketone peroxide (MEKP) was used as a ‘promoter’ (the supplied VE was pre-promoted by the manufacturer with 0.3% of cobalt naphthenate) together with 0.2% of 2,4pentanedione (2,4P) used as a ‘retarder’ in the chemical reaction. After that, the prepared resin was degassed and poured into prepared aluminum molds and left for 24 hours to cure under atmospheric pressure and room temperature. After an initial room temperature cure in the mold, each plate was post-cured at 90°C for 4 hours to ensure uniform material properties.

Neat resin specimens for mode I fracture testing and tensile testing were machined and prepared from cast plates of modified resins according to the ASTM D5405-91a [87] and ASTM D638M-91a [88] testing standards, respectively. Test specimens were cut using a water-cooled diamond saw and dried in a vacuum oven at 50°C for 12 hours, prior to the testing. Also, some of the specimens were polished to obtain optical micrographs of the particle distribution using a Zeiss Axioscope optical microscope. Polishing was carefully conducted using five different grades of sand paper (from 220 to 1200 grit) and 6µm diamond paste, which was shown to be sufficient for the purpose of this study.
The ABS tensile specimens were prepared from commercially available ABS plates obtained from the All Plastics Co. of Australia. The material contained approximately the same amount of rubber as the one used for the blends and therefore possessed almost identical mechanical properties.

For the purpose of Raman studies, there is not a specific size requirement for the specimen. The only constraint is that they are physically small enough to fit under the microscope stage. In order to obtain characteristic Raman spectra, small samples of test material taken from the tensile test program were used and cut to approximately 1cm$^2$ blocks.

2.2 Experimental techniques and modelling

2.2.1 Tensile testing

Uniaxial tensile testing of neat VE, toughened VE and pure ABS plastic was conducted using standard dog-bone specimens according to ASTM D638M-91a [88]. All specimens were machined to have a cross-section at the ‘neck’ of 2.5×3.5mm(±0.01mm) and were tested on an Instron 4505 Universal Testing Machine using strain gauges to measure uniaxial extension of the specimen during the testing. Data were collected for calculating the Young’s modulus, the yield stress and strain, and the failure (break point) stress and strain, for each material.

According to ASTM D638M-91a, the yield point (plasticity onset) is defined as the point where the increase in strain is no longer followed by the subsequent increase in stress (i.e. the maximum stress point in the case of our materials). In this study it was decided to use the 5% offset (of $\varepsilon_{\text{max}}$) yield point as the onset of irreversible deformation, based on observed fracture and yielding behaviour during the test and it
will be discussed in the following text. The definition of the yield point is depicted in Figure 2.1.

Figure 2.1: The typical stress-strain curve obtained from a neat VE specimen with definition of the yield point, being the intersection point of the curve and an offset line drawn from the 5% $\varepsilon_{\text{max}}$ point and parallel to the elastic part of the curve

2.2.2 Mode I fracture toughness testing using SENB specimens

In addition to the tensile testing, mode I fracture toughness of the neat VE and toughened resins was measured using single-edge-notched bend (SENB) specimens according to ASTM D5405-91a [87]. Nominal specimen dimensions were: width $W=16$mm and thickness $t=8$mm with a U-notch milled to a depth of 7mm with a tip radius of 0.5mm. A natural crack was introduced by tapping a new razor blade placed in the U-notch, to produce a total crack length ($a$) in the range $0.45 < a/W < 0.55$. Testing was performed using a three-point bend fixture with a span length ($2L$) of 64mm using a cross-head speed of 10 mm/min.
2.2.3 Raman spectroscopy

The Raman technique [89,90] is a simple one and involves irradiation of a sample with monochromatic light. The majority of this light is elastically scattered unchanged from the sample, but a small fraction will interact with the sample’s vibrational modes and be scattered inelastically (Raman scattering). The variation in wavelength of this Raman scattering will vary with the origin bond in the sample and hence the signal may be collected as a spectrum, and the various peaks that occur can be assigned to specific bonds.

In the field of advanced composite materials, the Raman technique has become extremely important for three reasons. Firstly, like infrared spectroscopy and associated techniques, the Raman technique can provide a spectrum of characteristic bandwidths which can be used to identify the chemical species and bond types present in a material under test. The advantage of the Raman technique over infrared is in the fact that the spectra obtained by the former technique are not masked by the presence of water molecules or hydrolysis products (a big problem with infrared techniques that give strong signals from polar species, such as O-H bonds). The strongest Raman signals originate from symmetrical bonds, such as C-C and C=O. Secondly, the concept of strain mapping has become very useful. This is where a grid or line of spectra is obtained, and so long as an appropriate calibration is available, any shift in characteristic Raman peaks can be attributed to straining of the material, through external or internal stressing. This technique is often used in the detection of interfacial phenomena in composite materials [91–94]. Thirdly, the Raman technique can provide important information on what has now become the most pressing issue in advanced materials research - degradation. Raman analysis of a material both before and after environmental ageing, gives information relating to degradation products and chemi-
cal modification, in addition to quantitative data regarding the change in the relative amounts of two or more species/bond types as ageing progresses. In addition, apart from chemical changes invoked by aging processes, this technique can be successfully used for assessing chemical modifications in constituents after blending. Any positional or size variations in characteristic Raman peaks can be directly linked to changes in the material, either through bond stretching, as with the strain mapping technique, or through chemical changes caused by the degradation or during blending process. It is important to note that although the Raman technique has many advantages over other techniques, one major disadvantage is that if water molecules actually need to be detected (quite common during hydrothermal ageing experiments) the Raman signal associated with O-H stretching is quite weak, and often masked by other species. The use of this technique is therefore limited to the detection and quantifying of changes in other chemical species as a result of water addition i.e. an indirect approach.

An example of this third use is the focus of the current study, where the Raman is used to assist in the identification of any chemical changes that may occur in the vinyl-ester resin on the addition of small amounts of ABS. For this purpose, comparative Raman spectra were obtained for neat cured VE, pure ABS plastic and cured VE/ABS blend, prepared by mixing 3.5% of ABS with VE.

### 2.2.4 Finite element modelling

In order to give more information on some issues raised by the experimental study, a finite element analysis study was initiated. For this purpose a small section $200 \times 200 \mu m$ filled with randomly sized spherical particles, randomly distributed under uniaxial tension loading was modelled. A model of this size was chosen in order to obtain a representative particle distribution, and to maintain the numerical efficiency of the model.
FRANC2DL [74] finite element code was employed to solve the corresponding plane stress model made from approximately 7000 second order isoparametric elements using an elastic-plastic incremental scheme. To obtain the randomness in size and distribution of the particles an algorithm was developed using a uniform random number generator to produce a particle distribution for an area of given boundaries. More details about the algorithm are given in Appendix A. Prior to particle generation, a statistical distribution of ABS particle sizes was devised based on optical micrographs of polished SENB specimens, as shown in Figure 2.2.

Figure 2.2: ABS particle distribution inside a toughened VE - particles are irregular in shape while size varies from 5 to 150 µm

An attempt to accurately simulate the realistic particle distribution would result in a model with extremely large number of elements due to the existence of numerous particles smaller than 5 µm in diameter. This would result in highly numerically inefficient model without improving the quality of the simulation. Therefore, the main objective of the analysis was to simulate accurate particle concentrations (i.e. bulk properties of the material), rather than exact particle size distributions. Nevertheless, the modelled particle size was random but kept between 10 and 150 µm. Also, the irregular particle
shapes visible in Figure 2.2 were neglected, under the assumption that the influence of the particle shape is negligible for this study. This assumption was based on experimental results elaborated in Chapter 4. Material properties used in the analysis were taken from the tensile testing results.

In addition to this model, two further models were developed using regular particle arrays (square and hexagonal) with a uniform particle size of 40µm in diameter (the average particle size used in the random model). The number of elements used in these two regular array models was approximately 5500. The aim of this was to support results obtained from the random model and to estimate the influence of the particle distribution randomness on the tensile properties.

2.3 Results and discussion

2.3.1 Tensile and fracture toughness testing

The main aim of the tensile testing was to establish input parameters for the subsequent numerical analysis and to give a better understanding of the materials’ mechanical behaviour before being applied as toughening agents into the fibre composite. Firstly, the neat VE8084 resin was tested and the results were compared with the material’s typical properties obtained from the manufacturer (Dow Chemicals). As expected, the results presented in Table 2.1 for the VE8084 (i.e. 0% of ABS) reflect excellent agreement with the typical properties obtained by Dow Chemicals [95]. The VE specimens failed after passing the maximum stress point at approximately 8% strain without exhibiting any necking. Although specimen necking was absent, significant whitening was observed even before the maximum stress level was reached.

During the testing, all ABS-toughened VE resins failed at the point of maximum
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<table>
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<th>ABS [%]</th>
<th>E [MPa]</th>
<th>σ_y [MPa]</th>
<th>σ_max [MPa]</th>
<th>ε_max [%]</th>
<th>G_{Ic} [J/m^2]</th>
<th>K_{Ic} [MPa \sqrt{m}]</th>
<th>r_p [\mu m]</th>
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<td>/</td>
<td>/</td>
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<td>1.6(0.12)</td>
<td>1382^\dagger</td>
<td>2.0^\ddagger</td>
<td>167</td>
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</tbody>
</table>

Table 2.1: Tensile and mode I fracture properties for ABS-modified VE resins (standard deviations are given in parentheses) - 0% stands for the neat VE while 100% stands for the neat ABS, † [96], ‡ calculated using K_{Ic}. (DC) stands for Dow Chemicals.

stress, which decreased with increasing ABS content, as shown in Figure 2.3. Accordingly, it can be noticed that ABS particle addition weakened the unmodified VE, lowering the failure stress.

Although, the tensile curves indicate a possibility of brittle-like failure for all VE/ABS blends, the observations during the test showed significant whitening of the material without necking, possibly caused by substantial micro-cracking and/or yielding of the plastic prior to main failure. Also, as in the case of the neat VE, stress whitening was observed before the maximum stress point. It is known that stress whitening is a proven sign of material plastic deformation [3], suggesting that the onset of plastic deformation for the tested VE/ABS blends and the neat VE occurred prior to the maximum stress point. Therefore, it was necessary to define more precisely the yield point, which is crucial to the proposed FEM analysis. A new set of specimens was tested in order to capture the yielding onset and to establish a consistent definition of the yield point for all materials. Two types of measurements were conducted to relate the onset of the stress whitening to permanent deformation of the material. In the first case, the specimens were loaded up to the stress level where the whitening was initially observed. At that point they were taken out from the test grips and their
length was measured with a micrometer and compared with the initial length before testing. The second method utilized the strain measurement capabilities of the Instron testing machine using a strain gauge. After the onset of stress whitening, the test was stopped and after unloading, the strain measurement would be checked for any residual permanent deformation. All measurements were repeated with three specimens. Both measurement approaches produced identical results, supporting the assumption of the yield point existence before the failure. The next step was to provide a consistent definition of the yield point. By careful observation of the deformation during the test, the stress level associated with onset of stress whitening was indicated on the recorded stress-strain curves. After summarizing the test data, it was found that the intersection of the recorded stress-strain curves and the 5% strain offset line defined with high
accuracy the recorded onset of stress whitening. Accordingly, the 5% offset yield stress was chosen to represent the yield point for all VE based materials in this study.

Finally, testing of the neat ABS gave a failure strain of approximately 20%, mainly due to significant necking, as shown by the typical stress/strain response in Figure 2.4. The necking reflects the significant presence of shear yielding that occurs in this multiphase polymer [3], which usually results in a stress whitening effect.

![Figure 2.4: Stress-strain curve of the neat ABS - after the yield point ABS behaves as an elastic-perfectly-plastic material, having the failure strain of approximately 20%](image)

A low departure from linearity was observed on the stress-strain curves for all tested plastics, and this was believed to be associated with significant non-linear elastic behaviour due to the presence of rubber particles. The same conclusion can be drawn for neat VE 8084 which has been chemically enhanced by grafting an elastomer (butadiene) onto the backbone of the polymer chain [95]. The reason for this enhancement was to improve fracture toughness.
A summary of the tensile and fracture test results is also presented in Table 2.1. Clearly, modifying the VE with ABS results in an increase in fracture toughness; a decrease in the Young’s modulus and yield strength and subsequent enlargement of the plastic zone developed in front of the crack tip, calculated according to Irwin’s plastic zone correction [47]. The variation of mode I fracture toughness with ABS weight content is illustrated in Figure 2.5.

An initial increase with 3.5% ABS addition, from 300 to 700 $J/m^2$ is noted, followed by a plateau region between 3.5 and 7%. Beyond that level of ABS addition, there is a further linear increase in $G_{Ic}$ tending towards a four-fold increase in the fracture toughness at 15% ABS addition, compared to the neat VE 8084. Clearly, the fracture toughness tests revealed the significant toughening potential of the blends. An explanation for the plateau region in the $G_{Ic}$/ABS% trend and the subsequent increase in toughness might be associated with a chemical reaction between the constituents invoked during mixing and curing procedures. As a consequence, the region on the
chart in Figure 2.5 around 7% of ABS addition represents a transition in the fracture toughness trend. The possible chemical reaction which may be responsible for such a toughness trend may be the dissolution of butadiene from the ABS into the VE. Since butadiene is present in the unmodified VE in order to improve toughness, it is reasonable to assume that additional amounts of butadiene may cause a further increase in fracture toughness. Also, a saturation level of butadiene addition may exist, leading to the definition of a composition-based saturation point. This can be related to the transitional zone around 7% of ABS weight content, where the change in the fracture toughness trend was noticed. Beyond this level of ABS modification, some additional toughening mechanisms are triggered, resulting in further toughness improvements.

SEM fracture surface examination of selected SENB specimens strengthened these assumptions. Figure 2.6 depicts typical fracture surfaces from 3.5 and 7% ABS/VE blends.

Figure 2.6: SEM images of the typical 3.5 and 7% ABS/VE blend fracture surfaces (crack propagates from bottom to top) - ABS particles are visible together with some amount of plastic deformation, they did not significantly influence crack propagation (crack propagated through the particles)

ABS particles remained visible after the crack propagation, suggesting that they were not influencing crack propagation and eventually resulted in a brittle like fracture
pattern. Some amount of plastic deformation in the VE matrix is obvious, but it is not severe and is probably not solely induced by the particle presence. A similar fracture surface obtained for 7% ABS addition supports this conclusion. Regardless of the twofold increase in particle content, fracture toughness was unchanged, as was the fracture pattern. This leads to the possibility that chemical modification of the VE by the ABS addition could cause a change in the toughening potential of these blends, causing the observed toughness increase. By increasing the ABS content beyond 7%, the fracture surface started to show a significant increase in plastic deformation of the materials, as shown in Figure 2.7. Particles are not visible at the fracture surface due to the extensive whitening and deformation of the material.

![SEM images of the typical 11 and 15% ABS/VE blend fracture surfaces](image)

(a) 11% ABS  (b) 15% ABS

Figure 2.7: SEM images of the typical 11 and 15% ABS/VE blend fracture surfaces (crack propagates from bottom to top) - ABS particles are not visible on the fracture surface which shows signs of severe plastic deformation

Beyond 7% ABS addition there was a significant change in the fracture pattern. The visible increase in the material’s plastic deformation during the crack propagation corresponds well with the increase in measured fracture toughness seen in Figure 2.5. It can be assumed that at some level of ABS modification between 7 and 11% a significant change in the mechanical properties of the blends occurs. This transitional level of ABS content separates materials with different toughening trends and with different
governing toughening mechanisms. Therefore, in order to collect more information on possible chemical reactions between the constituents and the materials’ composition, Raman Spectroscopy techniques were employed.

2.3.2 Raman spectroscopy

Derakane vinyl-ester 8084 is a complex material, containing a DGEBA backbone that has been internally modified with a reactive acrylonitrile-butadiene copolymer. The ABS is also quite complex, consisting of small regions of styrene acrylonitrile (SAN) embedded within a butadiene-based matrix, giving the combined structure shown schematically in Figure 2.8.

![Figure 2.8: Schematic showing the phases present in ABS-toughened vinyl-ester resin (single ABS particle only)](image.png)

The chemical structures of the 8084 backbone, methacrylate ester, SAN and butadiene are as shown in Figure 2.9. The vinylester resin is produced by the reaction of methacrylate monomers with the backbone molecule in the presence of a catalyst, and occurs at room temperature. With reference to Figure 2.9, further polymerisation occurs by cleavage of the C=C double bonds. The central R group is a proprietary group consisting of para-substituted aromatic rings, acrylonitrile groups and butadiene.
For the purpose of this study, three types of Raman spectra were obtained. Typical spectra from the cured neat untoughened resin (denoted VE), the pure particulate additive (ABS) and the cured complete system with 3.5wt% ABS addition (VE/ABS blend) are shown in Figure 2.10. The assignments of the significant peaks marked 1 to 15 have been made, and are listed in Table 2.2.

Clearly, some of the numbered peaks occur in all three spectra, whereas others do not. The areas of the peaks are required to assess quantitative information to see how the amount of one species has changed in relation to another. It is important to note that areas of peaks can only be compared on the same spectrum and not from one spectrum to another. However, the ratios of one peak to another can be compared across spectra and it is this comparison that makes the Raman technique useful in assessing chemical reactions. In order to make meaningful comparisons, the peak areas need to be referenced to a common peak in each of the spectra of interest, and this peak must be one that remains constant throughout all the spectra (i.e. is unaffected by the mixing process). Such a peak occurs at a bandwidth of 640 cm$^{-1}$. Therefore, to investigate the spectral changes in the material that occur on curing and/or mixing...
Figure 2.10: Raman spectra obtained for (a) cured neat untoughened resin-VE, (b) ABS particles and (c) VE/ABS blend. The numbers correspond to significant peaks.

with ABS, the areas of the significant peaks shown in Figure 2.10 were normalized relative to the area of the selected internal standard peak at 640 cm\(^{-1}\). This peak can be attributed to para-substituted deformation of the benzene rings present in the cured vinyl-ester backbone. The calculated relative areas for the cured untoughened material and the cured toughened material are also shown in Table 2.2. Figure 2.10 shows that the para-substituted groups responsible for the peak at 640 cm\(^{-1}\) do not occur in the ABS, hence their omission from Table 2.2. The information shown on Figure 2.10 yields several insights into how the ABS particles and VE interact during curing and/or mixing process. Comparison of spectra shows that on curing of a VE/ABS mixture, much of the contribution from the butadiene in the ABS particles (characterized by the C=C aliphatic stretch at a wavenumber of 1667 cm\(^{-1}\)) disappears. There could be several explanations for this, including the breakage of the C=C bond during the curing process due to some reaction. However, the most likely explanation is that on mixing, the butadiene component in the ABS dissolves into the VE matrix, thus
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<table>
<thead>
<tr>
<th>Peak</th>
<th>WaveNo. [cm⁻¹]</th>
<th>Assignment</th>
<th>Relative areas VE</th>
<th>Relative areas VE/ABS</th>
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<td>820 (m)</td>
<td>H₂C-C stretch</td>
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<td>1001 (vs)</td>
<td>ring breathing (aromatic)</td>
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Table 2.2: Vibrational assignments for the significant Raman bands in the cured vinyl-ester, ABS particles and their blend. (Key: w=weak signal, sh = shoulder signal, m = moderate signal, s = strong signal, vs = very strong signal)

resulting in a weaker signal (Raman examination was performed in areas of material known to contain particles). This is borne out by microscopic evidence presented in Chapter 4 that shows partial dissolution of the butadiene matrix occurring at low ABS concentrations.

2.3.3 Hypothesis on the composition of the blends

All experimental results presented so far identified the region around 7% ABS addition as a transitional zone in fracture toughness characteristics, possibly induced by the butadiene saturation at this level of ABS. However, at this stage a hypothesis will be made that based on the Raman Spectroscopy results that indicated butadiene dissolution from the ABS into VE at low levels of ABS addition (e.g. 3.5% ABS/VE blend), and using the fracture toughness trends seen in Figure 2.5, 7% ABS addition represents the butadiene saturation point. A transition in the materials’ mechanical properties also occurs at this point. At low levels of ABS addition, VE is clearly enriched with
butadiene and it possesses different properties to the initial VE. Obviously, increased amounts of butadiene improves the fracture toughness of the VE. This was clearly noticed with the 3.5% and 7% ABS blends.

On the other hand, ABS particles, by losing butadiene, become almost pure styrene-acrylonitrile (SAN). Beyond the saturation point, the amount of butadiene in the VE was unchanged, since saturation has been reached, but the renewed presence of butadiene in the particles brought their properties close to the initial ABS. All of this suggests that the particles do not strongly influence fracture toughness values below the saturation point. This conclusion is supported by the similar fracture toughness values at 3.5% and 7% ABS addition levels and is reflected in their fracture surface micrographs illustrated in Figure 2.6. It is possible that the toughness values of these VE/ABS blends are higher than that of the neat VE due to chemical modification of the VE, through increased butadiene content. This leads to the conclusion that it is only beyond the saturation point that the complete ABS particles start to influence toughness, possibly by increasing stresses and strains in the surrounding matrix promoting its micro-cracking and yielding. The butadiene migration is presented in Figure 2.11.

An important consequence of these observations is that the properties of the matrix beyond the saturation point can be approximated to the bulk properties of the 7% ABS/VE blend while the properties of the particles correspond to the properties of the neat ABS. However, this assumption cannot be fully proved by the existing experimental results, so finite element modelling was employed to support this hypothesis.
Figure 2.11: Schematic representation of the butadiene migration process (single ABS particle only): (a) Below the saturation point butadiene migrates from the ABS towards the VE, resulting in higher toughness through chemical modification. Small amounts of particles remain almost wholly in the form of styrene-acrylonitrile (SAN); (b) Butadiene saturation is reached. Any further ABS addition will result in the butadiene remaining in the particles since the migration has stopped. Particles still do not have any influence on fracture properties - toughness improvement is still through matrix modification. From this point upwards, the matrix will not change its properties; (c) Beyond the butadiene saturation the matrix possesses properties of the transitional blend (7% ABS/VE) while the particles, with both butadiene and SAN, possess properties of the original ABS. The particles now have significant influence on fracture toughness.
2.3.4 Finite element modelling

After defining the nature and extent of the VE chemical modification by ABS particle addition, finite element modelling was employed to obtain further insights into the existence of a butadiene saturation point and its influence on the materials' mechanical properties. The main purpose of the FEA modelling was to simulate tensile testing of the 15% ABS/VE blend, by employing a model that represents a small rectangular region of matrix $0.2 \times 0.2$mm in size filled with randomly distributed spherical particles of random size.

According to the hypothesis on composition of the blends, bulk 7% ABS/VE blend properties were used for the matrix while neat ABS properties were used for the particles. The properties of ABS are assumed to follow an elastic/perfectly plastic stress strain curve, which corresponds to the experimentally obtained curve illustrated in Figure 2.4. ABS particle concentration was equal to the measured particle concentration within the 15% ABS/VE blends. This concentration was found to be 27% of the area, and more details on this measurements will appear in Chapter 4. In order to prove the assumed particle influence above and below the saturation point, the model was subjected to a uniaxial quasi-static tensile loading and it was expected that it would produce a stress-strain curve that follows the experimentally obtained stress-strain curve for the 15% ABS/VE blend, as depicted in Figure 2.3. By fulfilling this expectation the composition hypothesis used in the models would subsequently proved to be correct.

Figure 2.12 depicts the final refinement of the mesh used for the analysis. The mesh is reasonably refined at the matrix/particle interfaces where the highest stresses were expected. A tensile stress was applied at top of the model and gradually increased from 0 to 46MPa in 2MPa steps. After each step an average strain was measured along
two cross-sections of the model. The latter were chosen to be at \( y = 0.195 \text{mm} \) and \( y = 0.074 \text{mm} \), measured from the bottom of the model, as illustrated in Figure 2.12.

![Figure 2.12: The final mesh of the tensile model (random particle distribution) - mesh is refined at the matrix/particle interfaces](image)

Applied boundary conditions simulated double symmetry (e.g. a quarter of the whole plate was modelled). The results are presented in Figure 2.13 in a form of stress-strain curves obtained from the analysis.

It can be noticed that the numerical tensile curves from both cross sections follow relatively similar trends, which are comparable to the 15% ABS/VE blend stress-strain curve obtained experimentally. The stiffness of the numerical model in the linear-elastic region lies in between two experimental curves, but after exceeding the yield stress of the ABS (36MPa), rapid straining of the ABS particles occurred, producing curves which followed the experimentally obtained trend of the 15% ABS/VE blend. Differences between the test and modelling clearly exist, but they are acceptable due
Figure 2.13: Experimentally and numerically obtained stress-strain curves - there is a reasonably good agreement between the experimental and numerical stress/strain curves for 15%ABS/VE blend to the initial simplifications of the model regarding material properties and geometry of the particles.

Although not shown, results obtained from regular array models produced almost identical material responses to those for the random model. Obviously, particle distribution did not have a strong influence on the tensile response of the models. Possibly, a much stronger influence was from the particle concentration, which was identical for all developed models.

The models proved the initial assumption on the existence of 7% ABS as the butadiene saturation point to be correct. Additionally, they directly supported the assumption that at ABS concentrations beyond the saturation point, the particles possess properties similar to those of the neat ABS, while the matrix possesses properties of the
saturated VE/ABS blend. The randomness of the model did not have a significant influence on the bulk material properties but it is reasonable to assume that it can contribute to a more accurate assessment of the stress and strain distribution. Application of this modelling technique on interlayer toughened composite materials will be presented in the following chapters.

2.4 Summary

In summary, this chapter investigated the fracture toughness and tensile properties of VE/ABS blends intended to be used as a toughening agent in interlayer toughened composites. The main variable was ABS particle weight content which is varied between 3.5 and 15%. The obtained fracture toughness trend was non-linear, suggesting possible reactions at the chemical level between the constituents of the blends. In order to prove this, Raman spectroscopy and FEA analysis were employed. It was concluded that butadiene dissolution from the ABS to the VE occurred at levels of ABS modification below 7%. At an ABS content of 7%, this chemical modification stopped because the saturation point had been reached. This point was also associated with an observed change in the fracture toughness trend. This chemical modification led to enhanced particle influence on the fracture toughness beyond the saturation point. These conclusions were supported by FEA models which exhibited good correlation with experimental results. Nevertheless, it can be concluded that the ABS modification of the VE resulted in a highly improved toughness of the original material and blends that can successfully be used for interlayer toughening. A basic knowledge of the materials’ fracture behaviour was gathered that can be a starting point in assessing toughening mechanisms in interlayer toughened composites.