EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M1

European Project for the development of HTR Technology - Materials for the HTR

<u>CONTRACT N°</u>
FIKI-CT-2000-00032
FIKI-CT-2001-00135

Assessment of the preliminary graphite irradiation results from INNOGRAPH 1A and comparison with previous data

by

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Dissemination level : CO
Document Number: HTR-M1 05/12 D 2 4 41
Deliverable D11

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C6857/TR/006
Issue 01

DOCUMENT ISSUE RECORD
(engineering documents)

Adding value through knowledge

Document Title :	Assessment of the preliminary graphite irradiation results from INNOGRAPH 1A and comparison with previous data
Project Reference:	C6857

Purpose of Issue : For use

Security Class : Commercial-in-Confidence

Issue	Description of Amendment	Originator/ Author	Checker	Approver	Date
01 Draft	First draft for comment	M W Davies	D E Buckthorpe		Dec 2005
01	Checker and partner comments incorporated	M W Davies	D E Buckthorpe	T Lennox	

Total number of pages:	Intro:	(i)-(v)	Text	1 - 10	Tables	T1-T3	Figures	F1-F15	Appendices	

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Distribution: SINTER, HTR-M1 Partners (via SINTER), NNC: M W Davies, D E Buckthorpe, EDMS

3050aJan01 Controlling procedure - QP11, QP40 *Docprodref*

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Summary

The first stage of an irradiation programme has been carried out in the Petten HFR involving ~200 samples manufactured from eight different grades of graphite, as part of the HTR-M1 Project within the 5th Framework EU part-funded Programme. The samples were first of all pre-characterised, and then irradiated to a maximum of around 1/3 peak fluence at a temperature of 750^{o}C. Results from the initial measurements on ~50% of the irradiated samples have been evaluated, and for two of the grades (NBG-10 and PPEA) have been compared with the German ATR-2E graphite. The measurements suggest that these two graphites have a higher initial shrinkage rate than ATR-2E, but with turn-around expected to occur at a higher fluence.

None of the current grades can be eliminated at this stage, and it will only be when the results from the second stage of the irradiation are available that meaningful conclusions can be made. The results however are promising and will make an important contribution to the evaluation of suitable graphites for the next generation VHTR.

1 Introduction

In order to support the development of a future European High Temperature Reactor (HTR), a number of suitable candidate graphites were selected for an irradiation programme in the high flux reactor (HFR) at Petten, which is being undertaken by NRG. The overall irradiation programme is aimed at establishing the irradiation behaviour of the selected graphites over the irradiation fluence and temperature range appropriate for a HTR, and eventually to provide all the graphite data necessary to undertake a core design. (Details on the selected graphites and testing requirements are given in Refs 1 and 2).

The first stage of this irradiation programme has been carried out within the 5th Framework Programme (HTR-M1). Appropriately sized discs/blocks of the different materials were supplied to NRG by three different graphite manufacturers and ~200 samples were machined from them. The samples were first of all pre-characterised, and then irradiated to a maximum of around 1/3 peak fluence[1] at a temperature of 750^{o}C. This is referred to as INNOGRAPH 1A. [The peak fluence to be achieved is ~25 displacements per atom (dpa), or ~200 x 10^{20} n.cm^{-2} Equivalent DIDO Nickel Dose (EDND). Thus in INNOGRAPH 1A the samples have been irradiate up to ~9 dpa, or ~70 x 10^{20} n.cm^{-2} EDND. The irradiation to peak fluence will be completed in INNOGRAPH 1B]. The test rig has been removed and dismantled and, at the time of writing of this report, around 50% of the samples have already been subjected to some post-irradiation examination (PIE).

For the pre-characterisation of the samples there was a need to measure their initial dimensions, mass, dynamic Young's modulus (DYM), coefficient of thermal expansion (CTE) and thermal conductivity (via measurements of thermal diffusivity). From these, their volumes and densities were calculated. For the irradiated samples subjected to PIE, only their dimensions and DYM have been re-measured to date.

All the pre-characterisation measurements and the PIE measurements already made (together with specific properties derived from them) are contained within Excel spreadsheets developed by NRG. However, before the experiment got underway, an Excel worksheet was proposed (comprised of individual spreadsheets for each graphite grade) that would be used to summarise the data in a convenient way and would enable the appropriate 'design curves' to be produce (Ref 3). At the conclusion of the HTR-M1 programme there was a requirement to review the available measurements and to enter them into this worksheet. This has been completed and is covered in Ref 4.

There was also a requirement to assess the measurements and compare them with those made on other graphites in the past at similar temperatures. A preliminary comparison has been carried out in this report for the graphite used in the German HTRs, namely ATR-2E. This is the subject of this report. A summary of the graphites tested is given in Section 2. The pre-characterisation of the graphites and the PIE measurements are covered in Section 3. The dimensional change behaviour and the calculated variations in DYM with irradiation fluence are covered in Section

[1] Peak fluence is that appropriate to a pebble bed core design. The replacable components in a prismatic core design should not exceed 1/3 of this value and thus the data requirements should be bounded by this first stage of the irradiation.

4, and an assessment of these is carried out in Section 5. A comparison with the ATR-2E behaviour is covered in Section 6. Future work is covered in Section 7.

2 Graphite selection

There is clearly a limit on the number of samples that can be contained within a given irradiation experiment and this has an influence on the number of graphites that can be tested. There is also a need to maximise the number of samples of each graphite selected to provide good statistics. One problem was that the general anisotropy of the different graphites requires samples to be machined from the two major directions, that is, 'with grain' (WG) and 'against grain' (AG). In addition, due to the inherent material variability within a block, samples should be taken from both the centre region of a block and from the outside region of the block (hereafter referred to as 'centre' and 'edge' in this report).

After careful consideration eight graphites were chosen from those available for this initial experiment, five of which were classified as 'major' grades, the other three being classified as 'minor' grades. The intention was to cover the two main sources of coke (petroleum and pitch), and the two most common manufacturing techniques (extrusion and iso-moulding). Due to a decision to use a mixture of two sample lengths (6 mm and 12 mm) it was possible to increase the number of samples that could be tested to 198. Therefore, in general, 30 samples of each were produced for the five 'major' grades (15 in each of the two principal directions), and 14 samples of each were to be produced for the 'minor' grades (7 in each of the two principal directions).

The selected major and minor graphites are shown in the Table below. (The actual number of samples of each included is given in parentheses after the classification.). All are medium grain graphites, with the exception of PCIB which is a super-fine grain graphite.

Manufacturer	Grade	Coke	Process	Classification
GrafTech	PCEA	Petroleum	Extrusion	Major (30)
	PPEA	Pitch	Extrusion	Minor (14)
	PCIB-SFG	Petroleum	Iso-moulding	Major (30)
SGL	NBG-10	Pitch	Extrusion	Major (32)
	NBG-20	Petroleum	Extrusion	Minor (14)
	NBG-25	Petroleum	Iso-moulding	Major (30)
Toyo Tanso	IG-110	Petroleum	Iso-moulding	Major (30)
	IG-430	Pitch	Iso-moulding	Minor (18)

3 Pre-characterisation and post-irradiation measurements

3.1 Pre-characterisation measurements

The graphite discs/blocks supplied by the manufacturers for each grade were sectioned and machined to produce the required number of samples. Each sample was cylindrically shaped with a nominal diameter of 8 mm and a nominal length of 6 or 12 mm. As mentioned earlier, the samples were machined from both the central and outer regions of each block, to take account of the known variability in properties throughout a block. An additional small flat was also machined so that each could be uniquely identified with an alphanumeric code, and its orientation within the block known for recording the measurements (Ref 5). In this way, initial property variation as a function of position and orientation in the disc/block could be determined (as well as for the irradiated properties).

The dimensions of each sample were measured together with its DYM, CTE and thermal diffusivity (used to calculate thermal conductivity). The mass of each sample was also measured, which together with the dimensions, allowed the initial density to be determined. Details of the testing methods used are given in Ref 6. (Although strength is a very important property, it cannot be measured on the samples to be irradiated as this will involve a destructive test. Nevertheless, strength measurements can be made on other suitable samples obtained from a block, and the strength distribution thus obtained should be representative of those being irradiated.) All the measurements have been recorded in the spreadsheet developed by NRG.

The initial task for this report was to transfer the measurements from the NRG spreadsheet into the proposed worksheet. This would then allow the property variations to be displayed in graphical form and the appropriate curves fitted. However, it soon became apparent that a single worksheet for all eight graphites would be too large and difficult to use and so it was decided that individual worksheets should be produced for each grade. There was also a need to amend each basic spreadsheet slightly in order to facilitate data entry and the generation of graphs/curves from them.

All the worksheets have been produced and the spreadsheet within each has been populated with the pre-characterisation measurement data (Ref 4). Table 1 is an example of the first 'page' of such a spreadsheet, and shows the pre-characterisation measurements for IG-110.

3.2 Post-irradiation measurements

All the measurements carried out for the pre-characterisation are also required on the irradiated samples. At the time of writing, a total of 96 samples have been subject to measurement (~50%), but to date, it has only been possible to measure their linear dimensions, mass and DYM, and to calculate (from the first two) their volumes and density. The spreadsheet within each of the worksheets has been populated with the PIE measurement data. Table 2 is an example of the second page of such a spreadsheet, and shows the PIE measurements for IG-110.

4 Changes in properties due to irradiation

It is known that the properties of interest to the core designer all vary with irradiation fluence and that this variation also depends on the irradiation temperature. The linear dimensional and volumetric changes that occur are traditionally given in terms of fractional changes, expressed as a percentage. The variation is normally expressed as a ratio so that the it can be used as a multiplying factor (f) for the initial modulus (E_o) to give the irradiated modulus (E_i) at the required fluence/temperature. In order to calculate the changes, the pre-characterisation measurements and the post-irradiation measurements are entered into the appropriate locations the first and second pages of the spreadsheet respectively. The variation are calculated in the required manner in the third page of the spreadsheet.

4.1 Dimensional change

The dimensional change behaviour of a graphite is arguably the most important selection criterion from a designer's point of view. Differential shrinkage strains within components give rise to stresses that could ultimately lead to cracks developing. Overall component distortions affect the stability and hence loading of the whole structure, which could be made worse by cracking. Excessive cracking is unlikely to be tolerable and could therefore result in a much shorter core life if the wrong graphite is used.

The 'ideal' graphite would have a very small shrinkage rate, a moderately high fluence at which turn-around occurs, and a high fluence at which it goes into positive growth (i.e. original dimensions/volume attained). In general all candidate graphites for a HTR will exhibit shrinkage over the temperature range of interest. However, there could be a large difference in this initial shrinkage rate. In addition, an ideal graphite would show very little difference in behaviour for the two principal directions, that is WG and AG. A large difference indicates a large anisotropy, and it is not recommended that such graphites be used as this could significantly increase the internal stresses within a component, thereby leading to cracking earlier in life than would be the case for a more isotropic graphite. (It is important to note that a manufacturer gives the anisotropy of a graphite as the ratio of the CTE in the two principal directions, but it does not follow that the anisotropy of the irradiation behaviour will be similar.)

Given the need to cover both principal directions, the cylindrical shape of the samples with the machined flat meant that great care had be used to ensure that the principal directions were maintained for each sample during manufacture. Figure 1 shows the orientations of the samples taken from both an extruded block and an iso-moulded block. It can be seen the extruded block has one principal WG direction and two principal AG directions, whereas the iso-moulded block has two principal WG directions and one principal AG direction. The figure also shows the three dimensions measured, namely the axial length (L), the major diameter (D) and the smaller diameter perpendicular to the flat (X). The samples are classified as WG or AG according to the axial direction, hence the axial length L is in this direction. The classification of the other two dimensions however depends on its orientation and also which type of block it came from. The table below gives the appropriate classifications.

Process	**Sample orientation**	**Classification**		
		L	**D**	**x**
Extrusion	WG	WG	AG	AG
	AG	AG	AG*	WG*
Iso-moulding	WG	WG	WG*	AG*
	AG	AG	WG	WG

* These classifications rely on the flat being machined with the sample in (or close to) the correct orientation. If this was not the case for any sample, these particular measurements will not be 100% WG or AG, but will be somewhere in between, and this would invalidate their use.

4.2 Dynamic Young's modulus

The initial Young's modulus of a graphite and its variation with fluence is important as it is used to calculate the internal stresses from the internal (shrinkage) strains. As mentioned earlier, the variation is normally expressed as a ratio so that the it can be used as a multiplying factor (f) for the initial modulus (E_o) to give the irradiated modulus (E_i) at the required fluence/temperature. Thus $E_i = f .E_o$.

5 Assessment of irradiation behaviour

5.1 Dimensional change

Although only around half the samples have been measured, a preliminary assessment of the dimensional change behaviour of the graphites tested can be made. It has been found that there is a significant difference in the shrinkage behaviour, with one graphite showing a particularly high shrinkage rate and another with a particularly low shrinkage rate. This large variation was to be expected, given the range of graphites tested. It must be remembered that the fluence attained so far is only ~ 1/3 of the peak fluence (see Footnote on Page 1), and none of the graphites appear to have gone through turn-around although some are clearly approaching it. Therefore a low initial shrinkage rate, although appearing to be a good sign, will be of little use if there is an early turn-around and change to positive growth. [This will not be known until the measurements have been carried out at the end of the next irradiation stage (INNOGRAPH 1B). At the end of this irradiation, the samples will have reached ~2/3 and the peak fluence. The former should allow the fluence at which turn-around occurs to be accurately determined, and the latter should allow the fluence at which the initial dimensions/volume are attained to be determined.]

The initial irradiation behaviour of the eight graphites in terms of the linear dimensional changes for the WG and AG directions, and the volumetric changes are given in Figures 2 to 17. These are covered below in terms of manufacturer.

5.1.1 SGL grades

The SGL grades cover both petroleum and pitch coke, and both extrusion and iso-moulding. For NBG-10, which is a pitch coke extruded graphite, it can be seen from Figure 2 that the shrinkage in the WG direction is slightly larger (at ~2.0%) than in the AG direction (at ~1.5%) at the maximum fluence (of ~9 dpa). This is as expected. The scatter on the data is not too large. There is no evidence of turn-around at the peak fluence reached. The volume change behaviour is shown in Figure 3. It appears to be decreasing linearly with fluence, reaching ~4.5% at the maximum fluence, and the scatter is less than for the individual dimensions.

For NBG-20, which is a petroleum coke extruded graphite, it can be seen from Figure 4 that the shrinkage in the WG direction is slightly larger (at ~2.5%) than for NBG-10 at the maximum fluence (of ~9 dpa). However, in the AG direction there is a very large difference, both in comparison with the WG direction, and with NBG-10. The dimensional change in the AG direction is very small being <0.5% at the maximum fluence. It is clear that this graphite exhibits a high level of anisotropy. However, this is not expected based on the relatively low anisotropy calculated from the CTE values in the WG and AG directions. The scatter on the data is not too large, and is broadly the same as that for NBG-10. There is no evidence of turn-around at the maximum fluence reached. The volume change behaviour is shown in Figure 5. It appears that the rate of change of volume is decreasing with fluence, suggesting it is approaching turn-around. The volume change at the maximum fluence is ~2.5%, which is much less than for NBG-10. The scatter is again less than for the individual dimensions.

For NBG-25, which is a petroleum coke iso-moulded graphite, it can be seen from Figure 6 that the shrinkage in the WG direction is lower than the other two at the maximum fluence. However, the scatter on the data is much larger. The dimensional change in the AG direction is much less than in the WG direction, and is somewhere in between that for the other two (NBG) graphites. The scatter on the data is also less. This graphite also exhibits a high level of anisotropy, which is again not apparent from the CTE measurements in the two directions. The volume change behaviour is shown in Figure 7. It appears to be decreasing linearly with fluence, reaching @ 4.2% at the maximum fluence, which is similar to NBG-10. The scatter is less than for the individual dimensions.

5.1.2 GrafTech graphites

The GrafTech grades also cover both petroleum and pitch coke, and both extrusion and iso-moulding. For PCEA, which is a petroleum coke, extruded graphite, it can be seen from Figure 8 that the shrinkage in the WG direction is slightly larger (at ~2.5%) than in the AG direction (at ~2.0%) at the maximum fluence of (~10 dpa). This is as expected. The anisotropy is similar to that for NBG-10, but the shrinkage is higher by ~0.5% in each direction. The scatter on the data is not too large. There is some evidence that the graphite is approaching turn-around at the maximum fluence reached. The volume change behaviour is shown in Figure 9. It appears that the rate of change of volume is decreasing with fluence, suggesting it is approaching turn-around. The volume change at the maximum fluence is ~6.3%, which is much higher than for NBG-10. The scatter is again less than for the individual dimensions.

For PPEA, which is the pitch coke equivalent of PCEA (and also the equivalent grade to NBG-10), it can be seen from Figure 10 that the shrinkage in the WG direction is larger (at ~2.0%) than in the AG direction (at ~1.4%) at the maximum fluence (of ~10 dpa). The anisotropy is similar to that for PCEA, but the shrinkage rate is lower. It is very similar to the behaviour of NBG-10 (which would be expected as it is the equivalent grade). The scatter on the data is not large, and arguably less than for NBG-10 and PCEA. The volume change behaviour is shown in Figure 11. It appears that the rate of change of volume is decreasing slightly with fluence. The volume change at the maximum fluence is ~4.5%, which is much less than for PCEA, but very similar to NBG-10 (as expected). The scatter is again less than for the individual dimensions.

For PCIB-SFG, which is a petroleum coke, iso-moulded graphite, it can be seen from Figure 12 that the shrinkage in the WG direction is lower than the other two GrafTech grades at the maximum fluence (of ~10 dpa). In the WG direction it is generally <1.0%, and in the AG direction <0.5%. However, the scatter on the WG data is quite large. Although the shrinkage rate is low, which is desirable, it appears that turn-around is happening in the AG direction at the maximum fluence reached. This can only be confirmed when the INNOGRAPH 1B data have been assessed. The volume change behaviour is shown in Figure 13. It appears that the rate of change of volume is decreasing slightly with fluence. The volume change at the maximum fluence is only~1.8%, which is much less than for extruded graphites, and even less than that for the other iso-moulded graphite (NBG-25), which reached ~4%. This difference is likely to be the effect of the much smaller grain side used. PCIB is a super-fine grain graphite whereas all the others are medium grain. The scatter on volume is again less than for the individual dimensions.

5.1.3 Toyo Tanso graphites

The Toyo Tanso grades cover both petroleum and pitch coke, but both are iso-moulded. For IG-110, which is the petroleum coke graphite, it can be seen from Figure 14 that the shrinkage in the WG direction (at ~2.0%) is again larger than in the AG direction (at ~1.3%) at the maximum fluence (of ~10 dpa). The scatter on the data is quite large, which is consistent with the other two iso-moulded graphites. Although the curve for the AG direction does not show it, there is a possibility that turn-around is occurring. This can only be confirmed when the INNOGRAPH 1B data have been assessed. The volume change behaviour is shown in Figure 15. It appears that the rate of change of volume with fluence is still linear at the maximum fluence. The volume change at the maximum fluence is ~5.0%, which is slightly higher than for NBG-25, but much larger than for PCIB. The scatter is very much less than for the individual dimensions.

For IG-430, which is the pitch coke graphite, it can be seen from Figure 16 that the shrinkage in the WG direction has a very high scatter, ranging from 0% to ~1.5%) at the maximum fluence (of ~10 dpa). In the AG direction, most of the samples show a slight growth of up to 0.4%, which has only arisen for some AG samples in NBG-20. The scatter on data is not as large as in the WG direction. The graphite has a high level of anisotropy. The volume change behaviour is shown in Figure 17, which shows a very large scatter in the data. This is the only graphite of the eight to have such a high scatter. The reason for this is not clear at the moment.

5.2 Dynamic Young's modulus

The variation in DYM for the eight graphites is given in Figures 18 to 25. All eight graphites show an increase in DYM, but by different amounts, and the data show a fair bit of scatter. The behaviour is exactly as would be expected and is typical of the changes observed in all graphites previously irradiated. It is known that all graphites show a significant increase at fairly low fluences. This is attributed to the pinning of mobile dislocations in the lattice structure. The DYM increases by a factor of ~1.6. (In the UK this is referred to as the 'pinning' term). At progressively higher fluences there is a further, but more gradual, increase in DYM attributed to structural changes within the crystals. (In the UK this is referred to as the 'structure' term.). The data presented in the Figure to not show the increases happening at low fluences, and so the true curve has not been fitted. It is possible however to construct the low fluence part of the curve from existing data on previously irradiated graphites.

The DYM of all the extruded graphites have increased by a factor of around 2.4 at the maximum fluence, whereas all the iso-moulded graphites have increased by a factor of between 2.8 and 3.0. (It should be noted that the strength of graphite also increases with fluence in a similar way to the DYM. The factorial increase is less than that for the DYM)

5.3 Discussion

It can be seen that the some of graphites tested show similarities in dimensional change behaviour, whereas others show significantly different behaviour. It is evident that the extruded graphites shrink at a faster rate than the iso-moulded graphites in both directions. However, the iso-moulded graphites exhibit a higher anisotropy and also have a higher scatter in the data. Although some of the graphites are exhibiting similarities up to the maximum fluence achieved, experience has shown that it is unlikely that each will exhibit similar behaviour beyond turn-around. This will only be known after the INNOGRAPH 1B results have been assessed. It is therefore not possible at the present time to rule out any of the graphites. The advantage of the lower shrinkage rates evident for the iso-moulded graphites might be outweighed by the much higher anisotropy and scatter in behaviour.

The DYM variations are as expected and completely consistent with those for previously irradiated graphites.

6 Comparison with previous graphites

The only graphite with freely available data that can be used to make comparisons with at the present time is ATR-2E. (Most of the data on other graphites previously irradiated are subject to restrictions, although these might be lifted in the future). Fortunately data for ATR-2E are available at 750^{o}C for both linear dimensional changes and DYM. ATR-2E was a pitch coke, medium grain extruded graphite and so is closely related to NBG-10 and PPEA. For this reason, the comparison has been limited to these two graphites only.

The comparisons in dimensional change behaviour for NBG-10 and PPEA are shown in Figures 26 and 27 respectively, and those for DYM are shown in Figures 28 and 29 respectively. It can be seen from Figures 26 and 27 that both NBG-10 and PPEA have higher shrinkage rates than ATR-2E although turn-around will occur at a higher fluence. NBG-10 and PPEA also show less anisotropy but …scatter. It can be seen from Figure 28 and 29 that the DYM behaviour is very similar over the fluence range covered. Fortunately data exist for ATR-2E at the lower fluences, and due to the similarity in behaviour of all other graphites in this region, it can be assumed with reasonable confidence that the behaviour of NBG-10 and PPEA will also be similar.

7 Future work

The remaining measurements on the samples subjected to PIE to date, and all the measurements on the remaining samples, will be carried out over the next 6-9 months.

The worksheets will be updated again when all the data are available and the plots redrawn. A further report will then be produced that assesses the complete data set.

The second stage of this irradiation to full fluence (INNOGRAPH 1B) will be undertaken shortly. Around 1/2 of the samples will be replaced by new samples of the selected graphites. These will therefore be taken to full fluence, with the newly installed samples being taken to ~2/3 peak fluence. The new samples are being pre-characterised and the data will be added to the worksheets when available. The complete set of PIE measurements on the samples at the end of this irradiation will not be available until ~2008. A further report will then be produced that assesses the complete data set up to the peak fluence.

A similar irradiation at 950^{o}C is to be carried out, initially to 1/3 peak fluence, in the 6th Framework Programme (Raphael). This is referred to as INNOGRAPH 2A. Pre-characterisation measurements on the prepared samples will be available during 2006. The worksheets will be updated to incorporate these data. Additional worksheets will be generated for each the three new graphites to be tested (NBG-18 as a major grade, and NBG-17 and BAN as minor grades). The initial PIE measurements are expected to be available from mid 2007, and a report will be produced to assess the results. The second irradiation stage to peak fluence at this temperature (referred to as INNOGRAPH 2B) will be undertaken between 2007 and 2009 and the full set of PIE measurements on the samples at the end of this irradiation will not be available until ~2010. A further report will be produced at this stage

8 Conclusions

The first stage of an irradiation programme has been carried out in the Petten HFR involving ~200 samples manufactured from eight different grades of graphite. The samples were first of all pre-characterised, and then irradiated to a maximum of around 1/3 peak fluence at a temperature of 750^{o}C. For the initial pre-characterisation of the samples their initial dimensions, mass, dynamic Young's modulus (DYM), coefficient of thermal expansion (CTE) and thermal diffusivity were measured. (The latter is used to calculate thermal conductivity.) From these, their volumes and densities were calculated. Around 50% of the irradiated samples have been subjected to some PIE, having their dimensions, mass and DYM re-measured.

All the pre-characterisation measurements, and the PIE measurements made to date (together with specific properties derived from them) are contained within Excel spreadsheets developed by NRG. These have been transferred to individual worksheets for each graphite grade by NNC. These worksheets have been used to calculate the changes in the properties due to irradiation and to display them in graphical form. These variations have been assessed and comparisons made with a graphite previously irradiated at the same temperature.

It was observed that some of graphites tested show similarities in dimensional change behaviour, whereas others show significantly different behaviour. It was evident that the extruded graphites shrink at a faster rate than the iso-moulded graphites in both directions. However, the iso-moulded graphites exhibit a higher anisotropy and also have a higher scatter in the data. Although some of the graphites exhibit similarities up to the maximum fluence achieved, experience has shown that it is unlikely that each will exhibit similar behaviour beyond turn-around. This will only be known after the INNOGRAPH 1B results have been assessed. It is therefore not possible at the present time to rule out any of the graphites. The advantage of the lower shrinkage rates evident for the iso-moulded graphites are likely to be outweighed by a lower fluence at turn-around, a much higher anisotropy, and higher scatter in the data. The DYM variations are as expected and completely consistent with those for previously irradiated graphites.

The comparisons in dimensional change behaviour for NBG-10 and PPEA with a previously irradiated graphite, ATR-2E, has shown that both NBG-10 and PPEA have higher shrinkage rates than ATR-2E, although turn-around will occur at a higher fluence. NBG-10 and PPEA also show less anisotropy but more scatter. The DYM behaviour, however, is very similar over the fluence range covered.

Further assessments will be carried out whenever future PIE measurements are completed. In the near future there will be the outstanding measurements on the samples from INNOGRAPH1A, and beyond that, the PIE measurements from the second stage irradiation at 750^{o}C (INNOGRAPH1B), and the two stages of the irradiation at 950^{o}C (INNOGRAPH 2A and 2B).

9 References

Ref	Title
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2	M W Davies. Assessment of new potential graphites and needs for HTR. HTR-M-02/11-D-3.2.53. NNC Report C6463/TR/019
3	M W Davies. Report on database of graphite properties for use by designers. HTR-M-02/06-D-3.1.22. NNC Report C6463/TR/012.
4	M W Davies. Review of the preliminary graphite irradiation results and updating of the graphite database. HTR-M1-05/12-D-2.4.40. NNC Report C6857/TR/005.
5	F Schmalz et al. Preliminary irradiation testing of selected graphite grades for HTR. HTR-M1-05/12 - D-2.3.39
6	A Vreeling. HTR-M1 report on specimen fabrication and procurement for the graphite irradiation tests. HTR-M1-03/04-D-2.2.13

Table 1 Pre-characterisation measurements for IG-110

Graphite materials property database

Graphite:	IG-110
Manufacturer:	Toyo tanso
Coke:	Petroleum
Grain size:	Fine
Process:	Iso-moulded

Spec code	Block region	Orient-ation	Unirradiated properties																	
			Length L_o (mm)	Diam D_o (mm)	Diam x (mm)	Vol V_o (mm^3)	Mass Mo (g)	Density ρo (g/cm^3)	DYM E_o (GPa)	CTE α_o ($x10^{-6}/K$) 30-120	30-750	30-200	Thermal conductivity (W/m/K) 27°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C
T004	CENTRE	AG	11.928	7.978	7.777	592.2	1.04036	1.757	9.2	3.35	4.52	3.55								
T005	CENTRE	AG	11.909	7.982	7.716	589.9	1.03910	1.762	9.1	3.57	4.68	3.79								
T006	CENTRE	AG	11.908	7.976	7.726	589.5	1.03201	1.751	9.3	3.51	4.55	3.68								
T007	CENTRE	AG	5.968	7.987	7.719	295.9	0.51890	1.754	9.1	3.26	4.50	3.48	117	111	102	86	82	72	70	62
T008	CENTRE	AG	5.933	7.966	7.729	294.3	0.51267	1.742	8.7	3.37	4.55	3.60	114	107	94	85	79	68	66	59
T009	CENTRE	AG	5.918	7.983	7.716	293.2	0.51242	1.748	8.7	3.35	4.57	3.58	116	109	99	85	81	72	68	61
T010	CENTRE	AG	5.837	7.986	7.725	289.5	0.50757	1.754	8.7	3.37	4.55	3.60	114	107	94	85	79	68	66	59
T011	CENTRE	AG	6.012	7.989	7.716	298.2	0.52359	1.756	8.8	3.45	4.65	3.69	116	106	96	84	79	71	67	60
T022	CENTRE	WG	5.928	7.982	7.631	292.1	0.51685	1.769	10.5	2.95	4.14	3.14	130	123	110	97	90	80	74	71
T023	CENTRE	WG	5.948	7.984	7.636	293.3	0.51998	1.773	10.8	2.96	4.15	3.16	129	122	109	96	87	80	74	71
T024	CENTRE	WG	5.935	7.989	7.633	292.8	0.52074	1.778	10.2	2.97	4.17	3.19	128	121	108	95	85	79	74	70
T025	CENTRE	WG	5.978	7.984	7.759	296.9	0.52684	1.774	11.1	2.93	4.14	3.15	130	125	112	99	89	83	76	72
T026	CENTRE	WG	5.876	7.982	7.631	289.5	0.51752	1.788	10.7	2.90	4.12	3.12	132	129	115	102	93	86	78	74
T027	CENTRE	WG	12.073	7.994	7.710	599.1	1.05841	1.767	11.3	3.20	4.25	3.38								
T029	CENTRE	WG	11.915	7.998	7.709	591.7	1.04984	1.774	11.2	3.02	4.12	3.20								
T031	CENTRE	WG	11.954	7.984	7.780	594.3	1.05234	1.771	10.6	3.09	4.03	3.12								
T035	EDGE	AG	11.949	7.989	7.722	592.8	1.04861	1.769	9.5	3.05	4.54	3.28								
T036	EDGE	AG	12.014	7.995	7.770	598.4	1.05726	1.767	9.4	3.54	4.57	3.76								
T037	EDGE	AG	5.957	7.993	7.719	295.7	0.52301	1.769	9.4	3.35	4.52	3.57	121	109	100	88	83	73	70	63
T039	EDGE	AG	6.044	7.979	7.712	299.1	0.52945	1.770	9.3	3.35	4.52	3.57	121	109	100	88	83	73	70	63
T041	EDGE	AG	5.907	7.979	7.715	292.4	0.51697	1.768	9.4	3.35	4.53	3.57	120	110	100	88	82	74	70	63
T043	EDGE	AG	5.998	7.978	7.714	296.8	0.52557	1.771	9.2	3.36	4.55	3.57	120	112	100	88	82	75	70	63
T045	EDGE	AG	5.886	7.983	7.716	291.5	0.51556	1.768	9.4	3.36	4.55	3.57	120	112	100	88	82	75	70	63
T047	EDGE	WG	5.970	7.949	7.689	293.3	0.51869	1.768	10.7	2.94	4.12	3.15	134	123	112	98	90	83	76	72
T048	EDGE	WG	5.895	7.991	7.706	292.3	0.51797	1.772	10.6	2.94	4.12	3.15	134	123	112	98	90	83	76	72
T049	EDGE	WG	5.907	7.994	7.710	293.1	0.51919	1.771	10.5	2.94	4.12	3.15	134	123	112	98	90	83	76	72

Table 2 Post-irradiation measurements for IG-110

Graphite materials property database

Graphite:	IG-110
Manufacturer:	Toyo tanso
Coke:	Petroleum
Grain size:	Fine
Process:	Iso-moulded

Irrad temp (°C)	Fluence: DPA	Fluence: EDND (10E20)	Length L_i (mm)	Diam D_i (mm)	Diam x_i (mm)	Vol V_i (mm^3)	Mass M_i (g)	Density ρ_i (g/cm^3)	DYM E_i (GPa)	CTE α_i ($\times10^{-6}$/K) 30-120	30-750	30-200	Thermal conductivity (W/m/K) 27°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C
750	7.73	60.8	11.7906	7.8506	7.6296	566.19	1.04038	1.8375	21.40											
750	0.00	0.0																		
750	0.00	0.0																		
750	6.85	53.9	5.9104	7.8778	7.6288	285.36	0.51834	1.8164	18.54											
750	7.71	60.7	5.8713	7.8568	7.6065	281.93	0.51211	1.8164	18.14											
750	9.84	77.4	5.8699	7.8066	7.5738	278.53	0.51242	1.8398	22.85											
750	0.00	0.0																		
750	9.68	76.2	5.9645	7.816	7.5689	283.47	0.5321	1.8771	24.60											
750	6.68	52.6	5.8438	7.8927	7.5714	281.98	0.51638	1.8313	20.63											
750	9.10	71.6	5.8202	7.8757	7.5514	279.56	0.52003	1.8602	27.87											
750	0.00	0.0																		
750	9.73	76.6	5.8344	7.8708	7.5936	280.72	0.52674	1.8764	28.95											
750	0.00	0.0																		
750	8.60	67.7	11.8466	7.8731	7.613	570.91	1.05766	1.8526	24.91											
750	0.00	0.0																		
750	0.00	0.0																		
750	0.00	0.0																		
750	0.00	0.0																		
750	7.99	62.9	5.8855	7.8547	7.6082	282.52	0.52292	1.8509	22.05											
750	9.09	71.5	5.9687	7.8233	7.5965	284.53	0.52905	1.8594	23.90											
750	0.00	0.0																		
750	0.00	0.0																		
750	0.00	0.0																		
750	7.87	61.9	5.8473	7.8494	7.6055	280.34	0.51847	1.8494	24.42											
750	9.12	71.8	5.7605	7.8788	7.6142	277.94	0.51723	1.8609	26.36											
750	0.00	0.0																		

Table 3 Fractional property changes for IG-110

Graphite materials property database

Graphite:	IG-110
Manufacturer:	Toyo tanso
Coke:	Petroleum
Grain size:	Fine
Process:	Iso-moulded

Location	Orientation	Fluence		Fractional change																
		DPA	EDND (10E20)	Length L (%)	Diam D (%)	Diam x (%)	Vol V (%)	Mass M	Density ρ	DYM E (Gpa)	CTE 30-120	CTE 30-750	CTE 30-200	Thermal conductivity 27°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C
CENT	AG	7.73	60.8	-1.1478	-1.5932	-1.8941	-4.3905	1.9E-05	0.04594	2.33575											
CENT	AG	0.00	0.0																		
CENT	AG	0.00	0.0																		
CENT	AG	6.85	53.9	-0.9646	-1.3619	-1.166	-3.5593	-0.0011	0.03576	2.04624											
CENT	AG	7.71	60.7	-1.0461	-1.6123	-1.5807	-4.1982	-0.0011	0.04266	2.07835											
CENT	AG	9.84	77.4	-0.8158	-2.2105	-1.8459	-4.997	-2E-16	0.05264	2.61332											
CENT	AG	0.00	0.0																		
CENT	AG	9.68	76.2	-0.797	-2.1605	-1.9009	-4.9259	0.01625	0.06891	2.78274											
CENT	WG	6.68	52.6	-1.4279	-1.1235	-0.781	-3.4631	-0.0009	0.03495	1.96152											
CENT	WG	9.10	71.6	-2.156	-1.3611	-1.1014	-4.6773	9E-05	0.04918	2.57512											
CENT	WG	0.00	0.0																		
CENT	WG	9.73	76.6	-2.404	-1.4232	-2.1288	-5.4594	-0.0002	0.05755	2.59676											
CENT	WG	0.00	0.0																		
CENT	WG	8.60	67.7	-1.8747	-1.5096	-1.2585	-4.7058	-0.0007	0.04864	2.19934											
CENT	WG	0.00	0.0																		
CENT	WG	0.00	0.0																		
CENT	AG	0.00	0.0																		
EDGE	AG	0.00	0.0																		
EDGE	AG	7.99	62.9	-1.1989	-1.7255	-1.4303	-4.4531	-0.0002	0.04643	2.34635											
EDGE	AG	9.09	71.5	-1.2508	-1.9553	-1.4926	-4.8806	-0.0007	0.05053	2.56371											
EDGE	AG	0.00	0.0																		
EDGE	AG	0.00	0.0																		
EDGE	AG	0.00	0.0																		
EDGE	WG	7.87	61.9	-2.0525	-1.2579	-1.0851	-4.4312	-0.0004	0.04591	2.27349											
EDGE	WG	9.12	71.8	-2.2739	-1.4076	-1.1853	-4.9093	-0.0014	0.0501	2.48352											
EDGE	WG	0.00	0.0																		

Figure 1 Orientation of samples

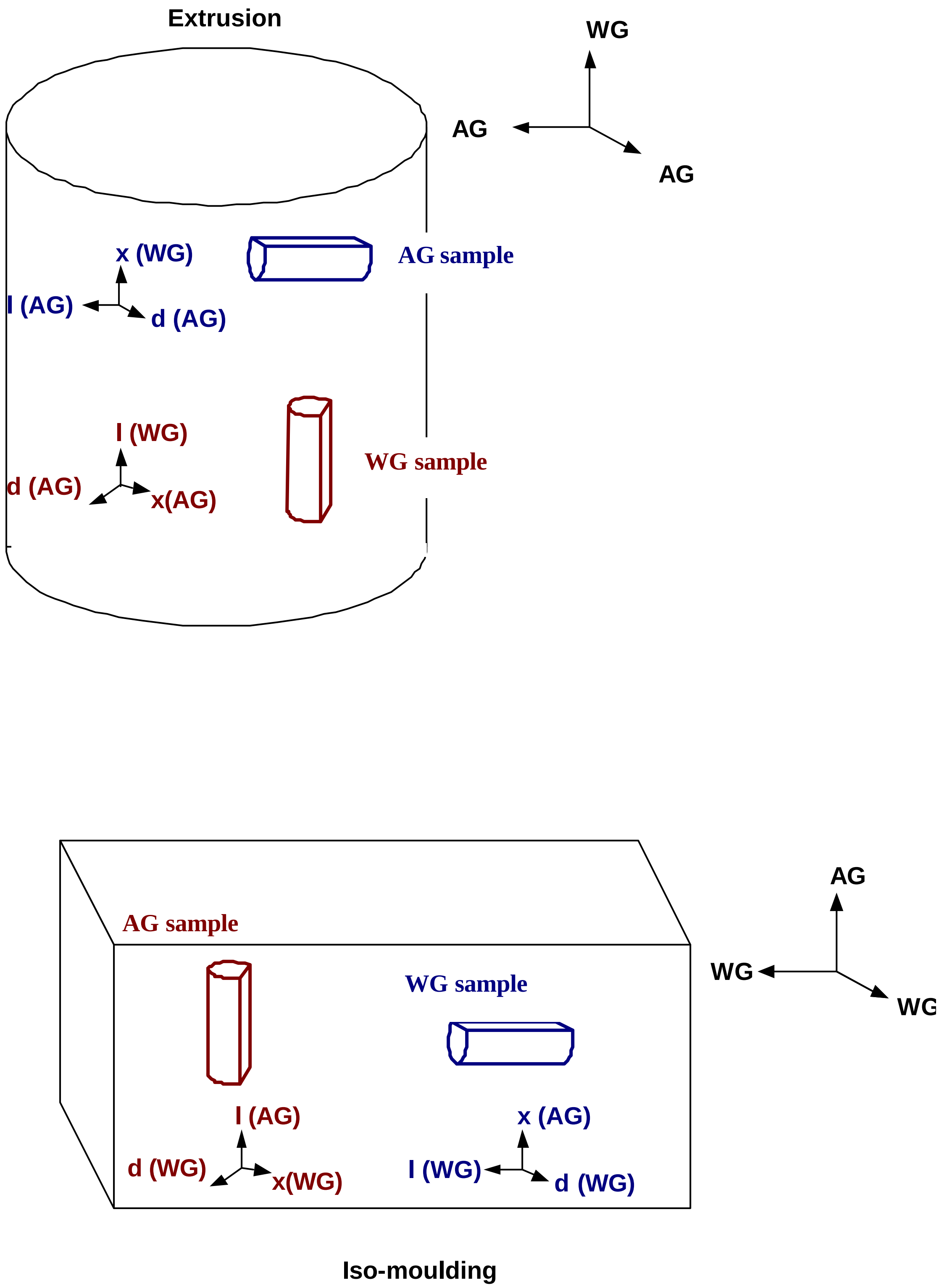

Figure 2 Dimensional change behaviour for NBG-10 (WG & AG)

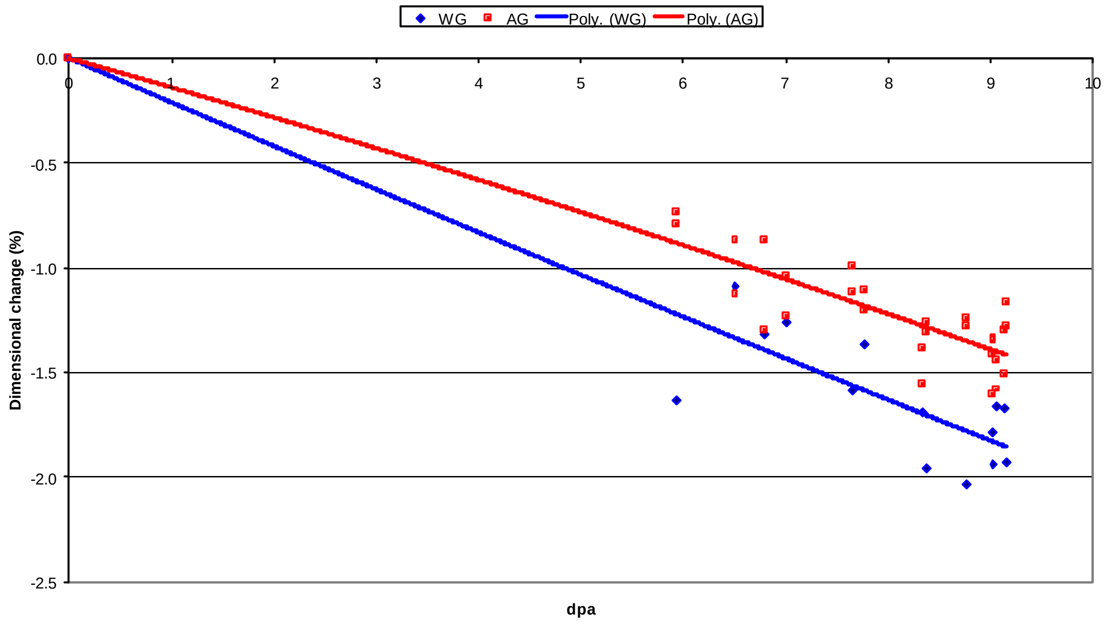

Figure 3 Volume change behaviour for NBG-10 (WG & AG)

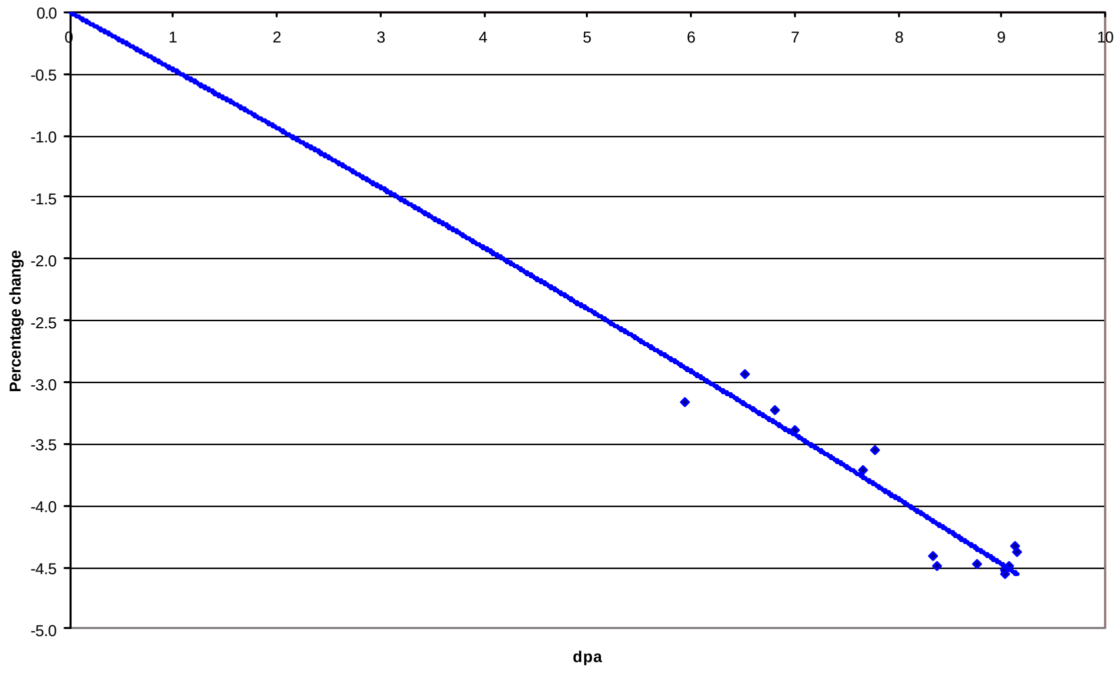

Figure 4 Dimensional change behaviour for NBG-20 (WG & AG)

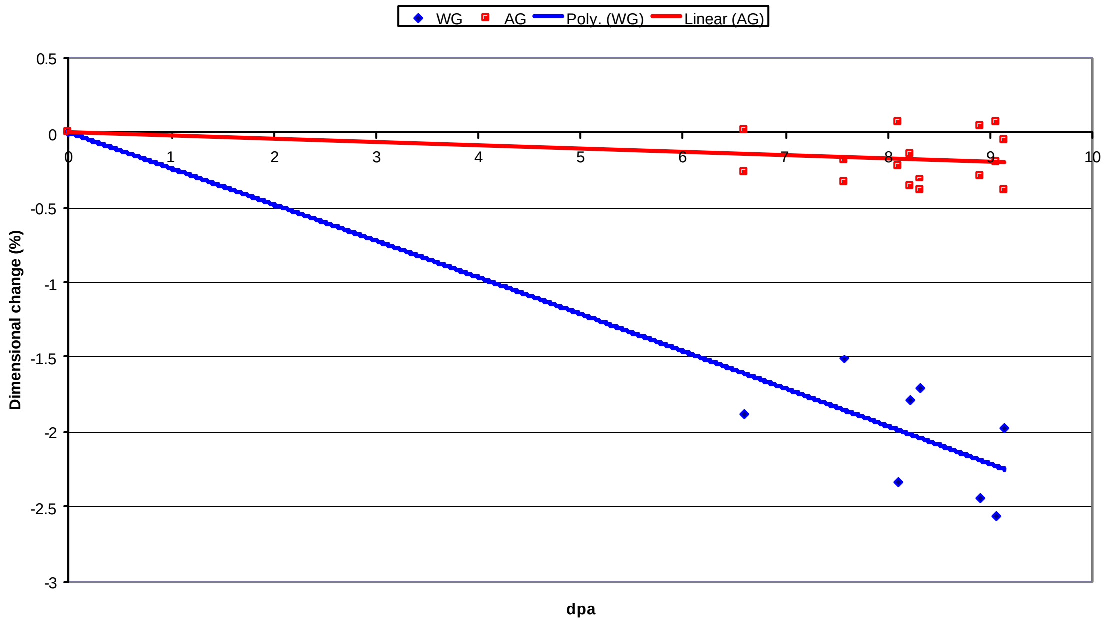

Figure 5 Volume change behaviour for NBG-20 (WG & AG)

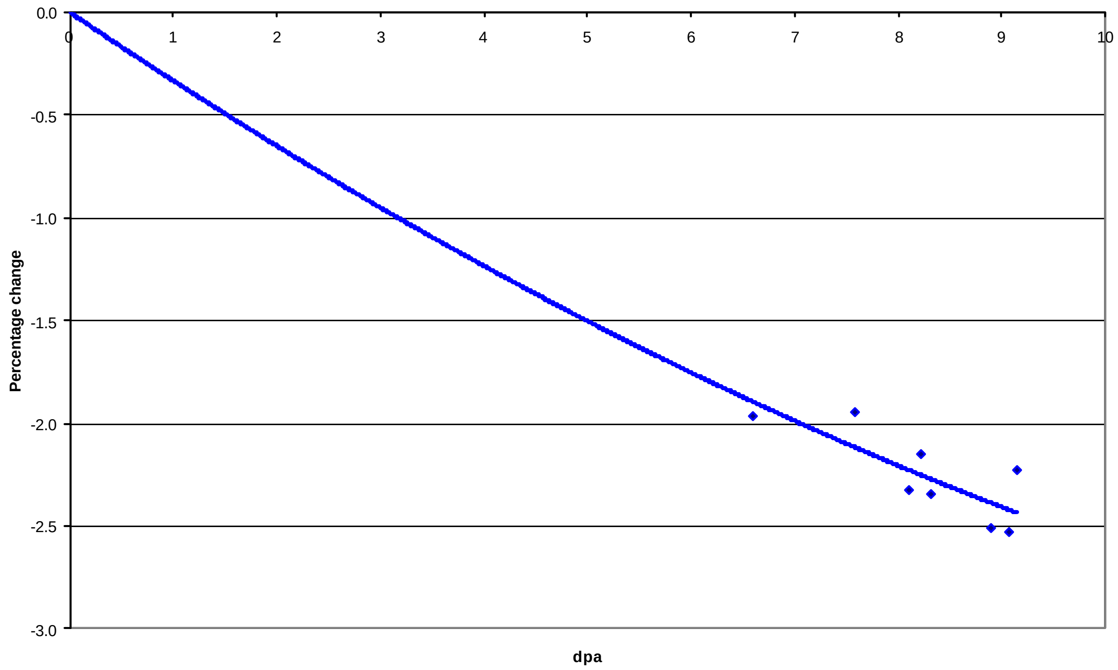

Figure 6 Dimensional change behaviour for NBG-25 (WG & AG)

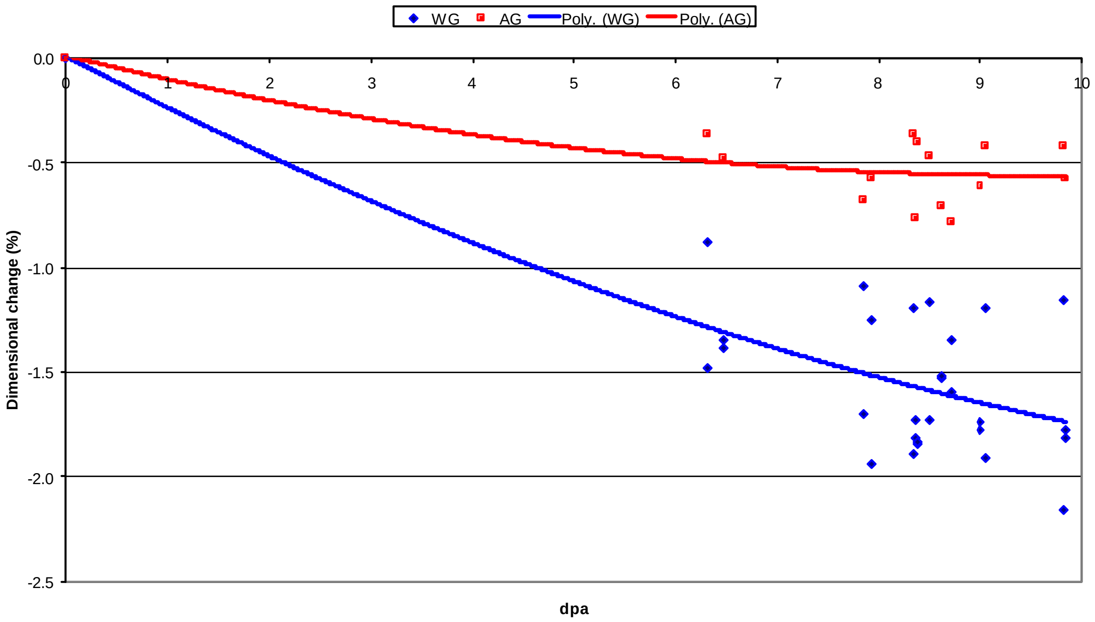

Figure 7 Volume change behaviour for NBG-25 (WG & AG)

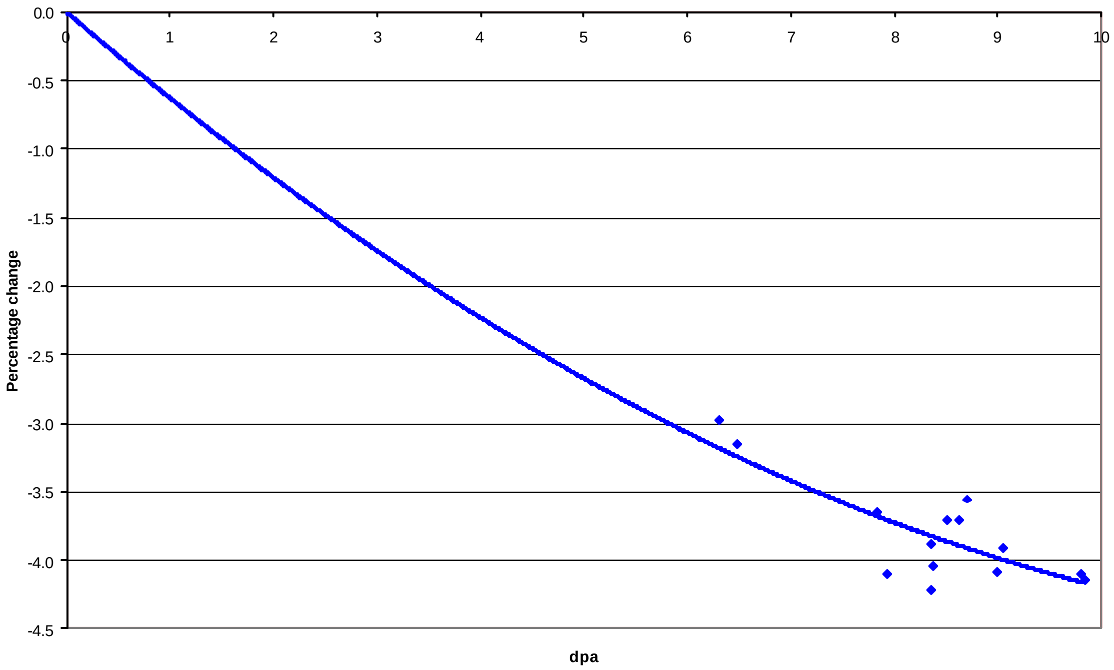

Figure 8 Dimensional change behaviour for PCEA (WG & AG)

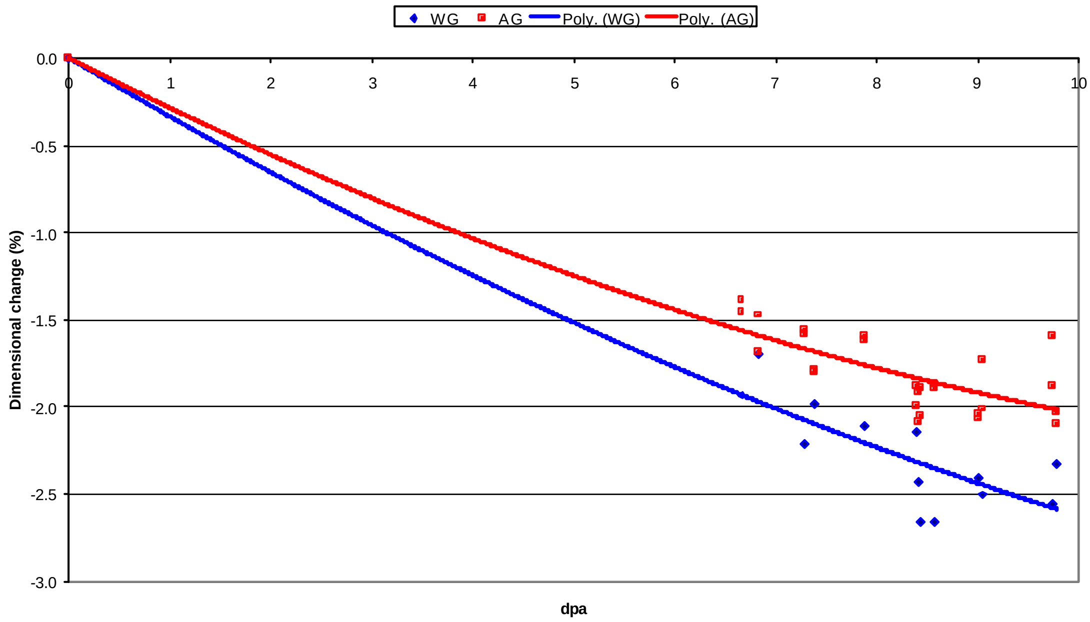

Figure 9 Volume change behaviour for PCEA (WG & AG)

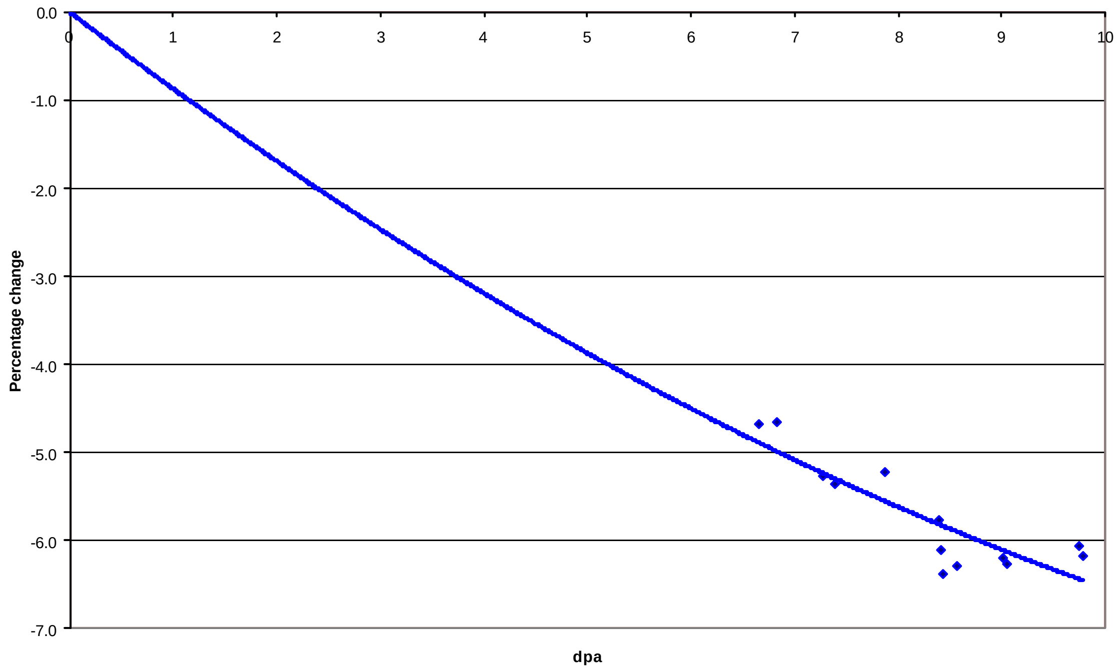

Figure 10 Dimensional change behaviour for PPEA (WG & AG)

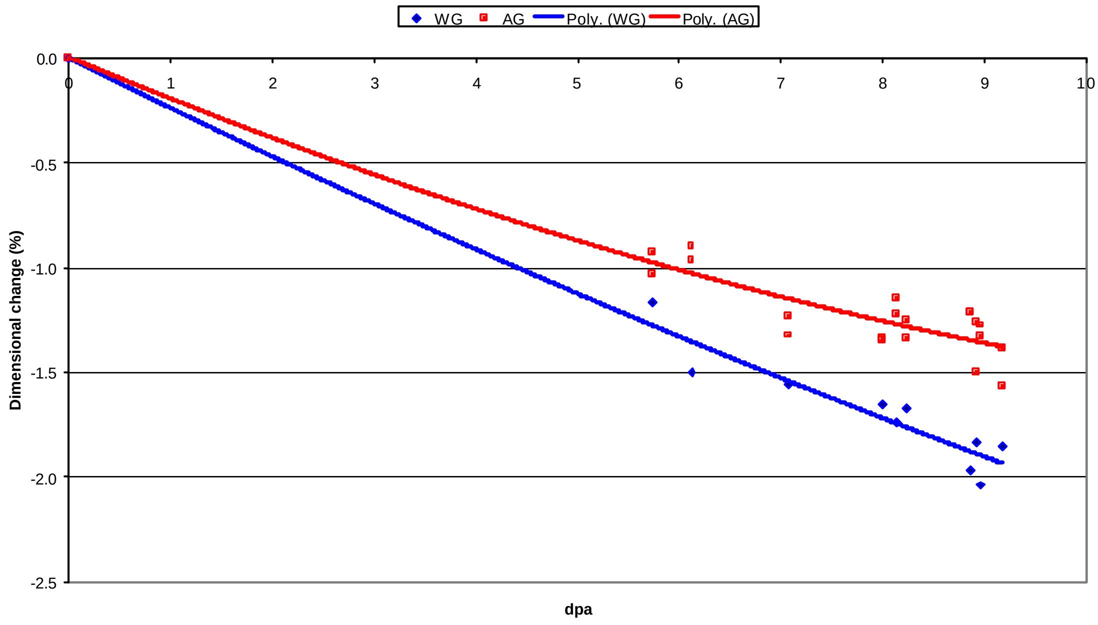

Figure 11 Volume change behaviour for PPEA (WG & AG)

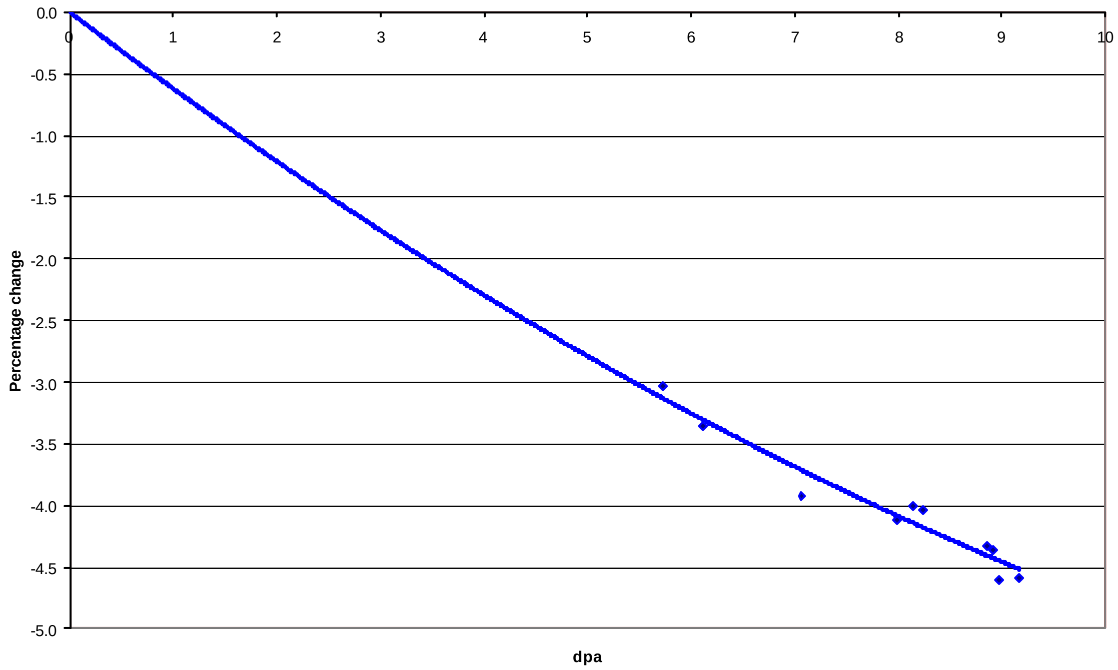

Figure 12　　Dimensional change behaviour for PCIB (WG & AG)

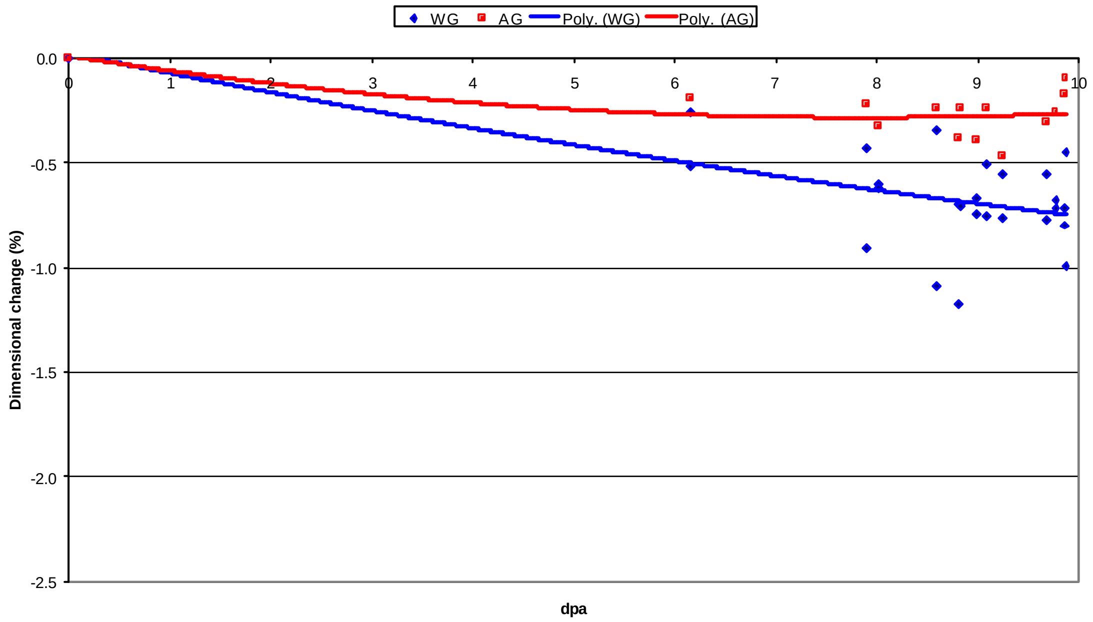

Figure 13　　Volume change behaviour for PCIB (WG & AG)

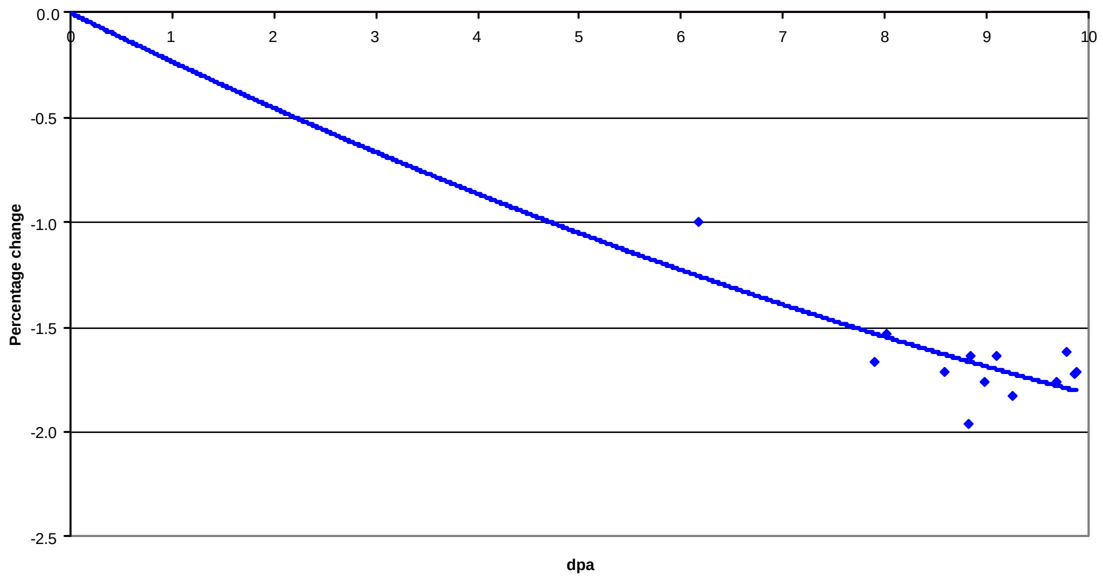

Figure 14 Dimensional change behaviour for IG-110 (WG & AG)

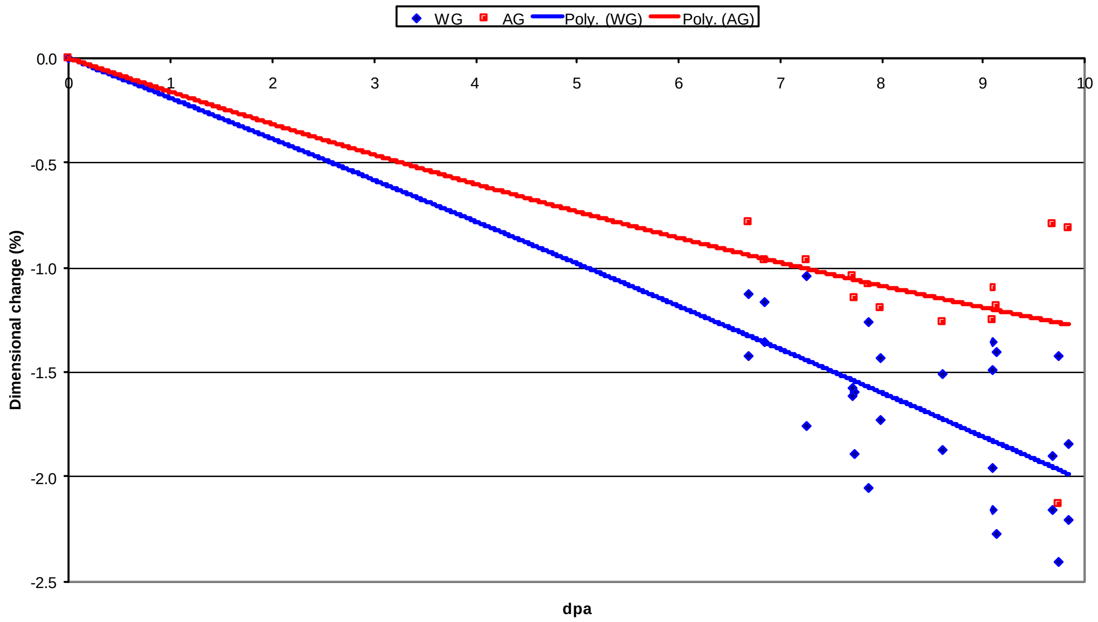

Figure 15 Volume change behaviour for IG-110 (WG & AG)

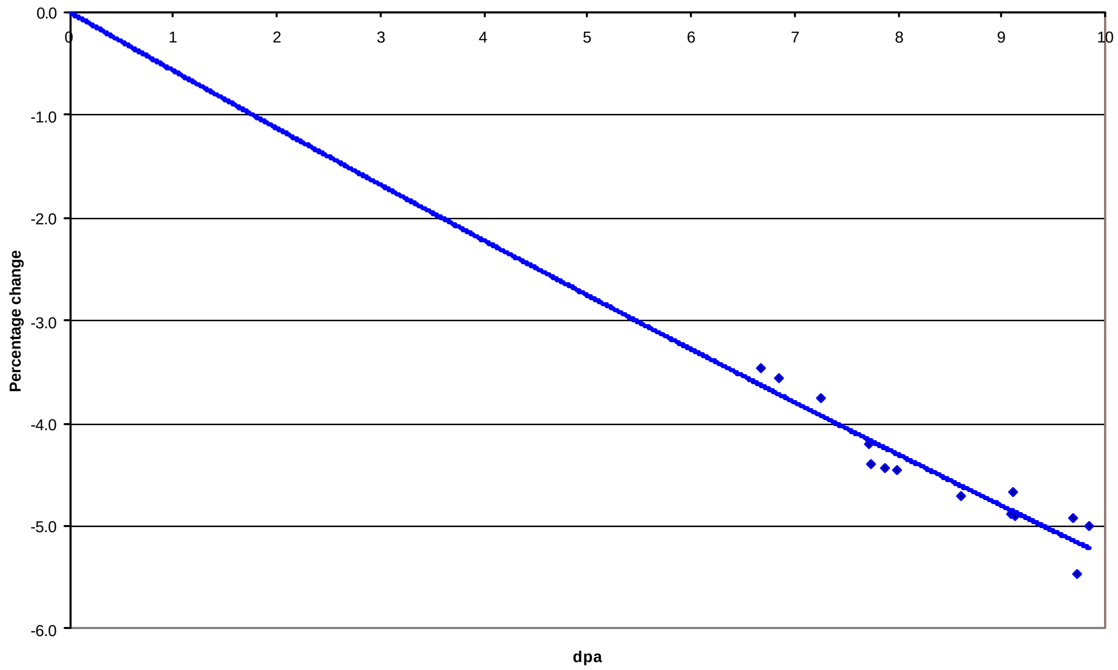

Figure 16 Dimensional change behaviour for IG-430 (WG & AG)

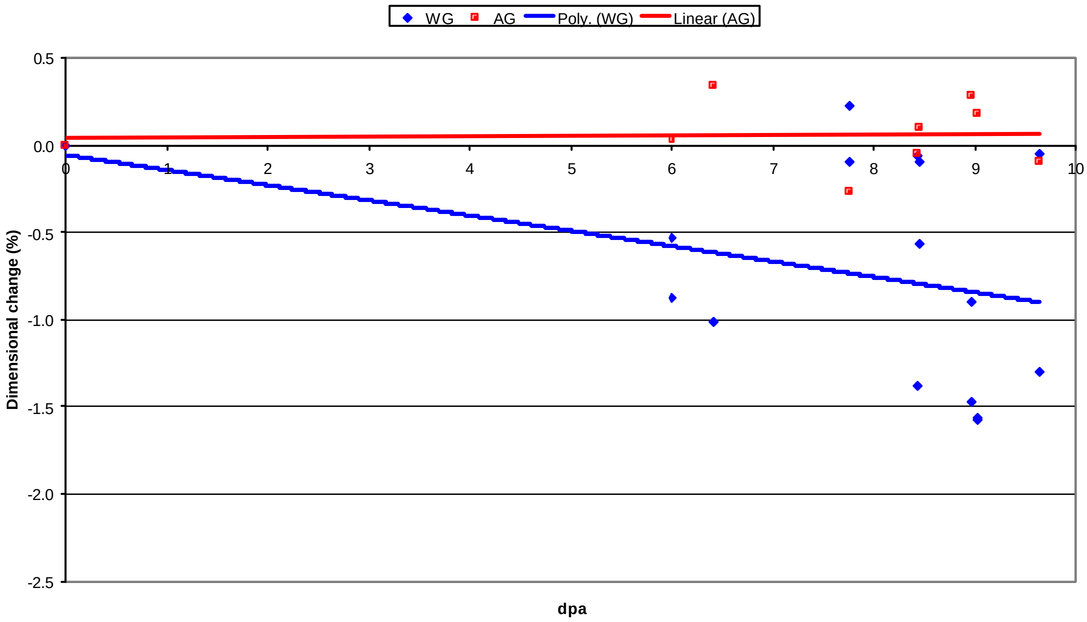

Figure 17 Volume change behaviour for IG-430 (WG & AG)

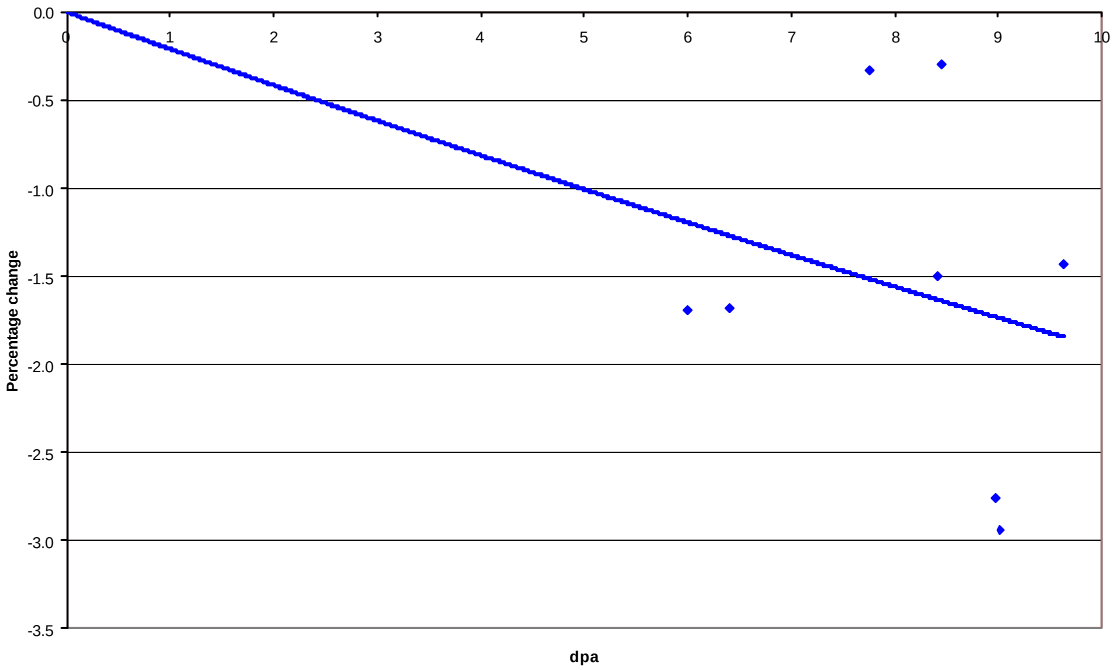

Figure 18 Change in DYM for NBG-10

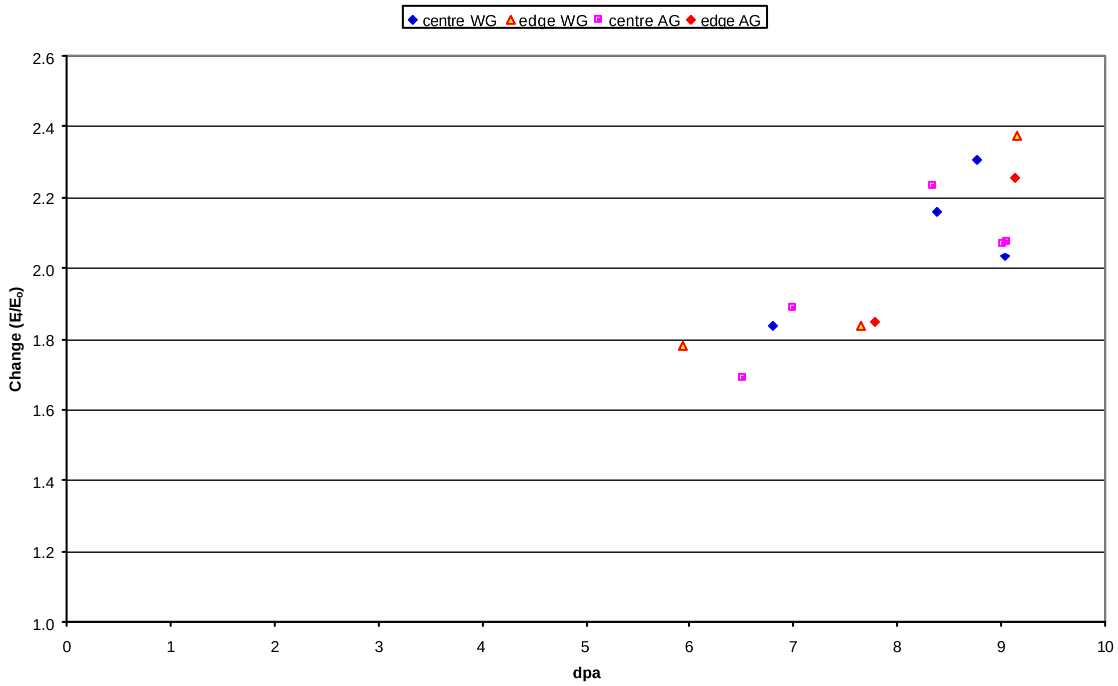

Figure 19 Change in DYM for NBG-20

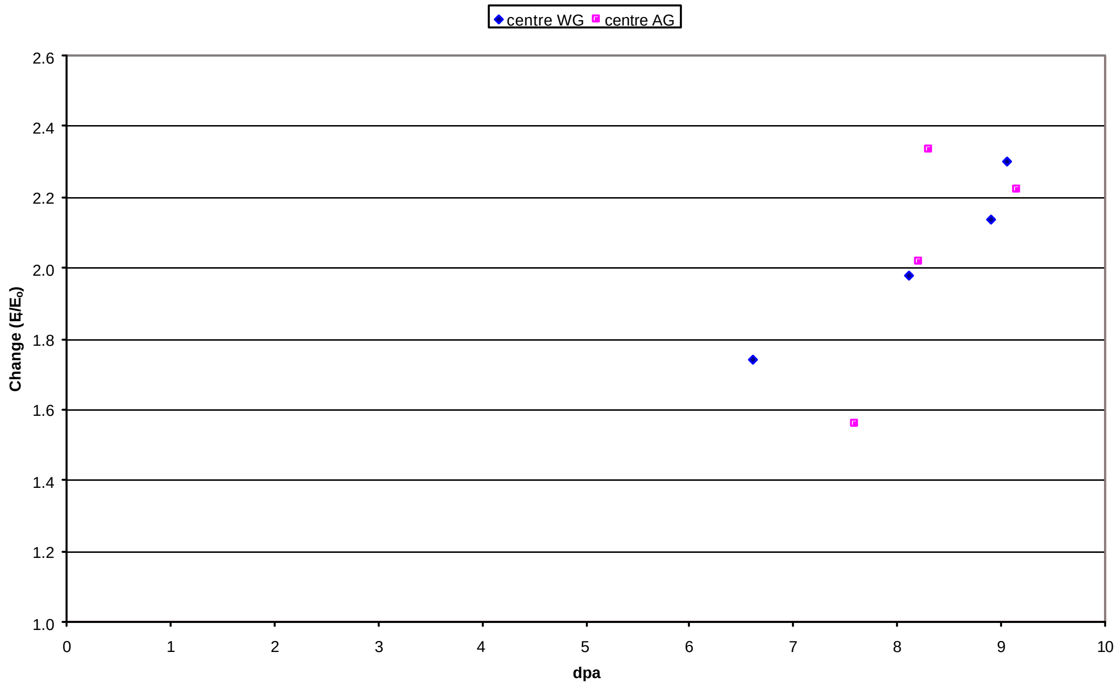

Figure 20 Change in DYM for NBG-25

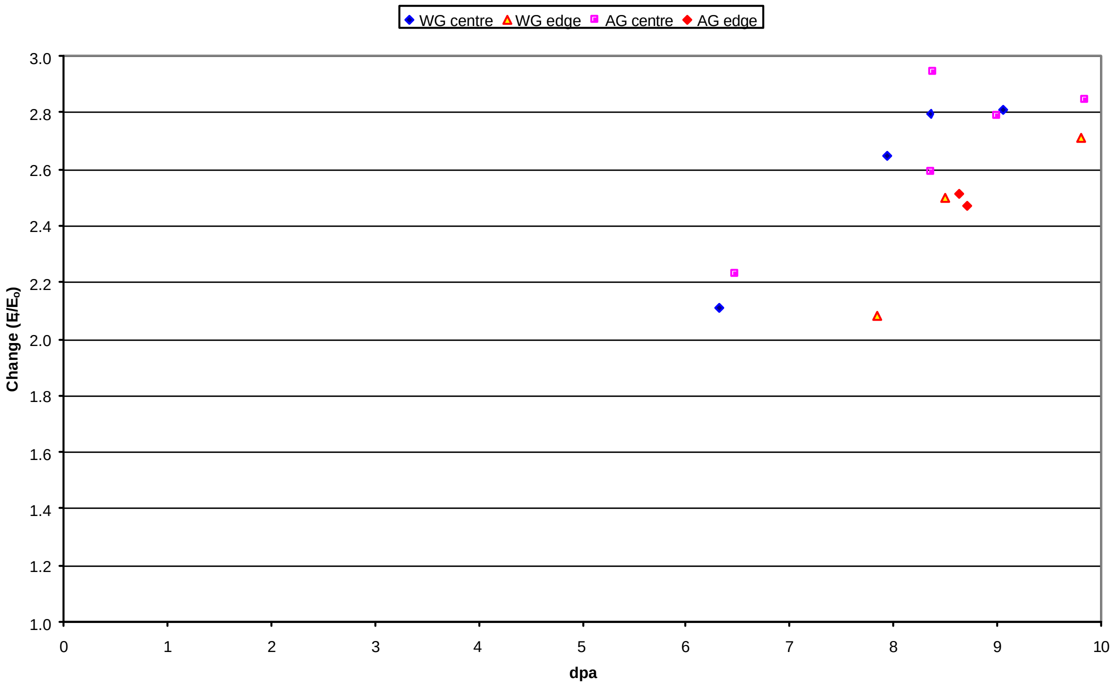

Figure 21 Change in DYM for PCEA

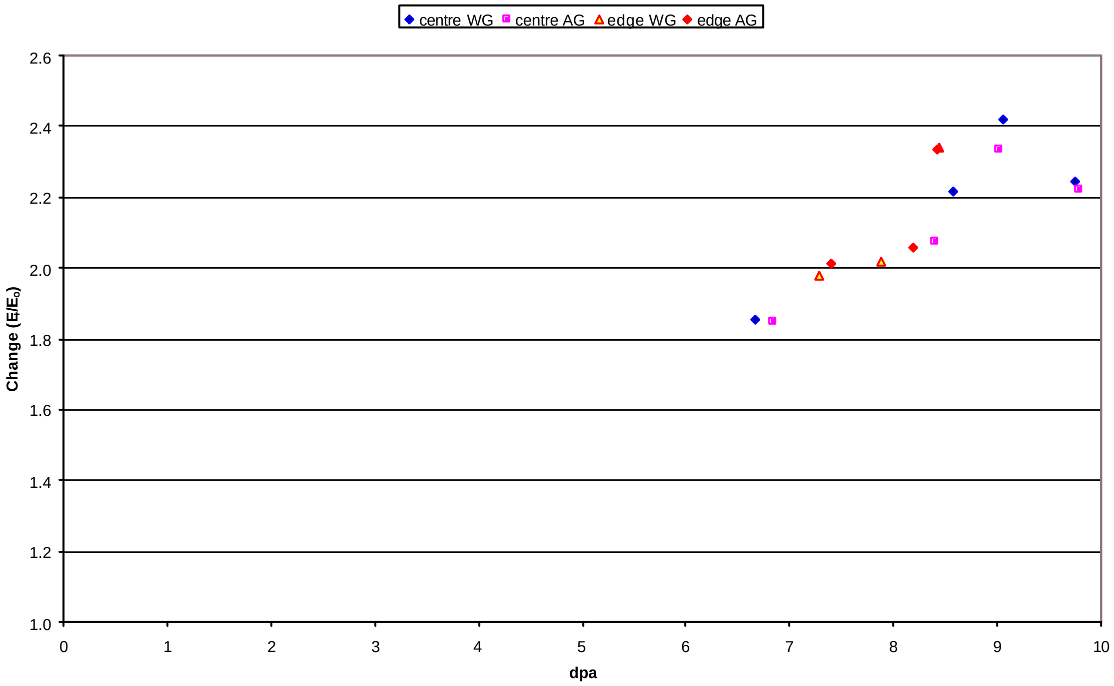

Figure 22 Change in DYM for PPEA

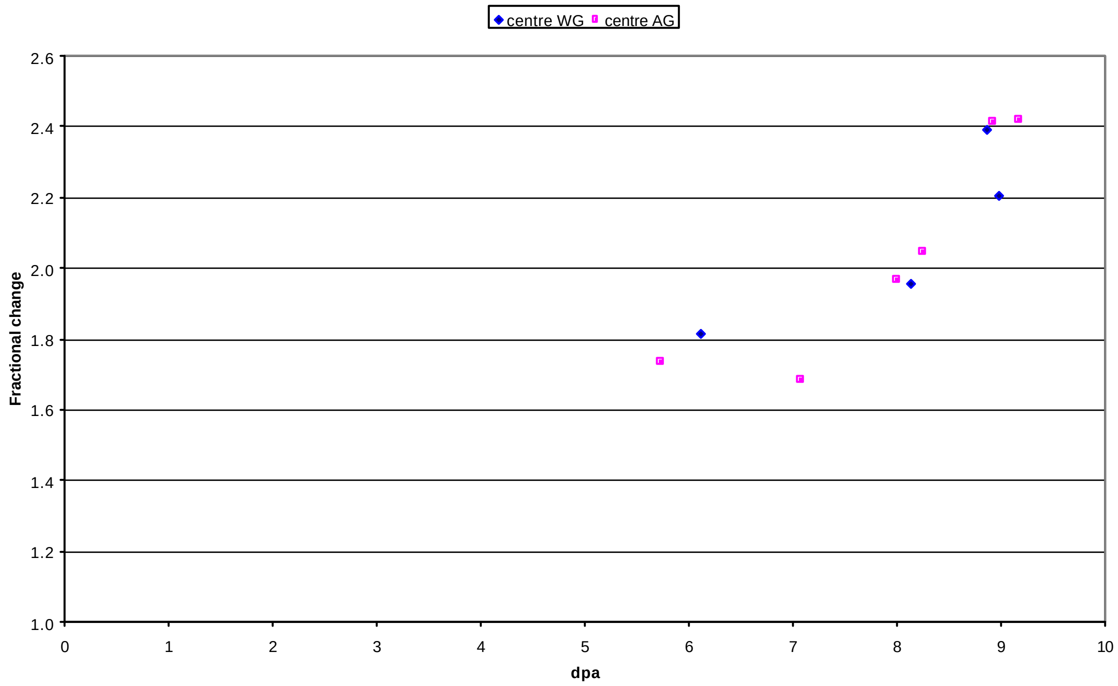

Figure 23 Change in DYM for PCIB

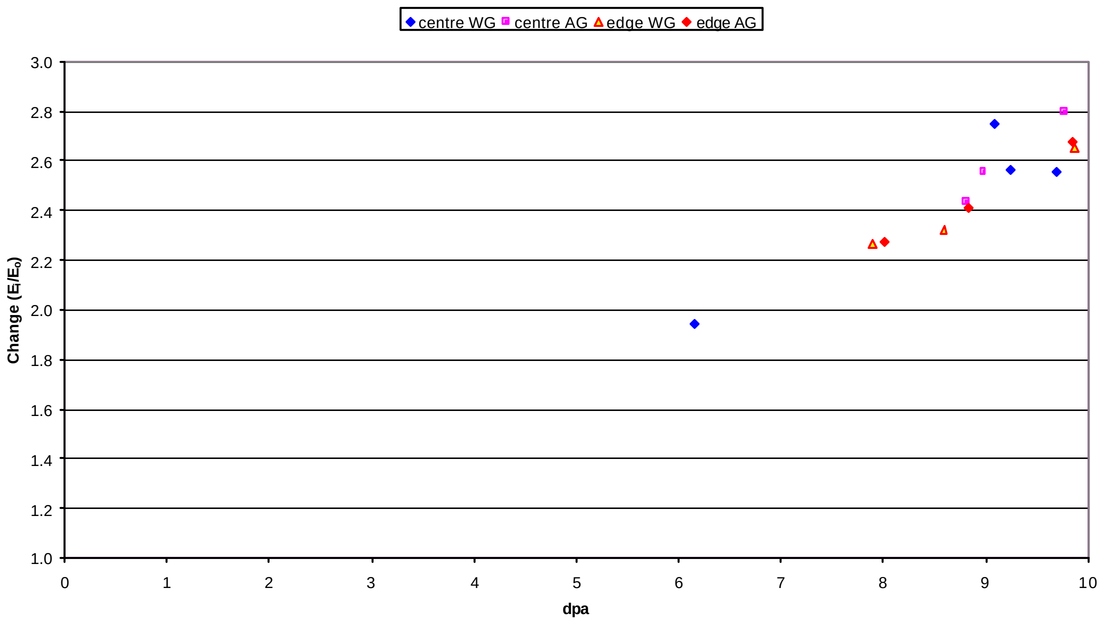

Figure 24 Change in DYM for IG-110

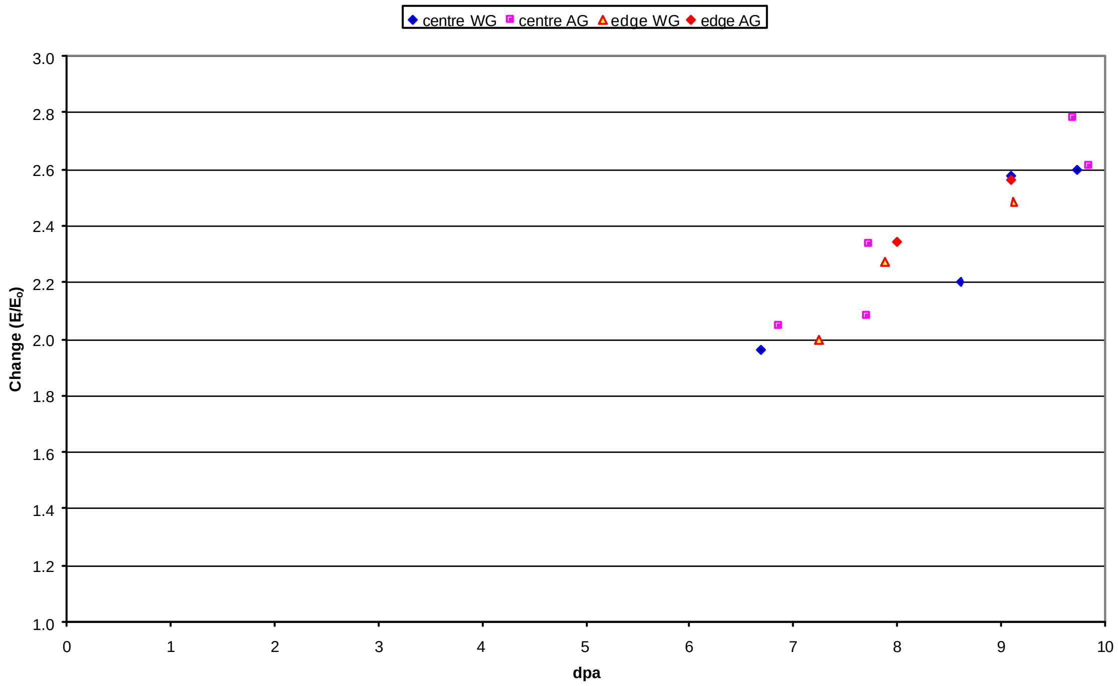

Figure 25 Change in DYM for IG-430

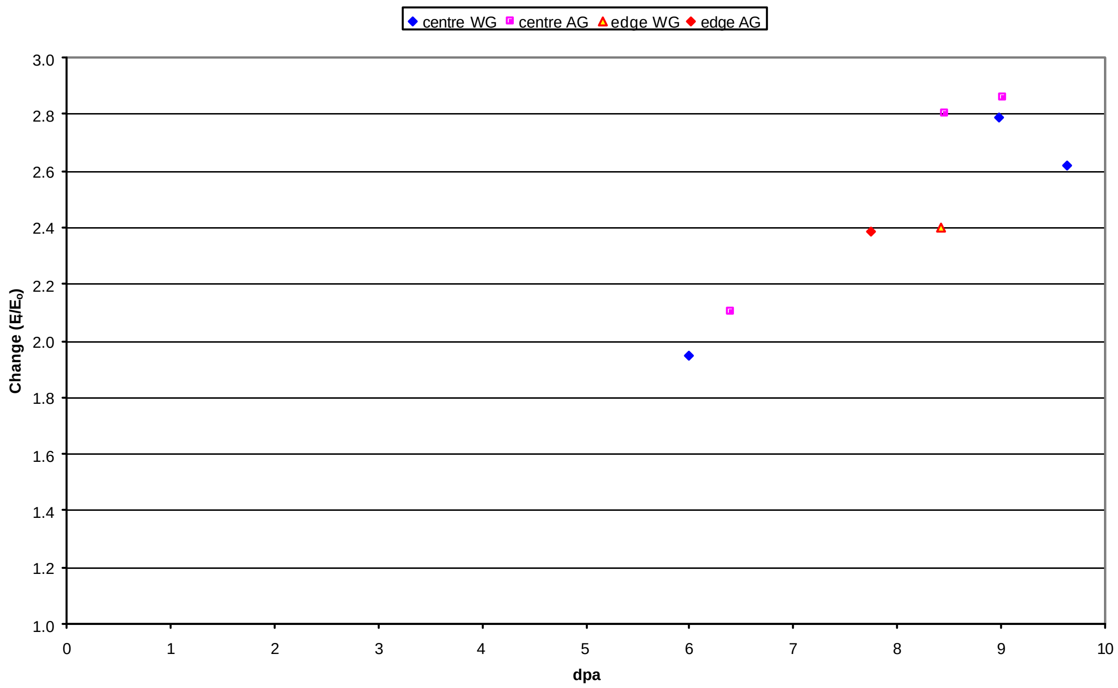

Figure 26 Comparison of dimensional change behaviour of NBG-10 with ATR-2E

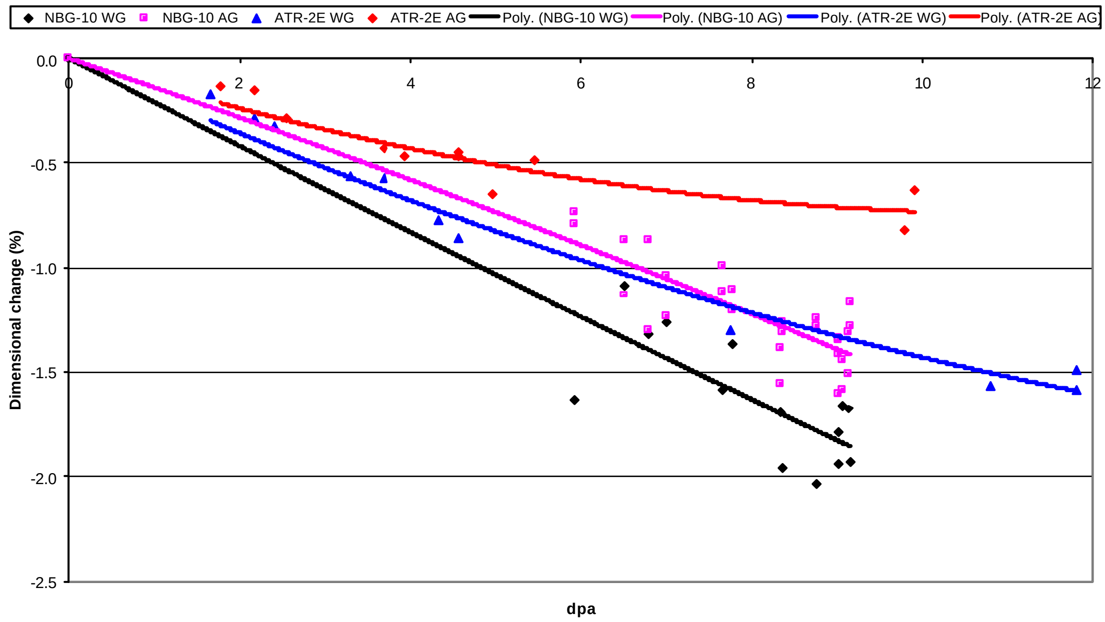

Figure 27 Comparison of dimensional change behaviour of PPEA with ATR-2E

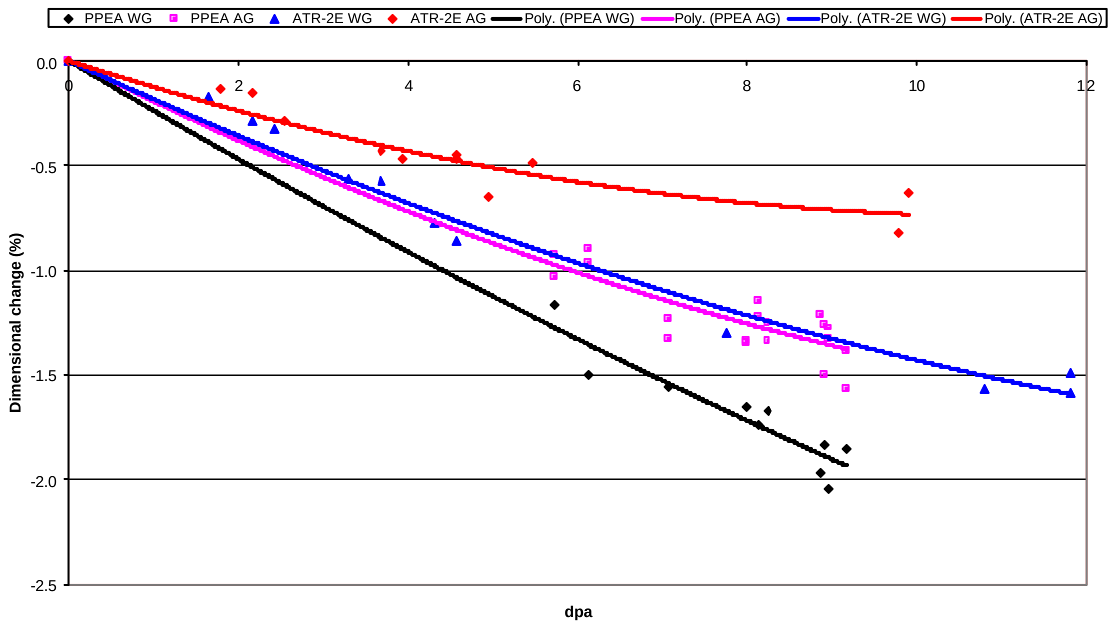

Figure 28 Comparison of changes in DYM for NBG-10 with ATR-2E

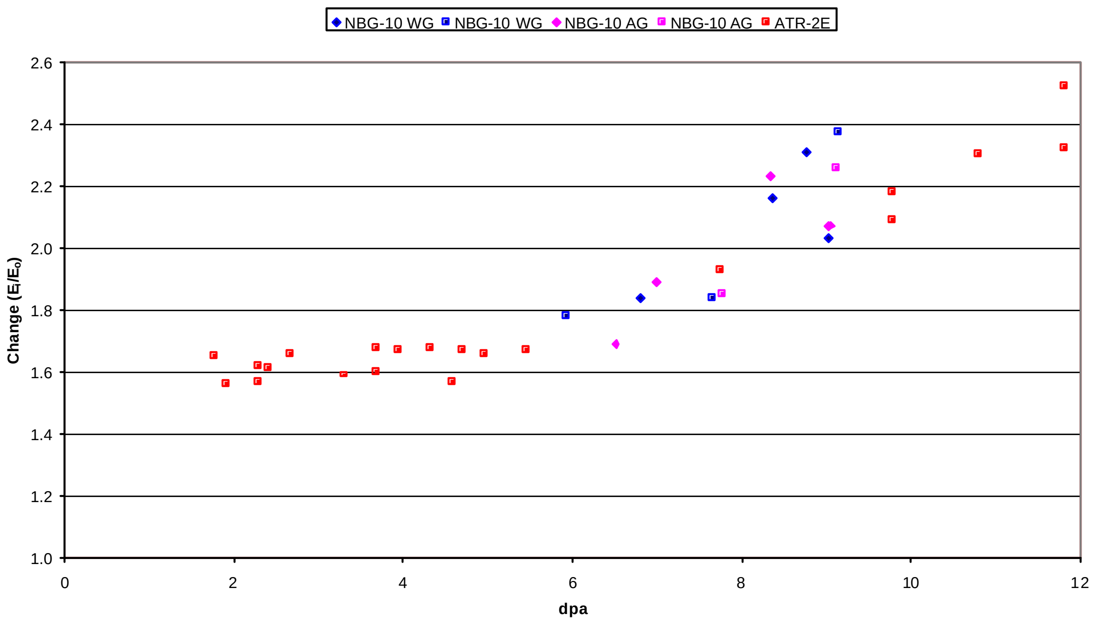

Figure 29 Comparison of changes in DYM for PPEA with ATR-2E