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2 ABSTRACT

The aim of this project has been to develop a recycling process for high performance engineering plastic composites. Short glass fibre reinforced PBT30%GF and PPS40%GF have been identified as most strategic materials for products of the industrial partners Danfoss and KEMA. Another important issue has been the quality and durability of recycled materiais. Especially the long-term performance of recycled materials should be guaranteed before manufacturers of high performance industrial components will implement recycled materials into their products. The project has show, that for a specific type of plastic waste stream — high quality and high price engineering thermoplastic composites — the concept of material recycling can be implemented with success both technically and economically. In particular PPS40%GF, that is not recycled nowadays has a large potential for recycling and reuse in high demanding applications again. The project has also shown that recycled materials appear almost as good as virgin materials in long term wet service conditions. A pre-classification database system has been developed to extend the work of this project to other applications in recycling of piastic materials.

Models have been developed and implemented in software, which can describe and predict the material behaviour of virgin and recycled materials under several long term sewice conditions.

3 INTRODUCTION

The increasing international focus on the environment and the exhaustion of natural resources leads to national and european legislation imposing recycling and reuse of manufactured products after their service iife. These fast growing trends of environmental protection force european production industries to recyciing of their products, design for recycling and use of secondary materials.

One of the Priority Waste Streams (PWS) as appointed by the European Commission inciude electronic and electrical products. Two major industrial partners in the project (Danfoss, Denmark and KEMA, Netherlands) are confronted with these environmental issues for their products, that faii within the PWS electronic and electrical products. Danfoss is a leading producer of precision mechanical and eiectronicai components and of intelligent mechatronic devices iike thermostats, vaives and pumps. KEMA is a private company in technicai consuitancy and R&D in the fields of energy, environment and quaiity, representing the Dutch Electricity Utiiity in this project. In the Electricity Utility industiy iarge amounts of electrical components are used that are nowadays iandfiiled after service.

These type of components have in common that they consist mainiy of various high quaiity metai and plastic parts. Landfili of these components after their service iife does not oniy put a heavy load on the environment, but is also economically a waste of money, since expens-ive high quaiity metal and piastic parts are dumped instead of reused.

In general recycling of metal components does not give technicai or economical restraints. However the recycling of piastic components is both technically and economically unfavorable at the moment. For plastic materiais with a low virgin price (1 to 2 ECU per kilo) such as LDPE, HDPE, PP or PVC, recyciing will be diff!cult to realise from an economic point of view. However piastic materiais iike glass fibre reinforced PBT and PPS as used in the type of components of interest to Danfoss and KEMA have typicai virgin prices of 3.5 ECU for PBT to 9 ECU for PPS. These high virgin prices make recycling of oid components economically feasible. This has lead to the definition of a research project aiming at developing a recyciing process for high performance engineering piastic composites. Short glass fibre reinforced PBT, PPS and PES have been identified as most strategic materials for products of Danfoss and KEMA.

Another important issue is the quality and durability of recycled materials. Especially the long-term performance of recycled materials should be guaranteed before manufacturers of high performance industrial components will implement recycled materials into their products. Required service life times of 10 to 30 years are common in this respect.

Therefore the two main goals of the project can be formulated as follows:
1 development of a recycling process for high performance engineering plastic composites
2 assessing the quality and durability of the resulting secondary materials.

4 TECHNICAL DESCRIPTION

The technical set-up of the project is presented in the project flow chart in figure 1, in which the subtasks of the project have been defined with their respective relations.

Initially three materials had been selected as case-study materials for recycling, based on the strategic importance of those materiais for the pati[cipants.

However after planning the project in detail, the amount of experiments became too large for continuing with three different starting materials. Therefore 2 materials — PPS40YOGF and PBT30YOGF — have been selected for investigation in this project.

In task 1 virgin test bars have been injection mouided. A part of the test bars have been aged in several ways artificially in order to simulate various degradation states. For classifying old components into different ageing states, a pre-classification system has been developed???. The various virgin and aged batches have been classified and characterised using different test methods. The test methods have been assessed in terms of suitability **for classification of** old components as part of the pre-classification system

Task 2 has involved the investigation and optimisation of the regranulation process with the main objective to produce a small but uniform particle size distribution. An experimental test plan was drawn up incorporating the granulator settings that were most likely to influence the particle size distribution. Apart from particle size, the fibre length distribution was measured.

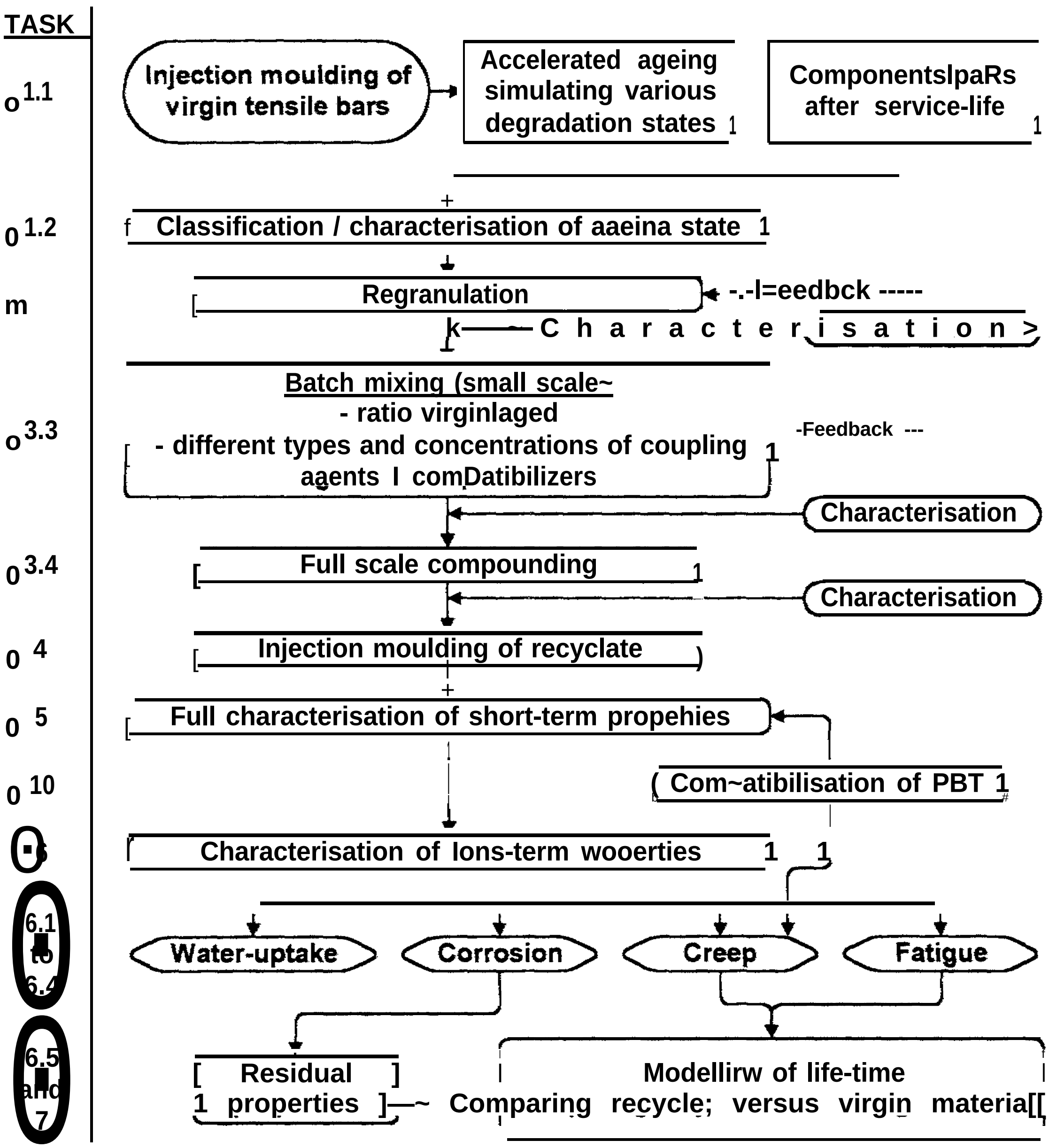

Figure 1 project flow diagram

In task 3 various commercially avaiiable coupiing agents of siianes, titarrates and zirconates were experimentally investigated in order to upgrade and re-establish good fibre matrix interface performance of aged grades of giass fibre reinforced PPS and PBT.

The upgrading has been performed by small scale compounding - batch mixing. Small test samples were produced by injection moulding of the compounds following material characterization by mechanical, theological experiments and SEM, SIMS, TGA and DSC analysis. Based on approximate 150 small scale compounding experiments 28 formulations were set up for full scale compounding of PPS and PBT including:
1 Upgrading of aged PPS grades by repairing the degraded fibre matrix interface
2 Upgrading of ages PPS grades by compounding of suitable ratios of virginlaged material
3 Upgrading of aged PBT grades by compounding of suitable ratios of virginlaged material,

Task 4 had three main objectives:
1 investigating the processability of recompounded and regranulated thermoplastic composites PPS40°AGF and PBT30%GF by injection moulding using the same processing parameters as with virgin materials. This is crucial for implementing recycled materials in the manufacturing process of precision components
2 injection moulding the 28 formulations that have been compounded in task 3 into test bars for subsequent investigation in tasks 5 and 6
3 investigating the effect of multi-processing (multi-recycling) on the mechanical properties of the resulting secondary material.

In task 5 the 30 injection mouided formulations have been fully characterized in terms of mechanical and physical/chemical properles directly after injection moulded. The materials have been characterized by impact strength, tensile properties, flexural properties, molecular weight (only PBT], melt flow index (only PPS}, thermal analysis (DSC, TGA), SEM fracture analysis and 13MTA. Based on the short-term characteristics of the recycled and virgin batches, in total fl 3 compounds have been selected for further long-term characterisation.

Task 6 has basically been divided into 3 subtasks:
I Samples have been exposed in accelerated environments, a.s extracted from the respective sewice conditions of PPS and PBT. The weight gain has been recorded continuously up to 4500 hours. At regular exposure time intervals, samples of various formulations have been extracted from the different environments and subsequently tested destructively by various mechanical and physical tests. h this way the properties of virgin and aged material could be followed as a function of exposure time. Extrapolation to real service conditions and life times of 10 years makes comparison between virgin and recycled formulations possible
1[Samples have been subjected to creep loads under various environmental conditions, that are accelerated based on service conditions
Ill Finally only PBT samples have been subjected to fatigue loading, since this type of loading was only of importance for PBT material applications.

Task 7 is the effort of developing models for materials behaviour as measured in task 6 as a function of the material formulations under environmental, creep and fatigue loadings.

The environmental effect on the different material formulations has been modelled by monitoring the impact strength as a function of the rnateria! weight change and as **a** function of exposure time. Models have been developed for the behaviour of virgin and recycled PPS and PBT under creep loading as a function of environmental conditions and material formulations. Modeis have been deveioped to predict the behaviour of virgin and recycied PBT under fatigue loading. The developed models have been validated by the test resuits as acquired in task 6 and were subsequently implemented into commercial software.

Based on the outcome of the recyciing effort for PBT materiai, it was decided that additional work would be required to try to upgrade old Pi3T materiai by using compatibiiizers. A task 10 was deveioped to investigate the potentiai of compatibilizers for repairing degraded PBT polymer. In task 10 a slightly aged PBT batch was compounded with two types of compatibilizer in two concentrations. Tensile bars were injection moulded and tested on tensile properties, moiecular weight and creep performance.

In this project a large amount of data on the materiais were generated. A database system has been deveioped to store and handle all these data and to make sure that they can be used beyond the scope of this project.

More detailed experimental details did not fit in the scope of this synthesis report.

5 RESULTS

5.1 Pre-classification system and REDAMAS*

Nowadays secondary materials from old components are often used in low value components without using the real potential of the materiais. They are oniy genericiy sorted. This can be done using separation techniques based on density differences (sinking, fioating, hydrocyclonage ect.), polymer surface propefiies (flotation} or eiectric propetiles (electrostatic separation, dielectric separation}. When all the components of a given type of poiymer are separated the components are granulated in one big batch. As an example: PBT used in humid environments and in dry environments is mixed. That means materiai that’s not degraded is mixed with degraded materiai, and the resuit is a batch of material with average or poor propetiles.

An alternative way of deaiing with it is to separate components of a given polymer-type that’s degraded differently, and granulate them in different batches. As an exampie: PPS used in air and in iiquid. The PPS used in air has f 00% of the virgin properties and can be used directiy into new components.

The PPS used in liquid can be maybe upgraded to 10OVO of the virgin properties and can then be used directly into new components. That gives the possibility of having optimum materials. Therefore a pre-classification-sy stem has been developed containing the following information items for the different materials:

- Successful quality assessment methods to classify the ageing state of components made of a given material
- Level of properties / ageing state after use under given conditions
- Suggestions how to upgrade or use the aged material.

A diagram of such a system is illustrated in figure 2,

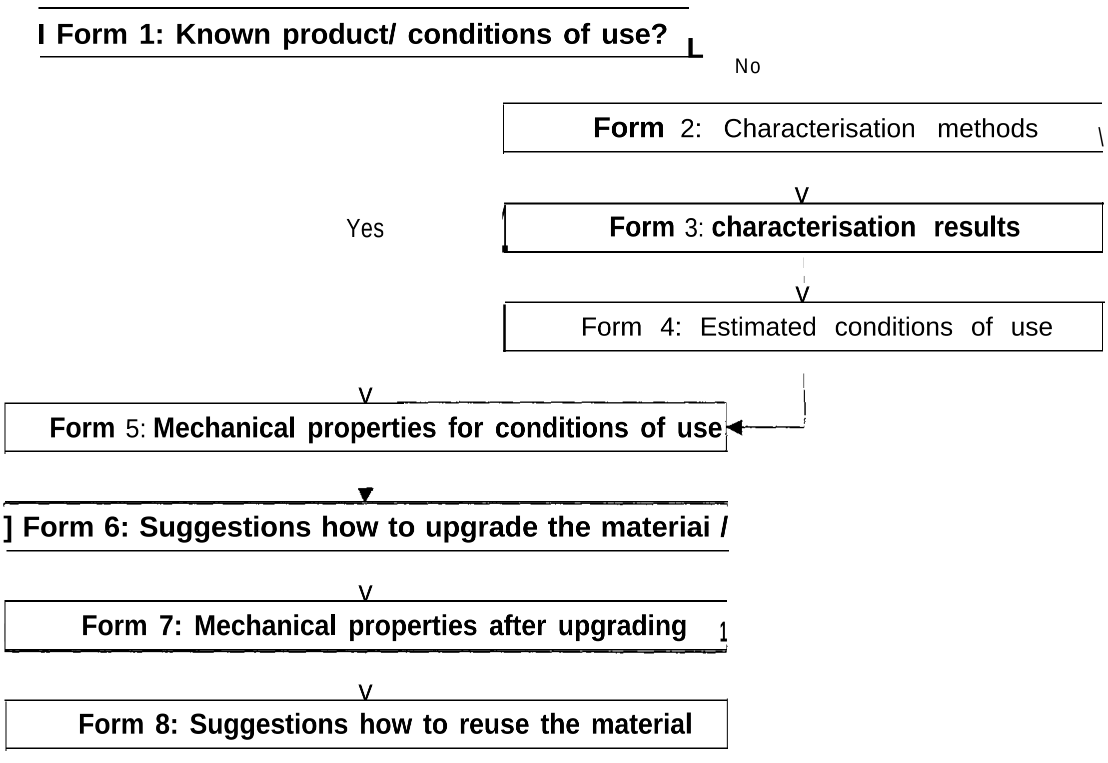

Figure 2 The pre-classification system

This pre-classification-system is meant to be set up in a database and to be continuously expanded with test results. The pre-classification system enables companies to determine / decide very fast how to reuse components with known and unknown history in an optimum way.

A relational data management system (REDAMAS$I has been developed to store and link all data associated with the characterisation and assessment of dd components, the recycling processing details and the characterisation of the resulting seconda~ materials.

The system will be used in combination with thepre-classification system. H has been based on the commercial software package Paradox. In figure 3 the outline of the system is presented with the relations between the tables.

PARADOX DATABASE FOR BE-5586: BASIC TABLES

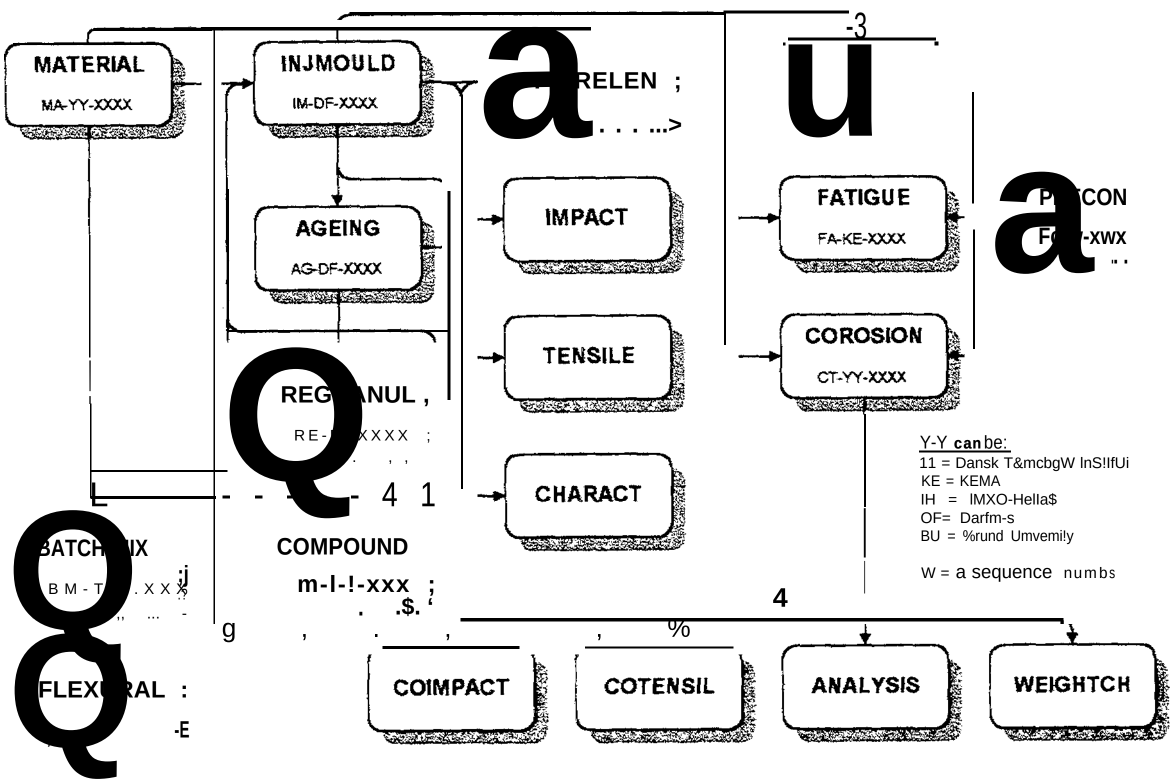

Figure 3 Relational data management system (REDAMAS~

All data of the respective tasks are stored in various tables that are related by different codes. Codes have been defined for material type, injection moulding run, ageing condition, regranulation run, compounding run, creep test, corrosion test and fatigue test. These codes are used in other tables for storing the data that belong to the various codes.

Through this system each produced sample has its own code and its history can be tracked down exactly. Through this relation it is possible to ask the system questions, named **'Queries". This is** clarified by the next example. Let us assume that we have performed two creep experiments with two samples that have respective creep codes TC-KE-0236 and TC-KE-0237. They are tested under identical conditions and have the same injection moulding code IM-DF-0039. This means that the samples had the following processing history before testing:

1 virgin material injection rnoulded (characterised by code IM-DF-0003)
2 these samples have been aged for 2000 hours at 140 “C at pH 2 (characterized by ageing code AG-DF-0006)
3 then they were regranulated (characterized by regranulation code RE-BU-0093)
4 then they were injection moulded into new test bars (characterized by injection code IM-DF-0039).

Let us assume that the two creep experiments show different results. The query could then be executed asking if the two samples were from the same cavity in the mould of the injection moulding machine. Thus by reiating the tables through the different codes any question can be asked about the material behaviour in relation to certain processing conditions.

This system for management of data is implemented into the pre-classification and used for the classification of incoming material after service. The system could aJso be coupled to other materials databases for more general use.

5.2 Recycling process for PPS40°AGF

As a first step in the recycling process of PPS40YOGF, the effect of different regranulation parameters on the material properties was investigated. This has been done for different ranges of particle size. [n table 1 the most significant parameters of the regranulation process are presented.

Table 1 Significant variables and interactions in the regranulation process

Partkle size {mm}	Significant variables	Interactions
< 0.5	Screen, Material condition	None
0.5-0.-71	Screen, Material condition	Material condition/Clearance
0.71 -1.0	Screen, i'vlateriai size, Material mncti- tion	Screerd!vlaterial condition Screen/Knives Material size/Knives Material condition/knives
1.0 -1.4	Screen, Materiai size, Material condi- tion	None 14 - 7(-l
Screen	None	
2.0-3.35	Screen, Material size	Screen/Material size Screen/Material condition
3.35 -4.0	Screen, Material size, Material condi- tion	None
4.0-4.75	Screen, Material size, Material cortdi- tion	Screen/Material size Screen/Material condition
~ 4.75	Screen, Material size, Knives	Screen/Material size Screen/knives

Also the effect of dust level !n the regranulate on the mechanical properties was investigated. The results are presented in table 2.

Table 2 Effect of dust level on the mechanical properties of PPS40?'OGF

~' "PFS {Ryton R4=XTj ~"'	Stress at Break (MPa}	Strain at Break (%)	Modulus (iVlPa}	Impact {kJ/m')
Regranulated	**198**	1.7	**14,800**	**36.7**
+ 3°~ dust	181	1.5	15,800	24.6
+ 8% dust	181	1.5	15,400	27.0
+ 13% dust	181	1.5	16,600	26.9

The mechanical properties of PPS40'%OGF undergoes a drop of approximately 10% in stress **and strain and 30V0 in impact properties.**

Virgin PPS40%GF has been regranulated 5 times to investigate the effect cm mechanical properties. This resulted in a decrease in impact strength to 44% of the initial value. For tensile strength this was 750A, for tensile modulus 92°/0 and for tensiie strain 8TY0. Additionai-Iy are tested multiregranulated Danfoss components (Socket for a radiator thermostat of PBT and a spindle of PPS). The impact propetiles of testbars and components are compared. There exits a relative good connection between the impact properties of testbars and the components, which indicate that it’s possible to use the data generated on testbars in development of industrial components.

The second step in the recycling process is the compounding process, where the effect of adding different coupling agents to the aged regranulated polymer composite was investigated. Parameters in this investigation were type and concentration of coupling agents, type of aged PPS40°AGF and ratio virgin / aged. The 30 best of 150 compounds were selected for producing on full scale. Their composition is presented in table 3. These compounds were injection moulded into tensile bars for further testing.

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Table 3 FM scale compounding of PPS

L-	PPS-feedstock	Glass fibres	5 p c PPS	4 ages at pH 2	4 aged at pH 7	PPS aged at pH 10	PPS aged at 10% RH	Marlex *	Ucarsil *	3-Amino *
M 0	01	03	05					14	12	15
bmimr--			100%							
Esw						100"LO				
	=1=1=					98.2%		0.5%	0.3%	
CO-TI-0032						74.3%		0.5%	0.3!40	
CO-TI-0035						49.5%		0.5!40	0.39!0	
TI-0034						24.8%		0.5%	0.3%	
O-TI-0020					~ 00?40					
TI-0033					98.2%			0.5?0	0.3%	
O-TI-0036			50.0%		49.5%			0.5"/$	0.39'0	
li55mm7--			75.0%		24.870			0.5%	0.3%	
CO-TI-0021				100940						
CO-TI-0023				98.2$'o				0.5%	0.3%	q .00~
C				99.1%				0.5%	0.3%	0.1%
C TI-0041	=1=1=			99.0%				0.5%	0.3%	
C			24.0%	74.3%				0.5%	0.3%	
C TI-0039			50	49. 5"/0				0.5%	0.3%	
C			75.09fo	24.8%				0.5%	0.3%	
O-TI-O042			75.	25.0!40						
TI-0022							100%			
O-T1-0029							99.1%	0.5%	0.3%	
lmmm---							99.0%	0.5%	0.3%	
mim5--	59.570 i	39.5% i						0.5%	0.3%	
CO-TI-0025**							98.6%	0.5"A0	0.3%	

5.3 Durability and quality of recycled PPS40"AOGF

Table 4 presents results of short term properties of injection moulded tensile bars (virgin and recycled PPS40YOGF). The compound codes refer to those in table 3. The corresponding injection moulding codes are given as well. Results presented include impact strength, tensile strength, flexural strength, Melt Flow Index (MFI) and interface strength r, as extracted from SEM fracture analysis.

in all cases the effects of different types and concentrations of coupling agents and ratio vkgin/aged is identical for the different aged batches. Therefore some general conclusions will be drawn here. Both coupling agents amino-silane and zirconate have significant effects on the melt viscosity of the PPS matrix. Zirconate decreases the melt viscosity, presumably caused by polymer degradation or decross-linking reactions. Amino-silane has a less pronounced effect on the melt viscosity. Adding 0.1 % decreases the melt viscosity, whereas adding 1.OOA leads to an increase.

These effects in all cases influence the mechanical properties (impact, tensile and fiexural strength): increasing melt viscosity leads to increasing mechanical propetiles. H could therefore be concluded that the status of the matrix determines to a large extend the short-term mechanical properties.

0.270 Zirconate is the optimum concentration at which the mechanical and theological properties only show a small decrease. At the same time the zirconate causes an increase of the interface adhesion as seen from the SEM fracture surfaces (annex 13}. This feeds the expectation that zirconate improves the long term properties of the composite material.

Adding amino-silane results in small improvements of the short-term properties. Also the qualitative impression from the SEM fracture surfaces (annex 13) shows interface improvement. The effect of the concentration amirto-silane is not clear from the results. The 1.OVO concentration shows slightly better mechanical performance, but only due to a large increase in melt viscosity. No better interface adhesion has been observed.

Table 4 Properties of the injection rnoulded compounds with the corresponding compounding codes

Compound no.	injection mould no.	Impact strength [kJ/m²]	Tensile strength [MPa]	Flexural strength [MPa]	MFI [g/l i)-rein]	r_t [MPa]
CO-TI-0018	IM-DF-0013	27,1	176	249	63	64
regranulah?d AG-DF-0006	IM-DF-0039	18.2	157	211		66
CO-TI-0043	IM-DF-0038	13.0	184	249	87	49
CO-TI-0019	IM-DF-0014	14.9	131	176	117	75
CO-TI-0030	IM-DF-0025	12,8	123	160	151	99
CO-TI-0032	IM-DF-0027	15.9	124	175	114	132
CO-TkO035	IM-DF-0030	16.7	139	192	93	113
CO-TI-0034	IM-DF-0029	21.6	144	210	83	71
CO-T-I-0020	IM-DF-0015	15.9	137	190	102	79
CO-TI-0033	IM-DF-0028	12,7	122	765	142	92
CO-TI-0036	IM-DF-0037	17,9	140	198	93	113
CO-TI-0037	IM-DF-0032	21,1	153	213	79	66
CO-TI-0021	IM-DF-0016	15.2	134	187	98	88
CO-TI-0023	!M-DF-0018	16,1	137	193	76	99
CO-TI-0024	IM-DF-0019	15.7	136	186	101	71
CO-TI-0041	IM-DF-0036	14.8	125	$65	108	88
CO-TI-0038	tM-DF-oo33	14.5	124	172	109	113
CO-TI-0039	IM-DF-0034	16.6	138	195	91	71
CO-TI-0040	IM-DF-0035	19.8	151	214	80	66
CO-TI-0042	!M-DF-0037	19.4	348	207	77	49
CO-TI-0022	IM-DF-0017	18.4	166	233	65	66
CO-TI-0029	IM-DF-0024	17.6	159	214	63	83
CO-TI-0031	IM-DF-0026	18.3	146	208	72	66
CS)-TI-0025	IM-DF-0020	13.7	155	201	83	53
(X3-TI-0026	IM-DF-0021	15.0	149	198	111	66
CO-TI-0027	IM-DF-0022	13.2	147	194	110	54

Based on the short term characterisations the 30 compounded batches are further reduced for long term characterisation. Table 5 gives an overview of the selected batches with their respective composition, additives and processing history.

Table 5 Material batches, selected for long-term testing

Material number	Material type	CwnpoStirm	Additives	I%cewing
IM-DF-0003 or 41	PPS	10070 v	-	-
lrvl-DF-oo13	PPS	700% v		RE=+C()+M
IM-DFO039 or 42	PPS	10OOA Al		REd/1
IM-DF-0016	PPS	100% Al		RE-G@IM
IM-DF-0019	PPS	100% Al	0.1 % am. sil.	REec@IM
IM-DF-0036	PPS	?OOYO Al	0.270 zirc.	R&.~(&IM
[M-DF-0034	PPS	501500/6 V /Al	0.2% zirc,	R&C@[M
IM-DF-0026	PPS	10070 A2	0.2% zirc.	R&~@\M

By combining injection moulding codes and compounding codes in tables 3 and 4, the composition of the different batches can be read. IM-DF-0003 is the code for virgin PPS40?JfO-GF as a reference.

The iong term stability (durability) of the selected virgin and recycled batches has been assessed. The source for selecting the type of long term characterisation methods has been the practical service conditions. Some of the results of the long term characterisations will be presented hereafter.

Figure 4 presents the results of water absorption experiments in pt-t 7 environment at 140 “C.

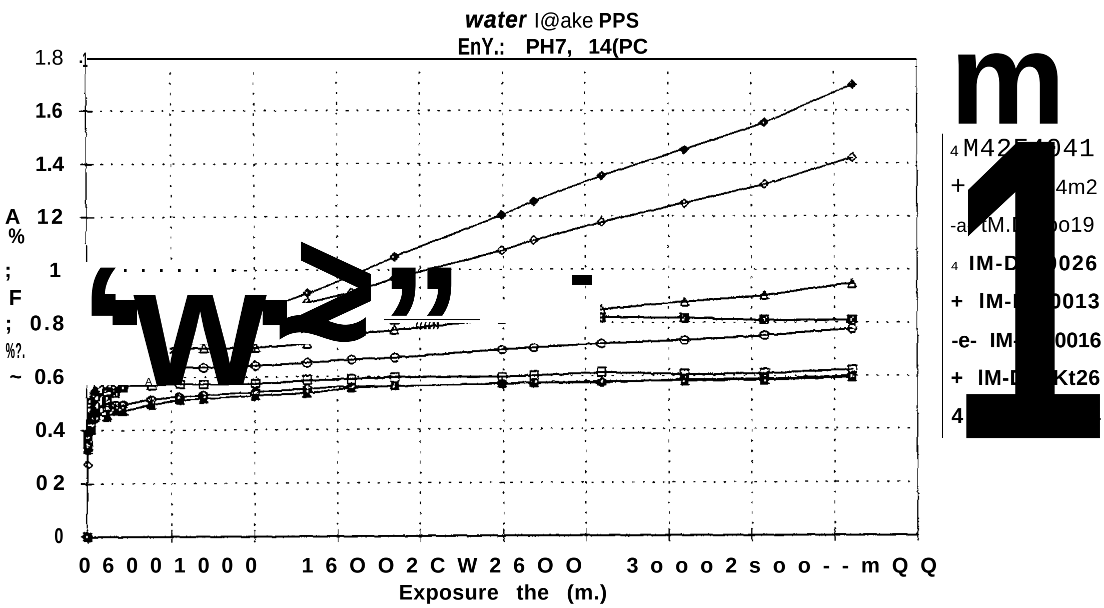

Figure 4 Weight change of PPS in pH 7 at fi40 ‘C

The virgin material, and also the virgin material after a compounding process (IM-DF-0013), c[early have a higher water uptake than all the aged samples. The mildly aged one (lM-DF-0026) has the highest uptake of the aged samples which fits well into the developing picture of ageing reducing water uptake. The three strongly aged and compounded versions have the same water uptake. The aged and granulated sampie (lM-DF-0042) has a little higher water uptake than aged and compounded versions and so has the aged sample with a 50 ‘A addition of virgin material (IM-DF-0034}.

Interesting to note is that at pl-12, 90 “C where severe degradation takes place, the virgin batches IM-DF-0003 and IM-13F-0013 take up most water (as in pH 7 and 10), but then degrade most. The batch with the least degradation after 4500 hours is lM-DF-0019 where amino-silane has been added. Apparently amino-silane decreases the degradation speed.

From the residual properties that were determined as a function of exposure time in the different environments the following conclusions have been extracted:

- ✓ virgin W’S has only slightly better mechanical properties on long-term basis compared to the best recycled batches
- ✓ regranulation is the best recycling option in this environment where no degradation takes place, ordy water uptake
- ✓ compounding with amino-silane gives on long-term basis equal mechanical properties as regranulation. On the long term amino-silane slows down the corrosion process in PPS40?40GF

- ✓ compounding with zirconate does not have any positive effect, both on shont and long term
- ✓ batches in wet service conditions must be judged on long-term basis, not only by short-term measurements
- ✓ virgin PPS is more subject to degradation then recycled batches, explained by the more open structure of the polymer
- ✓ therefore on long-term basis the performance of regranulated aged material is equal to that of virgin.

Figure 5 shows water absorption results at pH 2, 90 “C,

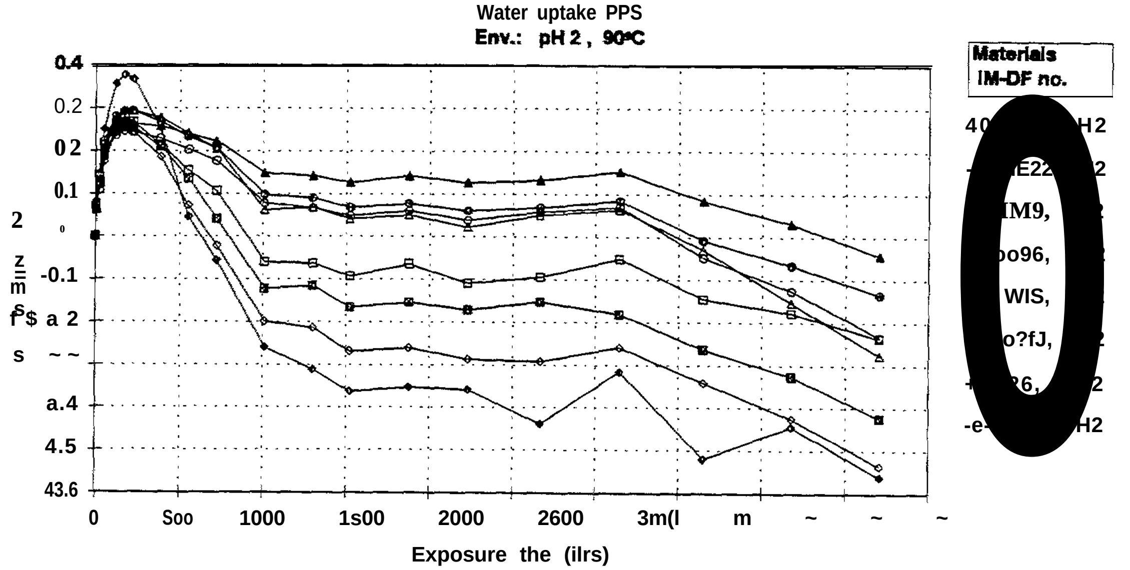

Figure 5 Weight change of PPS materiais at pH 2, 90 ‘C

In general it can be concluded that recycled material is as stable or even more stable then virgin PPS on long-term basis. Figure 6 shows creep results at 140 ‘C in dry air.

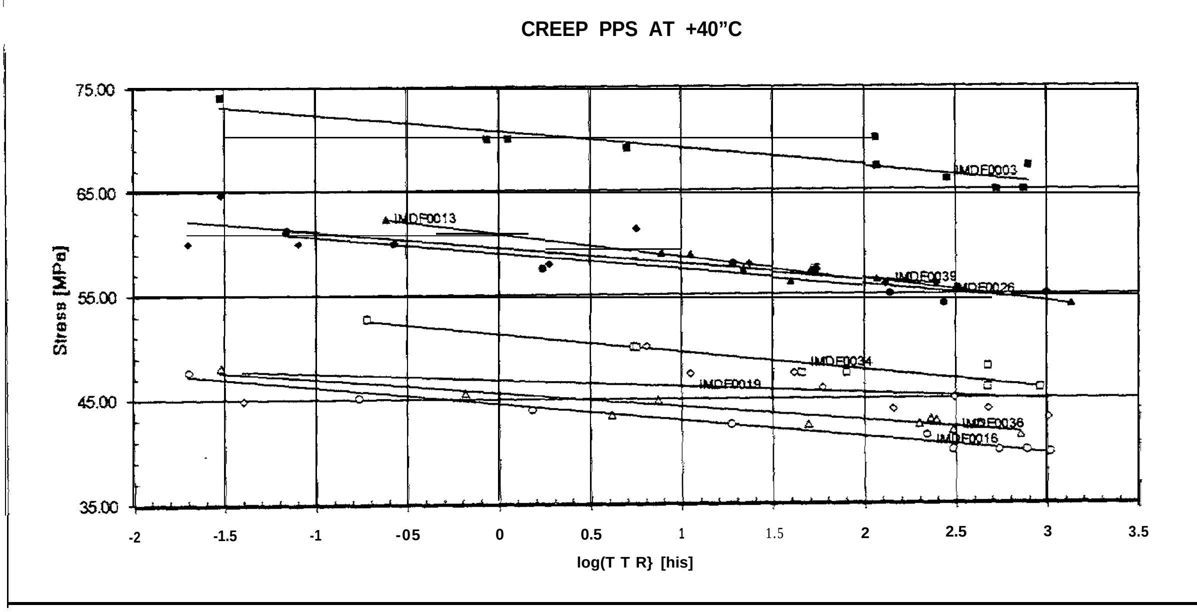

Figure 6 Creep behaviour of virgin and recycled PPS at 140 "C, 10% RH

The best material is the virgin material, IM-DF-0003. IM-DF-0013 (virgin, processed), **IM-DF-0026 (100'%** slightly aged) and IM-DF-0039 {IUYYo heavily aged, limited processed) are comparable in terms of ITR - stress-levels. IM-DF-0034 (5VY0 heavily aged, zircortate added) and IM43F-0019 (100% heavily aged, amino silane added) are comparable in terms of TTR - stress-levels. The worst materials are tM-DF-0016 (heavily aged, no additives) and IM-DF-0036 (100% heavily aged, zirconate added). Until the maximum time measured, 1000 ttrs, the slopes of the s - ITR curves are the same.

From these creep experiments in dry service conditions it appears that regranulation is the best recycling option.

5.4 Modelling of long term behaviour of virgin and recycled materiais

In alkaline environments it has been feasible to model impact strength degradation in an empirical way. A representative curve and match fitting are depicted in the figure 7.

For modelling the creep performance of virgin and recycled PPS40%GF starting point of the model formulation is the following relationship (Boltzmann's superposition principle) applicable to polymer based composites and usable in most cases where the material exhibits linear viscoelastic behaviour.

$$\varepsilon(t) = D_0\sigma(t) + \int_0^t \Delta D(t - t_0)\frac{d\sigma}{dt}dt$$ (uniaxial loading)

Taking into account the time dependent compliance of the material the evolution of compliante is expressed mathematically. CMce, the compliance evolution over time is known the strain response can be calculated with a generalised Kelvin-Voigt model type function. For a more general case where the material behaves in non-linear manner, viscoelastic mode[hng can be done using the so called Schape~'s nonlinear formulation:

$$e(t) = go@r(t) + g_1 f_o^t AD(v - /p')\frac{dgp}{dF}$$ (uniaxial loading)

Using a certain procedure, stress, temperature and moisture dependent functions g_o, g,, g,, a, are determined. "Knowing these for the entire applied tensile creep stress range enables accurate material response evaluation in both the linear and non-linear viscoelastic behaviour domain. Development of a thorough tensile creep response methodology yielding realistic predictions of creep strain in various operating environments, provided the creep is not of the accelerated type,

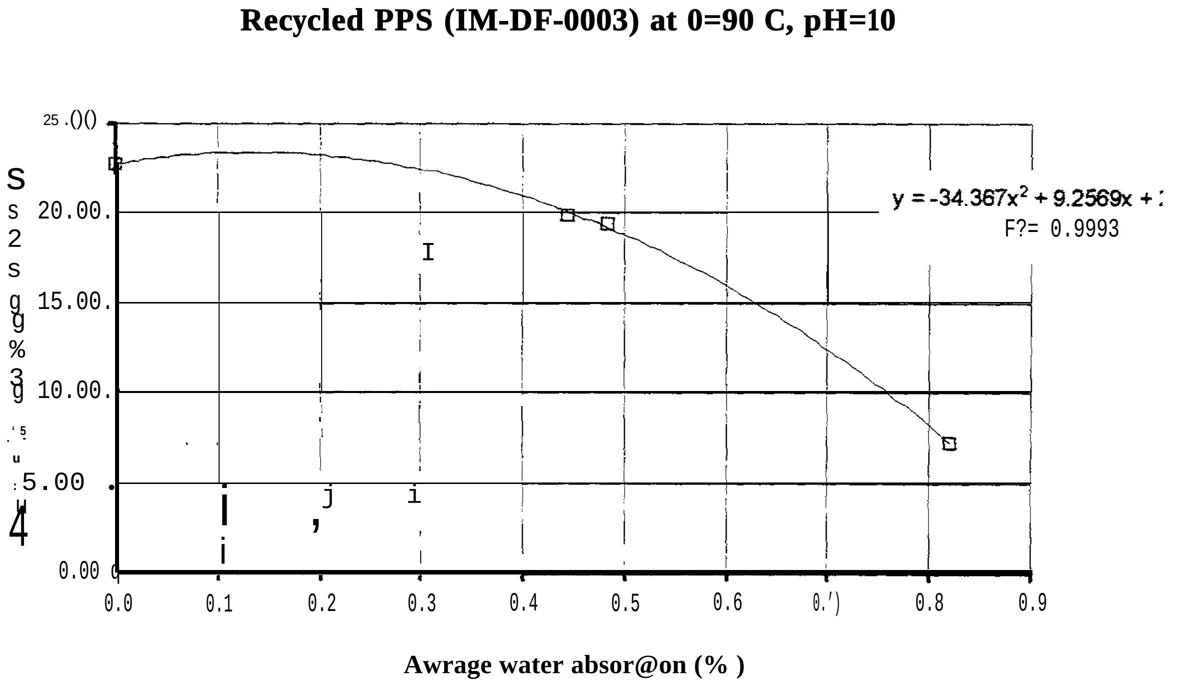

Figure 7 [mpact strength as a function of water uptake for a PPS40?40GF batch

6 CONCLUSIONS

6.1 Recycling process for PPS40!40GF

The investigation of the regranulation process indicated that the most **significant variable was the** screen size with the optimum occurring at 8 mm. Fibre length distribution measurements on the granulated material showed that on dust particles less than 500 pm there was a reduction in fibre length. Regranulation is the best recycling option in environments, where no degradation takes place, but only water uptake.

To upgrade the fibre matrix interface PPS40%GF, two coupling agents were selected for PPS, amino-silane and zirconate. They were added in optimum concentrations of respectively 0.1 and 0.2 WYO. To all recycled grades Ucarsil was added in an optimum concentration of 3 w%. The selected coupling agents for PPS40%GF — amino-siiane and zirconate — cause some matrix modifications resulting in no or even a small negative effect on the mechanical properties. The compounding process reduces the properties with some 18% and should therefore be avoided in the recycling process if possible. Recycled PPS4WOGF can be moulded with the same parameters as for virgin materials, but in some cases a tendency for overpacking and flashes has been found. Based on that a lower injection speed is recommended. Materials that were processed in the compounding process, show during subsequent injection moulding a lower thermal stability. This means that the time that a materia[can stay in the screw at a given temperature is shorter.

6.2 Durability and quality of recycled PPS40YOGF

Virgin PPS takes up almost twice the amount of water compared to recycled batches at any pH ievel. In pH 2 environment PPS material 1oss due to degradation is recorded after initial water absorption. Virgin PPS shows most severe material loss, while aged PPS recycled with amino-silane shows best resistance to material degradation. Virgin PPS has only slightly better mechanical properties on long-term basis compared to the best recycled batches. Compounding with zirconate does not have any positive effect, both on short and long term. The effect of adding amino-silane is clearly positive on the long term due to the improvement of resistance to degradation.

6.3 IVlodelling of long term behaviour of virgin and *recycled* materials

For acidic environments it has been impossible to obtain a moisture absorption regression model based on a Fick type behaviour. In alkaline environments it has been feasible to model impact strength degradation in an empirical way. The impact strength degradation trend is a negative exponential decrease for all temperatures and pH environments considered regardless of the material batch exposed. [t can be empirically modelled very well.

The prediction creep model had very good accuracy and reliability. The elevated temperature effect on PPS grades is the most critical compared to pH and relative humidity.

The probabilistic durabilityldamage tolerance analysis method complements the deterministic crack growth approach, which is based on the “worst case” and cannot provide the “extent of damage” type information for the entire population of structural details. The probabilistic durability analysis approach developed can be used to quantify structural durability. This quantitative prediction provides an effective basis for evaluating functional impairment, economic life and trade-offs as a function of the design and service variables.

6.4 Overall **conclusions**

This project has show, that for a specific type of plastic waste stream — high quality and high price engineering thermoplastic composites — the concept of material recycling can be implemented with success both technically and economically. In particular PPS40°LGF, that is not recycled nowadays has a large potential for recycling and reuse in high demanding applications again. Given the proper recycling process as investigated in this project, PPS40’?JOGF could be very well recycled by regranulation and upgrading. A pre-classification database system has been developed to extend the work of this project to other applications in recycling of plastic materials. The project has also shown that materials — either virgin or recycled — in wet service conditions should be assessed through long term tests like corrosion resistance and creep. These tests lead to much different conclusions than do simple short term tests. Recycled materials then appear almost as good as virgin materials which is not shown from short term testing. In dry service conditions, short term tests will be enough for performance assessment.

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An overview of publications and presentations in relation to the project is given hereafter. Further dissemination of the project results is foreseen by several partners.

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