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Advanced core material for thermoplastic sandwich structures

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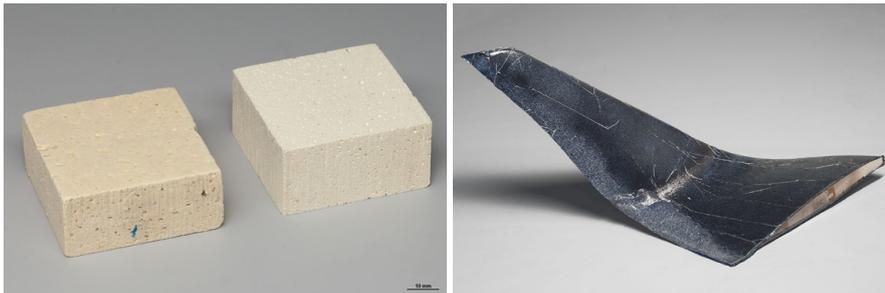
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Executive summary

Advanced core material for thermoplastic sandwich structures



Problem area

A new aramid syntactic foam was developed by Teijin Aramid BV. Preliminary tests showed that this specific foam material had good mechanical properties at temperatures above 350 °C, allowing it to be co-consolidated into a sandwich structure using thermoplastic PEKK-carbon reinforcement for the facings. Further characterisation of material properties was necessary to evaluate the full potential of this material.

Description of work

A number of tests were performed on aramid foam to establish moisture absorption, chemical resistance and strength and stiffness properties, as well as heat resistance and fire protection capabilities. The project was concluded with design and manufacture of a scaled winglet demonstrating the potential of creating complex shaped sandwich parts with a thermoplastic facing.

Results and conclusions

Syntactic foam consisting of an aramid matrix and hollow glass spheres was manufactured with densities between 0.20 and 0.30 g/cm³. Compared to commercially available foams, aramid foams have a higher density at approximately the same shear strength. When compared to other high temperature resistant syntactic foams with densities between 0.29 and 0.58 g/cm³, aramid foams have a lower density. An increasing share of aramid in the foam gives better mechanical properties at a higher density.

Compared to Rohacell WF, the moisture absorption at 70 °C and 85 % relative humidity of the tested aramid foam is considerably lower, approximately 1.5 % for aramid foam vs. 8 % for Rohacell. Average weight increase of the samples after 1601 hours was 348 % for immersion in gasoline, 266 % for immersion in jet fuel, 99.4 % for immersion in hydraulic

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oil and 219 % for immersion in Skydrol. Average volume increase of the samples after 1601 hours was 4 % for immersion in gasoline, 1.5 % for immersion in jet fuel, 1.8 % for immersion in hydraulic oil and 5.7 % for Skydrol. Skydrol 500B4 was observed to have the largest impact on the compression properties with reduction of 61.2 % of compression strength, followed by gasoline at 52.8 % decrease in strength. Jet fuel at 19.1 % and hydraulic oil at 20.8 % have less impact on the compression strength. A similar pattern was found for the decrease in modulus of elasticity with 70.6 % decrease for Skydrol 500B4, 48.9 % decrease for gasoline, 15.5 % for hydraulic oil and 15.0 % for jet fuel.

When heated up to 1200 °C, aramid foam showed virtually no smoke development or strong smell, no combustibility or temperature raise, only shallow damage with little cracks and good form retention. A complex shaped product in the form of a scaled winglet was successfully manufactured using aramid foam as a core and carbon/PPS as skin. It proved possible to consolidate the PPS/carbon laminate at 330 °C without collapse of the core.

Applicability

Possible areas of application are as core material for thermoplastic composite sandwich structures, lightweight tooling for thermoplastic.



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ADVANCED CORE MATERIAL FOR THERMOPLASTIC SANDWICH STRUCTURES

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ABSTRACT

This paper describes an investigation into mechanical and thermal properties of aramid foam, a novel development by Teijin Aramid BV. Preliminary tests showed that this specific foam material allowed the manufacture of a co-consolidated carbon-PEKK sandwich panel. Following this promising start, a number of tests were performed on this foam to establish moisture absorption, chemical resistance and strength and stiffness properties. In general it can be stated that the thermal stability of the material was above the requirements for thermoplastics manufacturing and promising fire, smoke and toxicity characteristics were found. The project was concluded with design and manufacture of a scaled winglet demonstrating the potential of creating complex shaped sandwich parts with a thermoplastic facing.

1. INTRODUCTION

Up to now most primary composite airframe components are made of thermoset materials. Compared to thermoset materials, thermoplastic materials have superior toughness resulting in lightweight damage tolerant structural components. However, one of the difficulties in using thermoplastics is the high processing temperature during manufacturing. Due to these high manufacturing temperatures no traditional core materials for sandwich structures can be used to create co-consolidated sandwich structures, as they lack the required strength and stiffness at these high temperatures. This limits the use of thermoplastic materials like PPS, PEEK and PEKK to mainly monolithic structures. The potential of fibre reinforced thermoplastics in advanced composite components will increase significantly in case not only discreet stiffened structures but also co-consolidated (mini)sandwich structures can be manufactured. The aramid foam opens that opportunity.

2. MANUFACTURE

The newly developed aramid syntactic foam^[1] consists of para-aramid^[2] mixed with hollow glass spheres where the ratio of aramid to spheres is approximately 10 to 90.

Para-aramid fibres have high tenacity (2100 mN/tex), high tensile modulus (78 GPa), high toughness high heat resistance and good chemical resistance.^[2]

The aramid dope (aramid polymer in N-methylpyrrolidone, NMP) and glass spheres are mixed and this mix is subsequently extruded into plate moulds after which the solvent is washed out using water. The resulting bulk plates are finally dried. After washing out the solvent, some microvoids remain. Plates of typically 1 or 2 cm thickness are manufactured using this method.

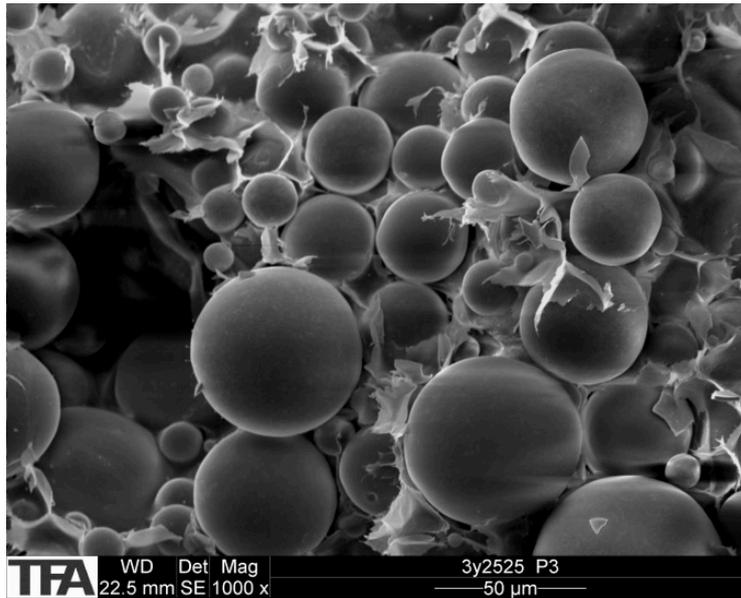


Figure 1: SEM image of aramid foam showing glass spheres and para-aramid matrix
More complex shapes can be manufactured by e.g. bonding panels and machining, see Figure 2.
The rough preform foam shape can be easily machined, sanded, drilled, etc. using conventional methods.

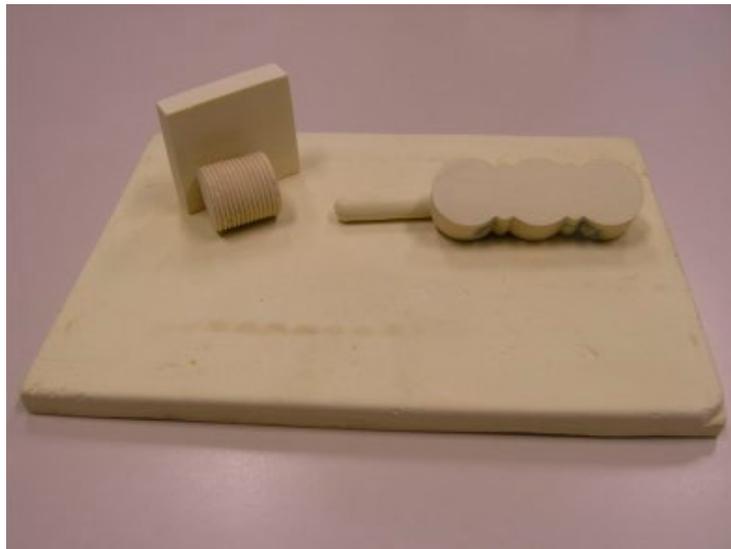


Figure 2: Aramid foam shapes

3. RESULTS AND DISCUSSION

Various tests were carried out to determine the properties of the foams manufactured. In this section, an overview of the tests performed and the results obtained is given, as well as a discussion.



3.1 Material properties

An overview of the material properties for two grades tested is given in Table 1. The “light” (0.20 g/cm³) version contains more glass spheres than the “strong” (0.30 g/cm³) version. The latter contains more aramid. Comparison of the foams will be related to the apparent densities, as it was not possible to release the exact composition of the foam due to confidentiality restrictions. As can be seen in Table 1, an increasing amount of aramid in the foam gives better mechanical properties at a higher density.

Table 1: Material properties of two variants of aramid foam

	Light	Strong
Apparent density (ASTM C272 ^[3])	0.20 g/cm ³	0.30 g/cm ³
Shear strength (ASTM C273 ^[5])	1.2 MPa	1.5 MPa
Shear modulus (ASTM C273 ^[5])	83 MPa	119 MPa
Tensile strength (ASTM C297 ^[6])	1.5 MPa	2.6 MPa
Compressive strength (ASTM C365 ^[7])	1.6 MPa	3.0 MPa
Outgassing	0,016 %	
Thermal stability	> 450 °C	
Limited Oxygen Index	99,5 %	
Adhesion PEEK, PPS	Good	
Thermal Conductivity	< 0,08 W/mK	
Water absorption	< 0,9 % @ 23°C 50 % RH	

Figure 3 shows a comparison of typical aramid foam with other commercially available (non-syntactic) foams. Its shear strength is broadly comparable to other foams, but its density is higher. Compared to other high temperature resistant syntactic foams, it has lower density. A foam manufactured using a polyimide resin and glass spheres has a density of 0.28 g/cm³ to 0.59 g/cm³^[1] where the aramid foams have a density between 0.20 and 0.30 g/cm³.

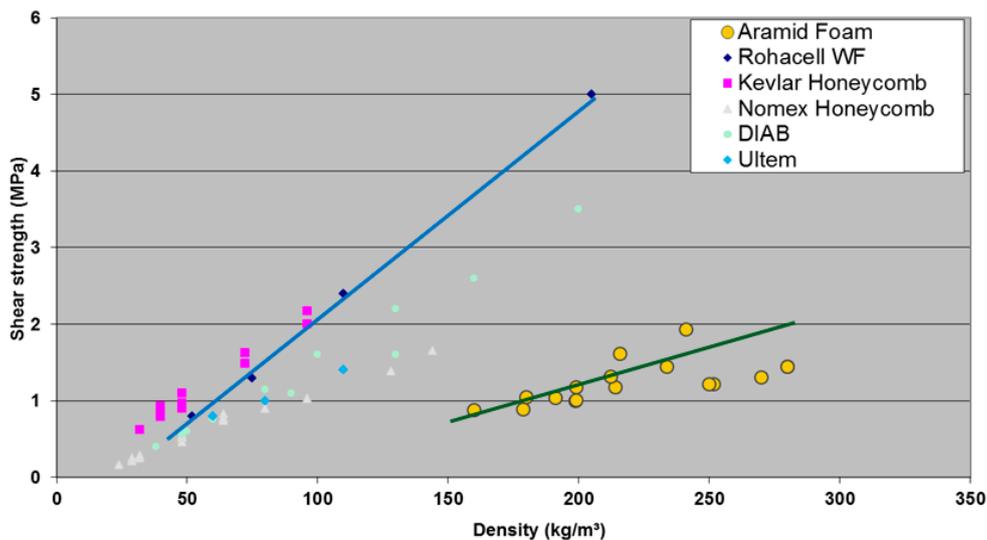


Figure 3: Comparison of shear strength and density of various foams

3.2 Moisture absorption

Moisture absorption tests according to ASTM C272^[4] §11.2 “Test method B–Elevated temperature humidity” were carried out to be able to compare the aramid foam to current core materials.

Five samples aramid foam core with dimensions 75x75x12.7 mm were supplied by Teijin and numbered V1-1 to V1-5. The average density of the material was 0.232 g/cm³.

Samples were dried prior to conditioning for 24 hours at 100 °C. After this, samples were conditioned in a climate chamber at 70 °C and 85 % relative humidity and weighed at regular intervals. The increase in weight is shown in Figure 4.

At day 3 and day 15, an error was made during weighing which lead to some desorption.

For samples V1-2 to V1-4, the maximum moisture absorption is around 1.5 %. For sample V1-1, this is about 0.8 %.

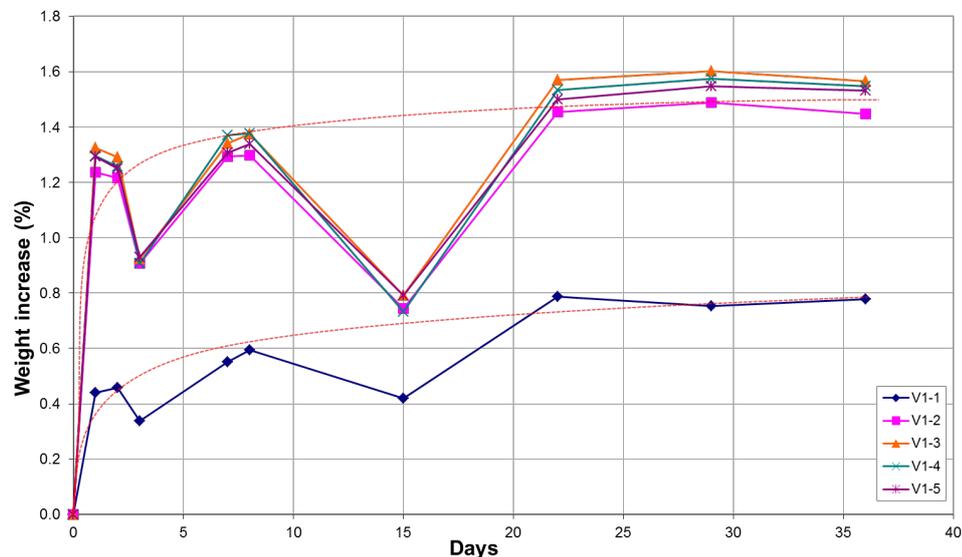


Figure 4: Moisture absorption of aramid foam core. Conditions: 70 °C and 85 % relative humidity. At day 3 and day 15, an error was made during weighing which lead to some desorption.

The density of sample V1-1 is approximately 9 % lower than that of the other samples (0.214 g/cm³ vs. an average of 0.236 g/cm³). It has also a slightly different shade than the other 4 samples. It is probably of a different composition than the other samples, maybe caused by variations in manufacturing process. See also Figure 5 and Figure 6. Samples in these figures were produced in an early stage of development. In current production no large voids are observed.



Figure 5: Moisture absorption sample V1-1



Figure 6: moisture absorption sample V1-2

Compared to Rohacell WF, a high temperature foam core used in high performance aerospace applications, the moisture absorption of the tested aramid foam is considerably lower, approximately 1.5 % for aramid foam vs. 8 % for Rohacell WF.^[8] See also Figure 7.

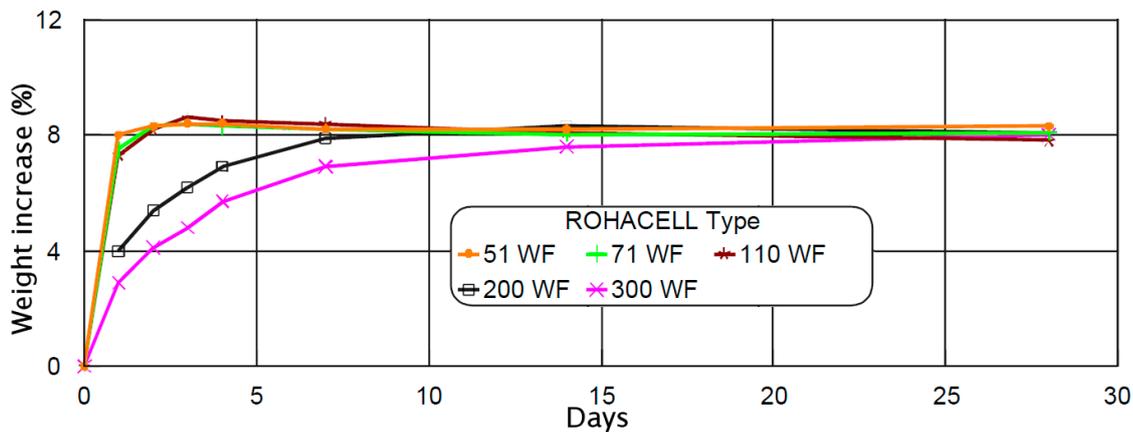


Figure 7: Moisture absorption of different types of Rohacell WF core material at 70 °C and 85 % relative humidity.^[8]

3.3 Chemical resistance

3.3.1 Exposure

A “light” version of the foam was dried and subsequently exposed to Skydrol 500B4, gasoline, hydraulic oil and jet fuel by fully immersing the specimens during 1601 hours. Dimensions and weight were measured at predefined intervals after which the specimens were tested in compression according to ASTM C365.

Average density of the foam before drying was 0.180 g/cm³, after drying 0.179 g/cm³.

No visible deformation, swelling or tearing of the specimens was observed during or after exposure. Some slight discoloration of the specimens was seen.

Average weight increase of the samples after 1601 hours was 348 % for immersion in gasoline, 266 % for immersion in jet fuel, 99.4 % for immersion in hydraulic oil and 219 % for immersion in Skydrol.

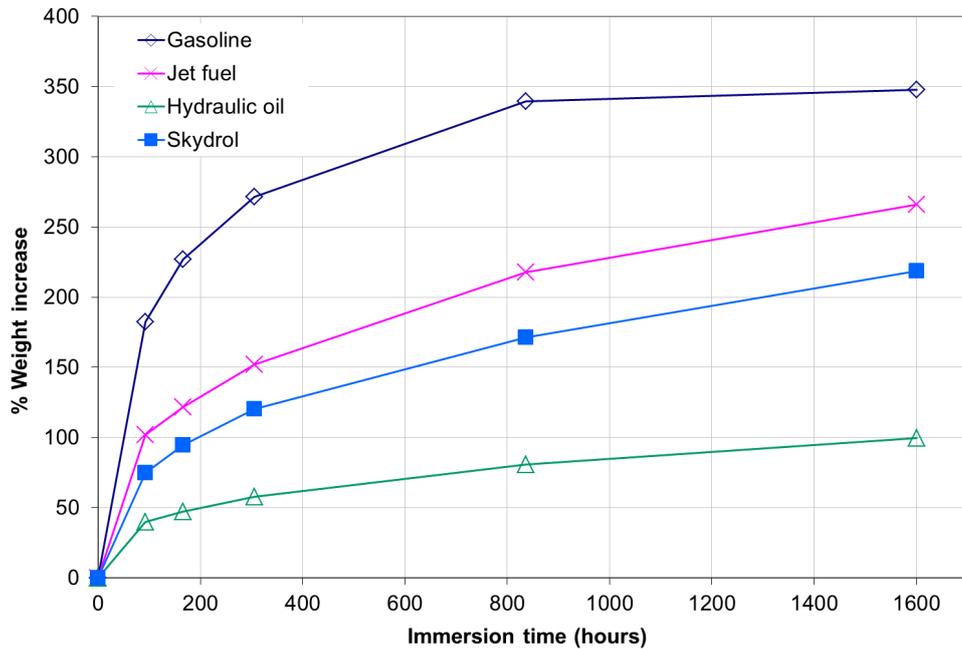


Figure 8: Average weight increase of specimens during immersion test in different chemicals

After an initial, relatively small, volume change, not much more change is observed. Average volume increase of the samples after 1601 hours was 4 % for immersion in gasoline, 1.5 % for immersion in jet fuel, 1.8 % for immersion in hydraulic oil and 5.7 % for Skydrol.

3.3.2 Compression strength and E-modulus

Table 2 gives an overview of the compression test results for the exposure to different chemicals.

Compression strength was determined at 2 % deflection of the specimen according to ASTM C365. Loading rate: 0.5 mm/min. After applying 2 % deflection, the load was released.

Table 2: Overview results from mechanical tests after chemical exposure

Fluid	Compression strength*			E-modulus**	
	σ MPa	Standard dev. MPa	Decrease %	E MPa	Decrease %
Gasoline	0.69	0.018	52.8	77.6	48.9
Jet fuel A4	1.17	0.022	19.1	129.1	15.0
Hydraulic oil	1.15	0.039	20.8	128.2	15.6
Skydrol 500B4	0.56	0.032	61.2	44.6	70.6
Reference	1.45	0.014	0.0	151.8	0

* Average compression strength at 2% deflection

** Average E-modulus calculated from slope of linear portion of load-deflection curve

The modulus of elasticity E was determined by determining the slope of the linear portion of the load deflection curve. The ASTM standard prescribes that the E-modulus shall be determined using the loads at the deflection values where deflection/thickness ratio is equal to 0.001 and 0.003. Strictly applying this rule did not yield correct results, as the foam is not as rigid as expected. For this reason, the linear portion of the curve was used in the calculation.

Skydrol 500B4 was observed to have the largest impact on the compression properties with reduction of 61.2 % of compression strength, followed by gasoline at 52.8 % decrease in strength. Jet fuel at 19.1 % and hydraulic oil at 20.8 % and have the less impact on the compression strength. A similar pattern was found for the decrease in modulus of elasticity with 70.6 % decrease for Skydrol 500B4, 48.9 % decrease for gasoline, 15.5 % for hydraulic oil and 15.0 % for jet fuel.

3.3.3 Compression test to failure

The compression test was repeated, but now until failure of the specimen. A more or less brittle failure was expected based on previous tests. However, the failure mode was relatively stable. The specimens were more or less crushed and flattened as can be seen in Figure 9.

This was not expected, the specimens were not fully compressed as the test set-up was not prepared for the full range of deformation. Typically, specimens were compressed to the maximum range of the load cell or 15 mm. The samples exposed to gasoline were compressed to 7 mm.

A higher loading speed of 5 mm/min instead of the prescribed 0.5 mm/min for loading to 2 % deformation was used for these tests to keep testing times acceptable.

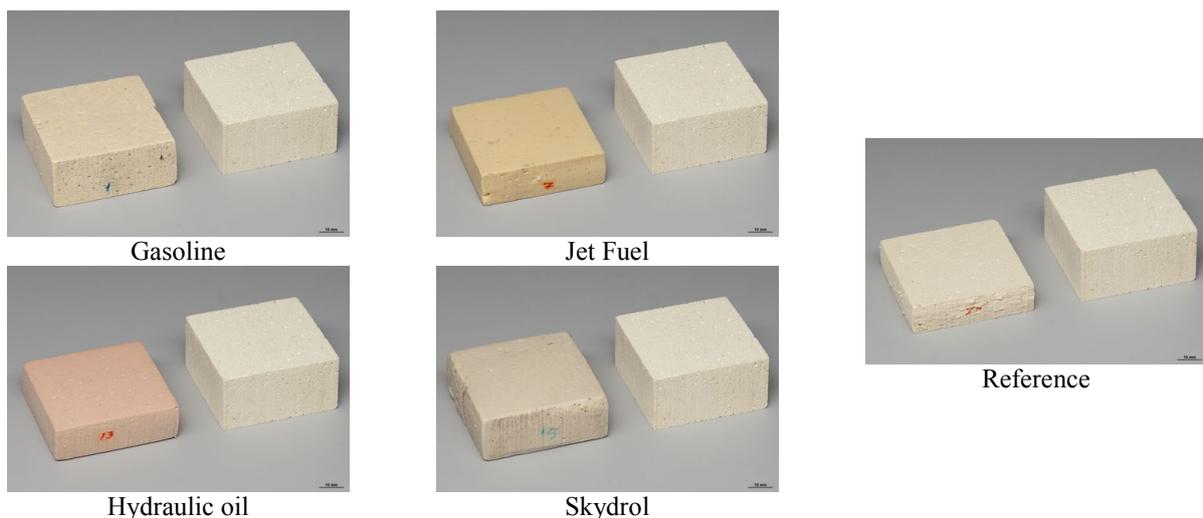


Figure 9: Overview of deformation of chemical testing specimens after loading above 2 % deflection. Note that the specimens were not loaded to the same deflection. The specimen on the right in each figure is an undeformed specimen for reference.

Figure 9 shows an overview of the specimens after fully loading the specimen. Note that the specimens were not loaded to the same deflection. Figure 10 shows the maximum force-displacement curves for the specimens shown on Figure 9.

A considerable amount of fluid was squeezed out of the gasoline exposed specimen and, to a lesser degree, also from the other specimens.

The curves for jet fuel and hydraulic oil exposed specimens show the same shape as the reference sample, only at lower load levels. The Skydrol exposed samples show also a similar behaviour.



The behaviour of the specimen exposed to gasoline is different. There appears to be two-stage behaviour. This may be caused by the large amount (348 % weight increase) of fluid it has taken up. Squeezing this relatively large volume of gasoline out the material may have had some influence. Loading rates used were relatively high and a relative high volume is displaced in a short time.

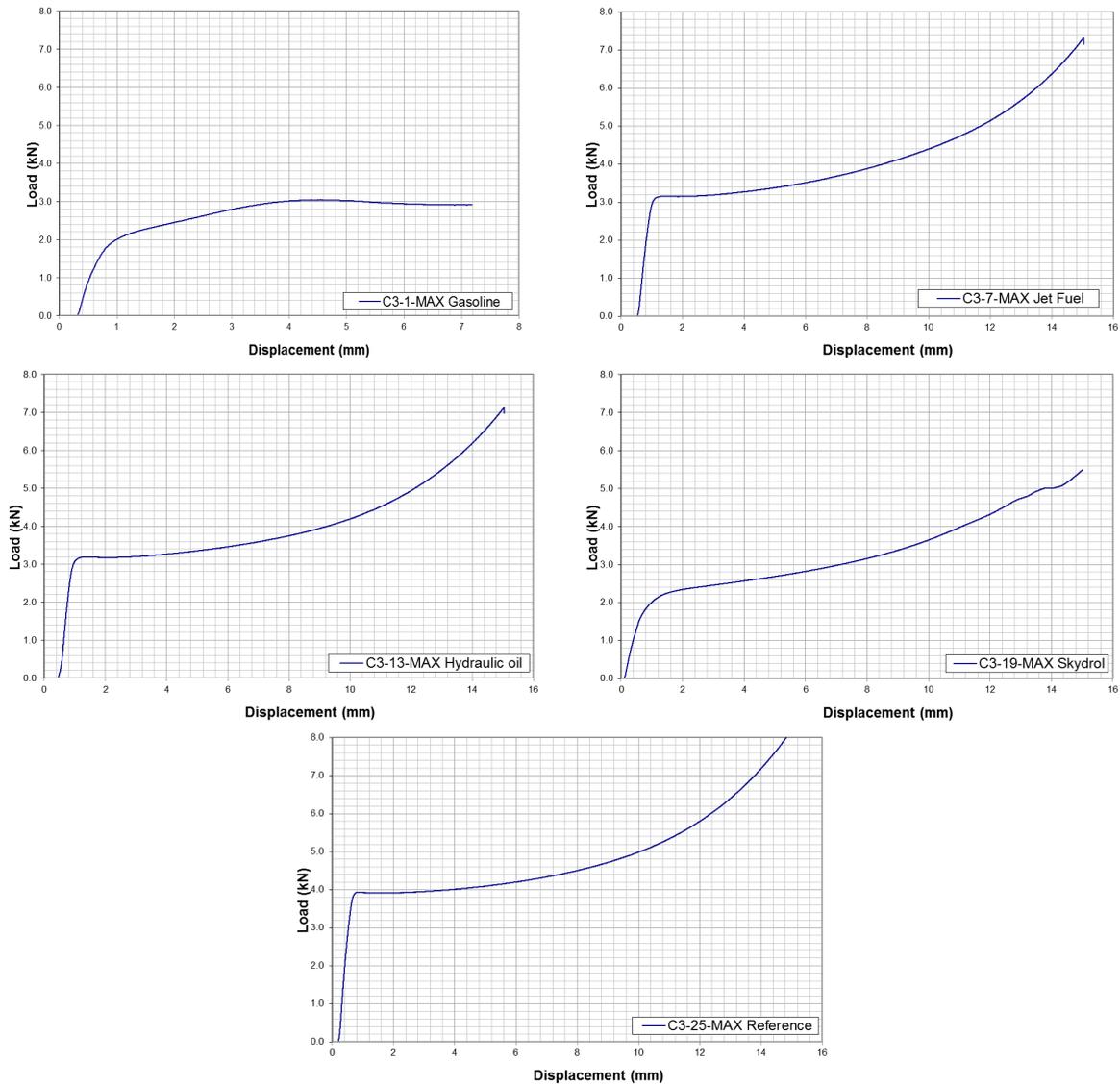


Figure 10: Maximum force-displacement curves for the compressive deformation of specimens shown on Figure 9.

3.4 Heat resistance and fire protection

A screening test was carried out to test the heat resistance of “light” foam. A specimen was placed on the open top of a furnace and the heat increase on both sides of the panel was monitored.

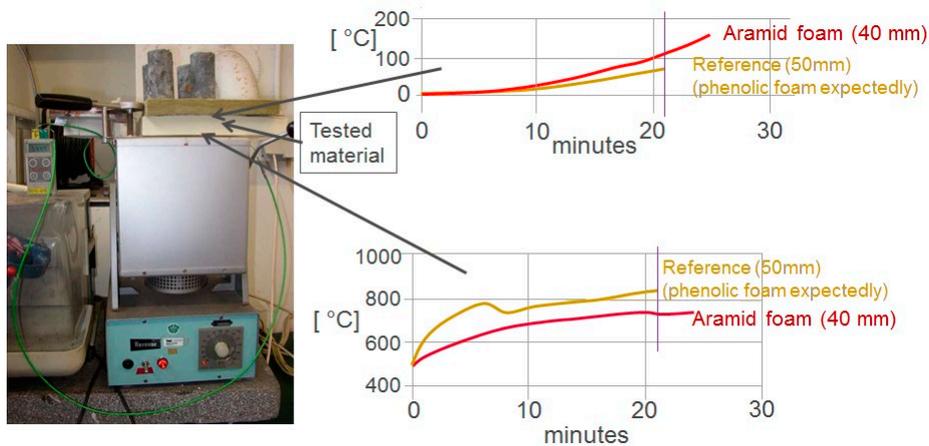


Figure 11: Heat resistance testing. A 40 mm thick panel was placed on the open top of a furnace and the temperature on both sides of the panel was monitored.

When heated up to 1200 °C, aramid foam showed virtually no smoke development and no smell, no combustibility or temperature raise, only shallow damage with little cracks and good form retention, see also Figure 12.

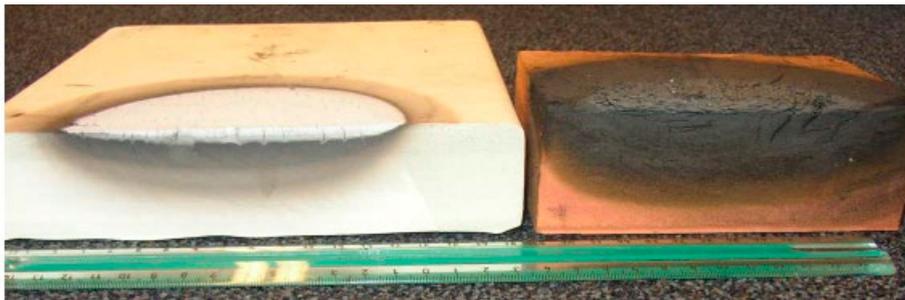


Figure 12: Affected zones after reaching 1200 °C. Left: aramid foam.

Aramid foam at light composition is officially classified as non-combustible in accordance with EN 13501-1:2007+ A1:2009. At another standard composition aramid foam is officially classified as nearly non-combustible in accordance with the same European Norm. Both classifications open opportunities for use as light weight fire protection structures.

3.5 Manufacturing

The high temperature resistance and good form retention of the aramid foam make it a suitable candidate to use it as a core for thermoplastic processing. Commercially available foams are not able to withstand the temperatures and pressures required to consolidate engineering thermoplastics such as PEEK or PEKK with melting temperatures well over 300 °C.

To demonstrate the possibilities of aramid foam, a scaled winglet was manufactured using aramid foam as core and Carbon/PPS semipreg 285 g/m² 3K 5H satin weave.

A rough core preform shape was created by bonding several aramid foam dope. The resulting rough preform was then machined and sanded to the desired dimensions, see Figure 13. Machining the trailing edges proved a delicate task due to the very thin edge that had to be formed.



Figure 13: Aramid foam core after machining and sanding



Figure 14: Finished winglet

The adhesion of carbon/PPS fabric proved insufficient, therefore a thin layer of pure PPS needed to be consolidated on the core first. After this, 5 layers of carbon/PPS fabric were laid up on the core with a semi-isotropic lay-up. Layers were kept in place by ultrasonic spot welding. Cuts were made at predetermined locations to accommodate the double curvature. The product was consolidated for 2 hours at 330 °C.

Figure 14 shows the finished product. The lines in the product are resin rich areas were formed due to creases necessary to accommodate the complex shape when vacuum bagging. Other than these lines, no manufacturing defects were observed and the trailing edge was successfully manufactured.

For certain applications, the density of the aramid foam may be too high. Due to its heat resistance and good form retention, it opens possibilities in areas where weight is not the main requirement. One area may be lightweight thermoplastic tooling, another in fire protection, e.g. in fire retardant doors, bulkheads or hatches in naval or industrial applications.

4. CONCLUSIONS

Syntactic foam consisting of an aramid matrix and hollow glass spheres was manufactured with densities between 0.20 and 0.30 g/cm³. Compared to commercially available foams, aramid foams have a higher density at approximately the same shear strength. When compared to other high temperature resistant syntactic foams with densities between 0.29 and 0.58 g/cm³, aramid foams have a lower density. An increasing share of aramid in the foam gives better mechanical properties at a higher density.

Compared to Rohacell WF, the moisture absorption at 70 °C and 85 % relative humidity of the tested aramid foam is considerably lower, approximately 1.5 % for aramid foam vs. 8 % for Rohacell.

Average weight increase of the samples after 1601 hours was 348 % for immersion in gasoline, 266 % for immersion in jet fuel, 99.4 % for immersion in hydraulic oil and 219 % for immersion in Skydrol. Average volume increase of the samples after 1601 hours was 4 % for immersion in gasoline, 1.5 % for immersion in jet fuel, 1.8 % for immersion in hydraulic oil and 5.7 % for Skydrol.

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strength. Jet fuel at 19.1 % and hydraulic oil at 20.8 % have less impact on the compression strength. A similar pattern was found for the decrease in modulus of elasticity with 70.6 % decrease for Skydrol 500B4, 48.9 % decrease for gasoline, 15.5 % for hydraulic oil and 15.0 % for jet fuel.

When heated up to 1200 °C, aramid foam showed virtually no smoke development or strong smell, no combustibility or temperature raise, only shallow damage with little cracks and good form retention.

A complex shaped product in the form of a scaled winglet was successfully manufactured using aramid foam as a core and carbon/PPS as skin. It proved possible to consolidate the PPS/carbon laminate at 330 °C without collapse of the core.

Possible areas of application are as core material for thermoplastic composite sandwich structures and lightweight tooling for thermoplastics manufacturing. Its good fire resistance properties make it suitable for applications where structures must withstand high temperatures, e.g. naval bulkheads, hatches or protection panels for battery compartments.

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