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FIRE RESISTANT ALUMINOSILICATE COMPOSITES

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Abstract: The fire response of a potassium aluminosilicate (Geopolymer) matrix carbon fiber composite was measured and the results compared to organic matrix composites being used for transportation, military, and infrastructure applications. At irradiance levels of 50 kW/m^2 typical of the heat flux in a well developed fire, glass- or carbon-reinforced polyester, vinylester, epoxy, bismaleimde, cyanate ester, polyimide, phenolic, and engineering thermoplastic laminates ignited readily and released appreciable heat and smoke, while carbon-fiber reinforced Geopolymer composites did not ignite, burn, or release any smoke even after extended heat flux exposure. The Geopolymer matrix carbon fiber composite retains sixty-seven percent of its original flexural strength after a simulated large fire exposure.

Keywords: *Aluminosilicate, ceramic composite, cone calorimeter, fire, fire barrier, fire hazard, flame spread, flammability, flexural strength, Geopolymer, heat release, smoke.*

Introduction

The flammability of organic polymer matrix, fiber-reinforced composites limits the use of these materials in marine platforms and ships [1], ground transportation [2], and commercial aircraft [3], where fire hazard is an important design consideration because of restricted egress. Although carbon fiber and glass fibers are inherently fire resistant and significant progress has been made in recent years to develop new, high temperature, thermo-oxidatively stable fibers from boron, silicon carbide, and ceramics [4], parallel work on high temperature/fire resistant matrix materials to bind the fibers has not kept pace. At the present time, affordable, low-temperature processable matrix materials for fire resistant composites are unavailable since most organic polymers soften and ignite at temperatures of 400-600°C characteristic of fuel fire exposure conditions.

The Federal Aviation Administration has recently initiated a research program to develop aircraft cabin materials with an order-of-magnitude reduction in fire hazard compared to current interior materials [5]. The flammability requirement for new materials is that they withstand a 50 kW/m^2 incident heat flux characteristic of a fully-developed aviation fuel fire without releasing significant amounts of heat or propagating an external fuel fire into the cabin compartment for several minutes [6]. The goal of the program is to eliminate cabin fire as cause of death in aircraft accidents. However, voluntary adoption of new fire resistant materials technology by aircraft and cabin manufacturers requires that it be cost effective to install and use [7]. To this end a new, low-cost, inorganic polymer derived from the naturally occurring geological materials is being evaluated.

Materials

Aluminosilicate Resin: The Geopolymer matrix resin being evaluated for fireproof aircraft cabin interior panels, marine structural composites, and infrastructure applications is a potassium aluminosilicate, or poly(sialate-siloxo), with the empirical formula: $Si_{32}O_{99}H_{24}K_7Al$. A representative structure deduced from the elemental composition, x-ray diffraction, and ^{29}Si magic angle spinning nuclear magnetic resonance spectroscopy (^{29}Si MAS-NMR) of the cured and dried Geopolymer is a linear poly(metasilicate) with tetracoordinate aluminate crosslinks as illustrated in Figure 1 [8]. This particular resin hardens to an amorphous or glassy material at moderate temperatures with a density of 2.14 g/cm^3 and is one of a family of inorganic Geopolymer materials described previously [8,9].

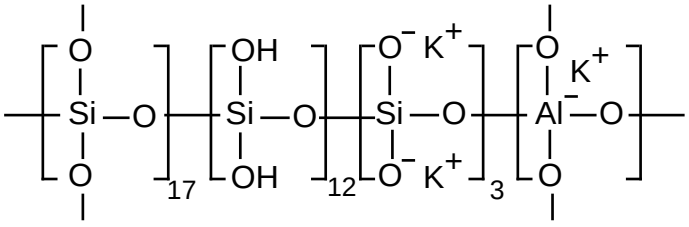

Figure 1. Geopolymer structure.

The Geopolymer potassium aluminosilicate resin was prepared by mixing 100 g of an aqueous silica + potassium oxide solution with 135 g of a silica powder having SiO_2/AlO_2 in a mole ratio of 27/1. The liquid and solid components were mixed for one minute at room temperature in a food processor. The as-mixed viscosity of the Geopolymer resin was measured at room temperature (20°C) in a dynamic rheometer (Rheometrics RDA-II) using parallel plate mode with 25 mm diameter stainless steel plates. Figure 2 is a plot of the room temperature viscosity of the Geopolymer resin versus time after mixing. The initial mix viscosity of the Geopolymer resin is about 2 Pa-s (20 Poise) and the resin remains workable for about 4-5 hours at room temperature.

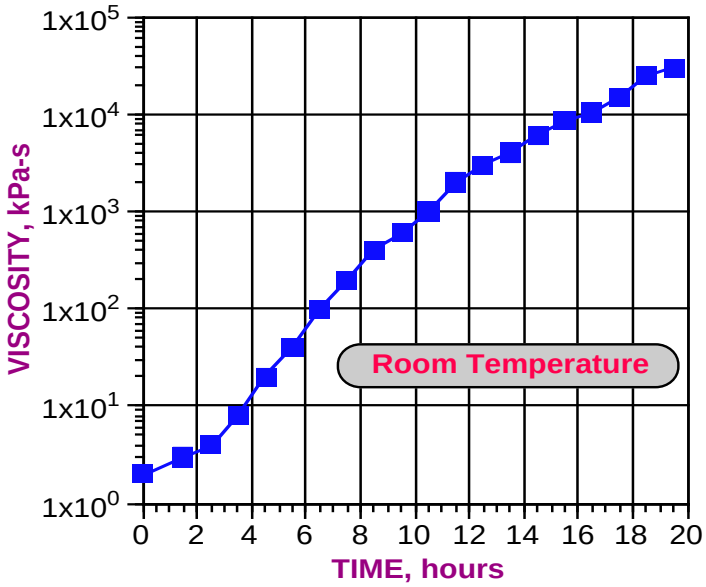

Figure 2: Room temperature (20°C) viscosity of Geopolymer resin versus time after mixing

Differential scanning calorimetry studies were conducted to determine the extent of reaction of the Geopolymer resin during the 3 hour, 80°C composite cure cycle. The isothermal conversion of the Geopolymer resin as a function of time at 80°C was determined using a Perkin Elmer DSC-7 Differential Scanning Calorimeter on resin samples of approximately 50 mg which were mixed and immediately placed in sealed stainless steel sample pans. Heat flow versus time for the cure exotherm was recorded and the instantaneous extent of reaction was calculated from the cumulative heat evolution divided by the total heat of the reaction. The total heat of the curing reaction was determined to be 16.42 ± 0.49 J/g in separate temperature scanning experiments. Figure 3 shows data for the extent of reaction and viscosity of the Geopolymer resin versus curing time at 80°C. The onset of rapid viscosity increase corresponds to approximately 50% completion of the Geopolymer reaction. The curing reaction reaches 99% completion after 1 hour at 80°C.

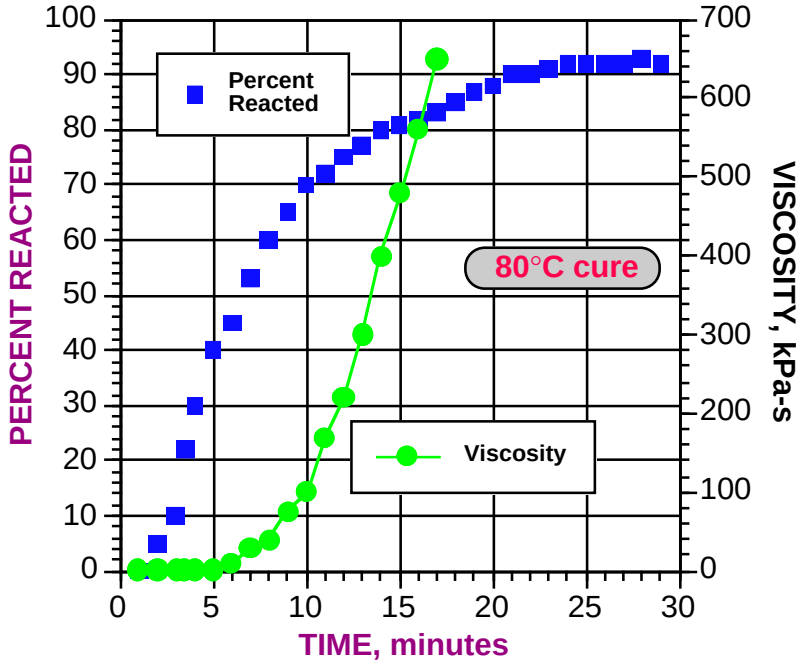

Figure 3: Extent of cure (B) and viscosity (J) of Geopolymer resin versus time at 80°C.

Thermogravimetric analyses were conducted on a Perkin Elmer TGA-7 Thermogravimetric

Analyzer to determine the weight loss history of the cured Geopolymer resin at elevated temperatures. Samples of 10 mg were heated at 10°C per minute in an inert environment (99.99% nitrogen) and the mass of the sample recorded versus temperature. Figure 4 shows the residual mass and its first derivative versus temperature for the cured Geopolymer resin in the TGA experiments. It is observed that the resin is thermally stable up to about 250°C, at which temperature a seven percent

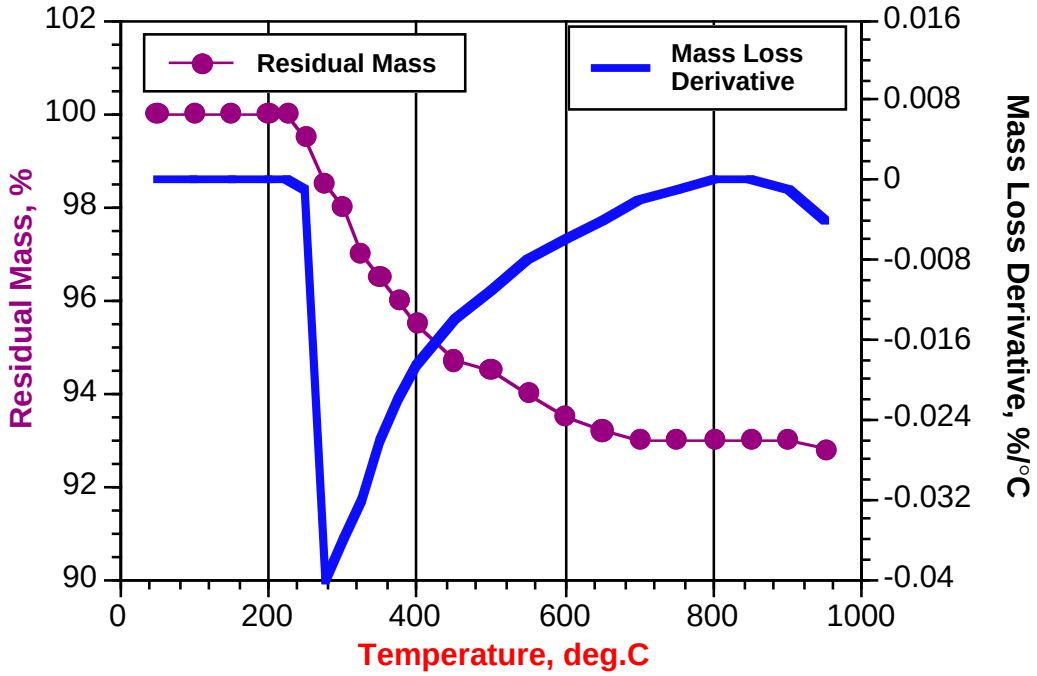

Figure 4: Thermogravimetric data for Geopolymer resin heated at 10°C/min. Heavy line (▬) is the mass loss derivative and doted line (J)is residual mass .

weight loss occurs over the range 250-625°C. The mass loss at temperatures >250°C is assumed to occur through a dehydration reaction which yields gaseous H_2O according to

$$2(SiO_3^{-2}.2M^{+})\text{-}OH \overset{\Delta}{\Longrightarrow} (SiO_3^{-2}.2M^{+})_2O + H_2O(\uparrow) \quad (1)$$

The dehydration reaction produces steam at many times its liquid volume and pressure resulting in an unconstrained volume expansion of the resin of 488 ± 48% at 850°C. The resulting morphology is a microcellular amorphous material at room temperature. At temperatures above 850°C a small secondary weight loss occurs producing a strong, fused, glassy resin. The secondary weight loss temperature is near the melting point (976°C) of potassium metasilicate (K_2SiO_3 in Figure 1) and may be final dehydration of the molten resin.

Composite Fabrication: Cross-ply fabric laminates were made by hand rolling the deaerated Geopolymer liquid resin into a 0.193 kg/m2 (5.7 oz/yd2), 3K plain weave, Amoco T-300, carbon fabric and air drying 30 seconds at 80°C to remove residual moisture and develop tack. Unidirectional tape was used to fabricate cross-ply laminates for off-axis tensile testing of inplane shear properties. In all cases hand impregnated plies were cut, stacked, and cured in a vacuum bag at 80°C in a heated press with 0.3 MPa pressure for three hours. The panels were then removed from the vacuum bag and dried for an additional 24 hours at 100°C or until constant weight was achieved. Approximately 22% of the as-mixed liquid resin is water, about half of which is removed during

the curing and drying process.

Final thickness of the 25 layer fabric laminates was a uniform 5.6-mm and the density was 1.85 g/cm^3. Warp direction tensile specimens were cut from 4 layer fabric laminates. Visual inspection of cut edges revealed that the laminates were substantially free of large voids. Hand impregnation and layup resulted in a fiber volume fraction of approximately 50-55% and void fraction of less than 5% in the Geopolymer laminates.

Organic matrix crossply laminates of polyester (PE), vinylester (VE), epoxy (EP), cyanate ester (CE), bismaleimide (BMI), PMR-15 polyimide (PI), and phenolic (PH), thermoset resins as well as thermoplastic polyphenylene sulfide (PPS), polyetheretherketone (PEEK), polyetherketoneketone (PEKK), polyarylsulfone (PAS), and polyethersulfone (PES) resin matrices were prepared from commercial S-glass, E-glass or carbon fabric prepregs. The details of material composition and fabrication have been described elsewhere [10-12]. Some of the phenolic laminates were hand impregnated [13] and contained only about 34 volume percent fiber compared to a nominal 60 percent fiber volume for all of the commercial prepreg materials. The density of these cured laminates ranged from about 1.55 to about 1.98 g/cm^3 at the nominal 60 volume percent carbon and glass fiber loading, respectively.

Methods

Ignitability, Heat Release, and Smoke (ASTM E-1354): Peak heat release rate, 300-second average heat release rate, total heat release, mass loss during burning, ignitability (time-to-ignition), and the specific extinction area of smoke produced were measured in an oxygen consumption calorimeter employing a conical radiant heater to provide 50 kW/m^2 of radiant energy to the surface of a 10-cm by 10-cm sample having a nominal thickness 6-mm. The sample is positioned horizontally on a weighing device with a spark igniter 2.54-cm above the surface to ignite combustible vapors (piloted ignition). The mass flowrate of air past the burning sample is measured as well as the amount of oxygen consumed from the air stream by the combustion process and these measurements are used to calculate the heat release rate (HRR) of the burning material using a factor of 13.1 kJ of heat produced per gram of oxygen consumed [14].

Flame Spread Index (ASTM E-162-83): Flame spread across a surface is one measure of the propensity of a material to propagate a fire. Downward flame spread was measured after ignition of a 15-cm by 46-cm sample by a radiant heat source. Only the combustible organic matrix composites were tested in this procedure as the Geopolymer sample would not support flaming combustion.

Residual Flexural Strength (ASTM D-790): Specimens were tested for flexural strength before and after the fire test to determine the residual strength of the composite panels after fire exposure. Specimens having dimensions 7.6-cm by 7.6-cm were exposed to a 25 kW/m^2 radiant heat source for a duration of 20 minutes according to ASTM E-662 protocol for smoke generation in a flaming mode. The panels were reclaimed and 5 coupons, 1.27-cm wide by 7.6-cm long were

cut from each for flexural testing on a universal testing machine. The Geopolymer composites were not subjected to the ASTM E-662 protocol because they would not burn. Instead panels were tested at room temperature (22°C) or subjected to temperatures of 200, 400, 600, and 800°C for more than 60 minutes in a forced air oven. The oven exposure at 400°C is comparable to the equilibrium surface temperature of a vertically oriented, unit-emissivity surface exposed to25 kW/m^2 of radiant energy in quiescent air for the same time period [15]. The original sample thickness was used to calculate a nominal flexural strength after the fire (organic resins) or thermal exposure (Geopolymer) test.

Tensile Properties (ASTM D3039-76): Tensile strength and modulus of cross-ply fabric laminates were measured in the warp fiber direction using four (4) ply specimens.

Inplane Shear Properties (ASTM D3518-76): The inplane shear strength and stiffness of a unidirectional Geopolymer laminate was determined by measuring the tensile stress-strain response of ±45-degree laminates fabricated from unidirectional carbon fiber tape.

Interlaminar Shear Properties (ASTM D3846): Interlaminar shear tests were conducted on Geopolymer-carbon fabric laminates by applying direct shear over an area of approximately 80 mm^2 on an 80 x 12 mm double-notched compression specimen which was 6 mm thick. Failure occurred between the notches in all cases and the failure plane was interlaminar. Tests were conducted at ambient temperature (22°C) on samples which were subjected to a one hour (or more) exposure at 200, 400, 600, 800, and 1000°C in a forced air oven. The interlaminar shear strength of a phenolic resin/T-300 carbon fabric laminate was determined using a short beam shear specimen according to ASTM D2344 and the specimen was a [0/±45/90] quasi-isotropic layup of phenolic resin impregnated Hercules IM-7 carbon fabric.

Results and Discussion

Table 1 lists the inplane shear, interlaminar shear, warp tensile, and flexural properties of the Geopolymer-carbon fiber/fabric crossply laminates. The room temperature strengths of the Geopolymer-carbon fiber/fabric laminates are 343, 245, and 14 MPa for warp tensile, flexure, and interlaminar shear, respectively. The corresponding values for a phenolic resin-T-300 carbon fabric crossply laminate are 436 and 290 MPa for warp tensile and flexural strength, respectively, and 24 MPa for interlaminar (short beam) shear strength (13). Moduli for the Geopolymer resin crossply fabric laminate in the warp tensile and flexure tests are 79 GPa and 45 GPa, respectively, compared to 49 GPa and 29 GPa for the corresponding moduli of a phenolic resin composite (13).

Table 2 summarizes all of the cone calorimeter data for the composite specimens. Individual values for percent weight loss during the fire test, time to ignition, peak heat release rate, 300-second average heat release rate, total heat released per unit area, and specific extinction area of smoke are reported for each material. Average values of these fire parameters were calculated for families of the organic materials grouped together according to chemistry (condensation/phenolics, addition/thermosets), physical properties (engineering thermoplastics), or end-use applications (high

temperature/advanced thermosets). It is seen that this somewhat arbitrary grouping leads to variations within groups which can be greater than the variation between groups. However, the averages are fairly representative of each type of material, and it is clear that the Geopolymer composite is non-combustible while all of the organic polymer matrix composites support flaming combustion. It was noted that the Geopolymer resin became white after fire exposure but did not ignite or smoke even after ten minutes in the cone calorimeter.

Table 1: Mechanical Properties of Geopolymer carbon fiber composites

PROPERTY	MAX. TEMP. (°C)	n	MODULUS (GPa)	STRENGTH (MPa)
Inplane Shear	22	3	4.0 ± 0.1	30.5 ± 1.2
Interlaminar Shear	22	5		14.1 ± 0.6
	200	5		12.5 ± 0.3
	400	5		6.8 ± 0.4
	600	5		4.6 ± 0.1
	800	5		4.6 ± 0.2
	1000	5		5.6 ± 0.5
Warp Tensile	22	5	79 ± 2	343 ± 31
Flexure	22	5	45.3 ± 0.9	245 ± 8
	200	5	36.5 ± 4.0	234 ± 10
	400	5	27.5 ± 2.5	163 ± 6
	600	5	18.3 ± 1.4	154 ± 24
	800	5	12.3 ± 0.5	154 ± 9

It is important to try to understand how or if the fire parameters in Table 2, measured in a small scale bench test, relate to the actual fire hazard of a composite material in the use environment. This is a very difficult task and it is necessary to realize that no single parameter will provide the best estimation of the fire hazard of a material in all situations because the hazard depends to a large extent on where and how the material is used (e.g., enclosed space, open space, structural, non-structural, etc.).

It has been suggested that heat release rate of a material measured in small scale tests under simulated radiant exposure conditions is the single most important parameter in characterizing the hazard of a material in a fire [16]. Recently, it was shown that a combined parameter which is the ratio of the peak heat release rate to the time to ignition, also known as the flame propagation index (FPI) or flashover parameter, is a more accurate predictor of time-to-flashover in both room and aircraft compartment fires because it more accurately accounts for thickness effects of the material [17]:

$$\text{Flame Propagation Index (FPI)} = \frac{\text{Peak Heat Release Rate (kW/m}^2\text{)}}{\text{Time-to-ignition (seconds)}} \quad (2)$$

Table 2: Fire Calorimetry Data for Crossply Laminates at 50 kW/m^2 Irradiance [10-12]

RESIN	FIBER	Weight	Time to Loss	Peak Ignition	Average HRR	Heat HRR	Smoke Release
		%	Seconds	kW/m^2	kW/m^2	MJ/m^2	m^2/kg
Isophtalic polyester	Glass	-	77	198	120	-	378
Vynil Ester	Glass	-	78	222	158	-	861
Vynil Ester	Glass	26	74	119	78	25	1721
Epoxy	Glass	-	105	178	98	30	580
Epoxy	Glass	19	18	40	2	29	566
Epoxy	Glass	28	49	181	108	39	1753
Epoxy	Glass	22	50	294	135	43	1683
Epoxy	Carbon	24	94	171	93	-	-
THERMOSETS		**24**	**68**	**175**	**99**	**33**	**1077**
Cyanate Ester	Glass	22	58	130	71	49	898
PMR-15 polyimide	Glass	11	175	40	27	21	170
Bismaleimide	Glass	25	141	176	161	60	546
ADVANCED THERMOSET		**24**	**124**	**115**	**86**	**43**	**538**
Phenolic	Glass	-	210	47	38	14	176
Phenolic	Glass	12	214	81	40	17	83
Phenolic	Glass	6	238	82	73	15	75
Phenolic	Glass	10	180	190	139	43	71
Phenolic	Glass	3	313	132	22	12	143
Phenolic	Carbon	28	104	177	112	50	253
Phenolic	Carbon	9	187	71	41	14	194
PHENOLICS		**11**	**206**	**111**	**66**	**23**	**142**
Polyphenylenesulfide	Glass	13	244	48	28	39	690
Polyphenylenesulfide	Carbon	16	173	94	70	26	604
Polyarylsulfone	Carbon	3	122	24	8	1	79
Polyethersulfone	Carbon	-	172	11	6	3	145
Polyetheretherketone	Carbon	2	307	14	8	3	69
Polyetherketoneketone	Carbon	6	223	21	10	15	274
ENGINEERING PLASTICS		**8**	**207**	**35**	**22**	**15**	**310**
GEOPOLYMER	**Carbon**	**0**	**∞**	**0**	**0**	**0**	**0**

Flashover is a phenomenon unique to compartment fires where incomplete combustion products accumulate at the ceiling and ignite causing total involvement of the compartment materials and signaling the end to human survivability. Consequently, in a compartment fire the time to flashover is the time available for escape and this is the single most important factor in determining the fire hazard of a material or set of materials in a compartment fire. The Federal Aviation Administration has used the time-to-flashover of materials in aircraft cabin tests as the basis for a heat release and heat release rate acceptance criteria for cabin materials for commercial aircraft [6]. Figure 5 shows the calculated time to flashover of the 6-mm thick composite material groups from Table 2 if they were used as wall linings in an 8 ft x 12 ft room which is 8 feet high. The equation used to estimate the time to flashover from the peak heat release rate / time to ignition ratio (FPI) from Table 2 is [17]

$$\text{Time-to-flashover (sec)} = 991 - 629\log_{10}\text{FPI} \quad (3)$$

Equation 3 is an empirical equation which correlates EURIFIC full scale fire test data [18] for 13 different lining materials ($r^2 = 0.94$) obtained according to ISO 9705 corner wall/room fire test using the 100/300 ignition option (100 kW fire for 10 minutes + 300 kW fire for additional 10 minutes) in the corner of a room 3.6-m long x 2.4-m wide x 2.4-m high. For comparison to the predicted behavior of the composite materials in Figure 5, materials in the ISO 9705 test with 10-12 minute flashover times include a melamine high pressure laminate on non-combustible board, steel faced polymeric foam with mineral wool backing, fire-retardant PVC on gypsum wallboard, fire retardant particle board, and a fire retardant textile on gypsum wallboard.

The calculated values for time-to-flashover of organic and Geopolymer composites in a full scale room test shown in Figure 5 provide a qualitative ranking of the fire hazard of these materials in a compartment. The engineering thermoplastics are predicted not to reach flashover during the 20 minute ignition period but could generate appreciable smoke, while the Geopolymer composite will never ignite, reach flashover, or generate any smoke in a compartment fire. It is possible that the actual time to flashover of the continuous fiber reinforced composite laminates listed in Table 2 would be significantly different from the calculated values displayed in Figure 5 and full-scale validation tests of these materials are required to design for fire protection.

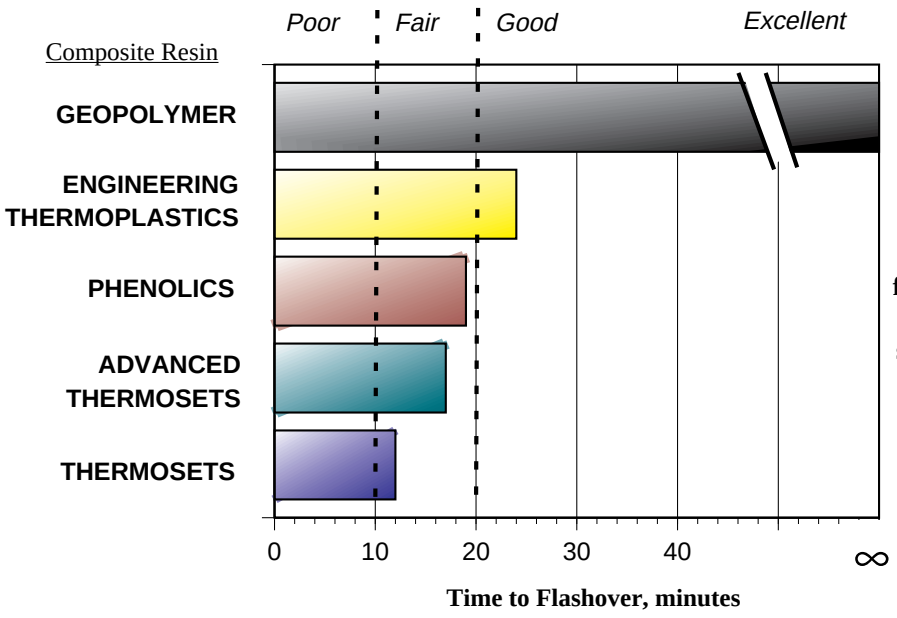

Figure 5: Predicted time to flashover in ISO 9705 corner/ room fire test with various structural composites as wall materials.

The flame spread index provides a relative measure of the speed at which the flame front of a burning composite travels. Consequently the flame spread index provides a qualitative ranking of the rate of fire growth in an open environment. Figure 6 shows a plot of the ratio of the peak heat release rate / time-to-ignition (FPI) from Table 2 for selected materials which were also tested for flame spread index. The correlation is seen to be very good between the flame propagation index determined in the bench scale cone calorimeter test and the measured ASTM E-162 flame spread index for these cross-ply composite laminates. According to this plot, the Geopolymer composite would have a flame spread index of zero, indicating that the Geopolymer composite would be an excellent fire barrier.

In general, the initial matrix dominated strengths (i.e., inplane shear, interlaminar shear, transverse tension, compression) of addition cured thermoset or thermoplastic organic matrix compos-

ites are significantly higher than for the Geopolymer resin composites because of better fiber-to-matrix adhesion and potentially fewer voids. Fiber dominated strengths (i.e., tension, flexure) of organic matrix composites are generally somewhat higher than for the Geopolymer resin composites because of the higher fiber-to-matrix adhesion which results in better load transfer between broken and unbroken fibers during testing to failure. However, thermoset resins such as the phenolic which crosslink via a condensation reaction to form volatile products which can be trapped in the composite as voids, have comparable resin dominated failure strengths.

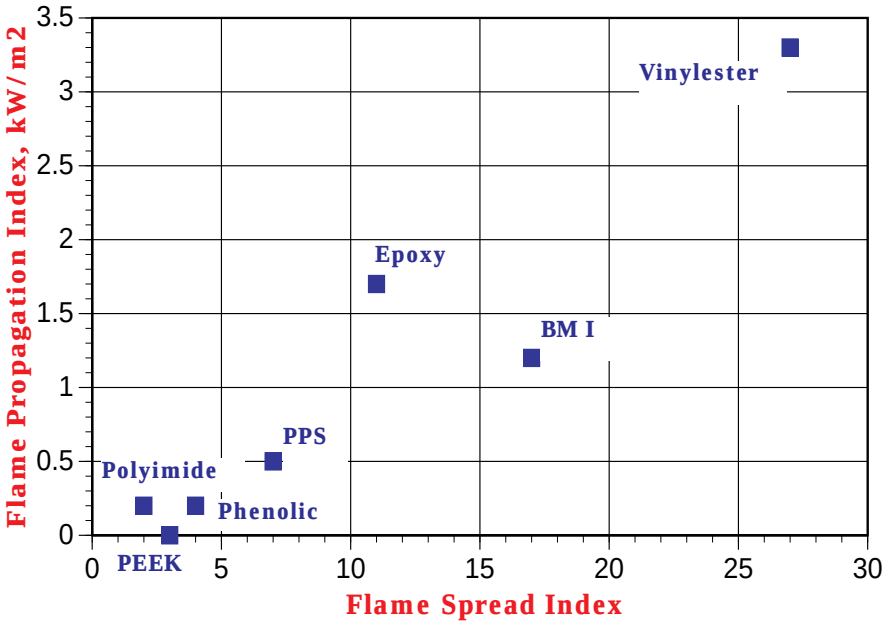

Figure 6: Flame Propagation Index at 50 kW/m2 incident heat flux versus flame spread index for a number of glass-reinforced organic polymer composites.

Differences in the initial strength of organic matrix and Geopolymer resin composites can be compensated in the design phase of a component or structure by simply modifying the dimensions of the structural element. However, the residual strength of a fire exposed composite structure is determined not only by its physical dimensions but also by thermal transport properties, material chemistry, and thermal stability of the composite. Comparison of the composite resin categories on the basis of percent residual flexural strength retained after the fire exposure is shown in Figure 7. The values represent a combined average for the thermoset (vinylester, epoxy), advanced thermoset (BMI, PI), phenolic, and engineering thermoplastic (PPS, PEEK). The Geopolymer-carbon fabric crossply laminate which was subjected to a 400°C oxidizing (air) environment for one hour instead of the 25 kW/m^2 radiant exposure retains 67% of its original 245 MPa flexural strength. The failure mode in the 400°C exposed Geopolymer composite flexural test was a shear delamination near the neutral axis corresponding

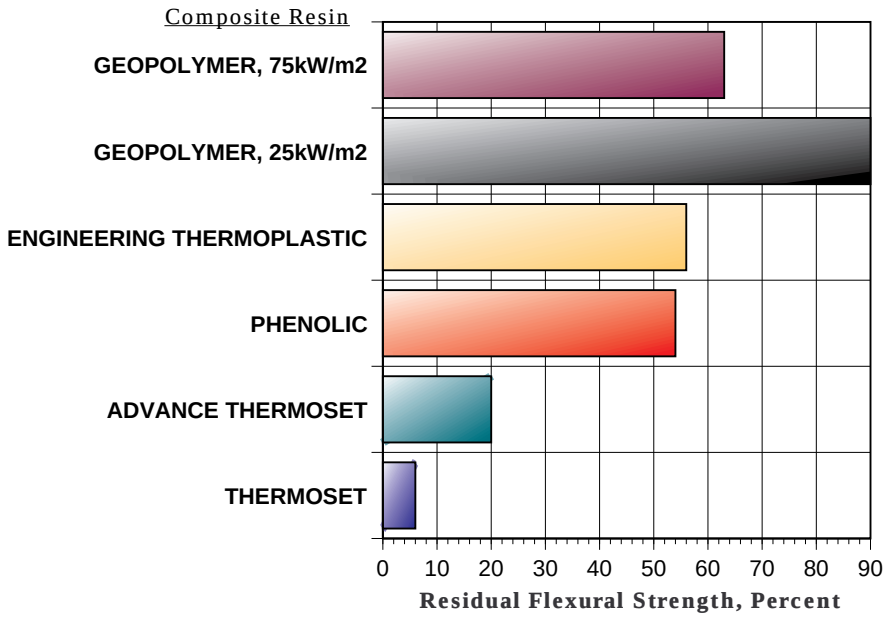

Figure 7: Residual warp-direction flexural strength of crossply laminates after fire/thermal exposure

to a maximum shear stress at failure of about 6.5 MPa, in close agreement with the value of 6.8 MPa obtained for the interlaminar shear strength of the notched compression specimen after 400°C aging in air.

Table 3 compares some thermomechanical properties of fiber reinforced concrete [19,20], structural steel [20,21], a 7000-series aluminum [22] used in aircraft structures, a phenolic- E glass fabric crossply laminate [13], a phenolic-carbon fabric crossply laminate [13], and the Geopolymer-carbon fabric crossply laminate [8]. Maximum temperature capability is defined as the temperature in air at which the nominal tensile or flexural strength falls to one-half of its room temperature value. The Geopolymer-carbon fiber composite, even in the prototype configuration tested, significantly outperforms fiber reinforced concrete with regard to flexural strength and surpasses concrete and structural steel in temperature capability.

Table 3.Typical Properties of Structural Material

MATERIAL	Density	Tensile Modulus	Specific Modulus	Flexural Strength	Specific Flexural Strength	Maximum Temperature Capability
	kg/m3	GPa	MPa-m3/kg	MPa	MPa-m3/kg	°C
Fiber-Reinforced Concrete	2300	30	13.0	14	0.006	400
Structural Steel	7860	200	25.4	400	0.053	500
7000 Series Aluminum	2700	70	25.9	275	0.102	300
Phenolic-Carbon Fabric Laminate [13]	1550	49	31.6	290	0.187	200
Phenolic-E Glass Fabric Laminate [13]	1900	21	11.0	150	0.074	200
Geopolymer-Carbon Fabric Laminate	1850	76	41.0	245	0.132	≥ 800

Specific flexural strength is the flexural strength of the material divided by the bulk density and is the figure of merit for weight-sensitive applications such as aerospace and surface transportation vehicles. Similarly, specific modulus is defined here as the tensile (Young's) modulus of the material divided by its bulk density. In the case of the anisotropic crossply laminates the warp tensile modulus is used for the calculation. The Geopolymer composite is superior to all of the materials listed with regard to specific modulus and is second only to the phenolic-carbon crossply laminate in specific strength. However, the Geopolymer-carbon fabric laminate is unique in its high temperature structural capability and fire resistance.

Conclusions

Carbon fiber reinforced potassium aluminosilicate resin (Geopolymer) composites are non-combustible materials which are ideally suited for construction, transportation, and infrastructure applications where a combination of fire endurance, non-combustibility, and specific flexural strength is needed. Carbon fabric reinforced Geopolymer crossply laminates have comparable initial strength to fabric reinforced phenolic resin composites but have higher use temperatures and better strength retention after fire exposure. In comparison to structural steel the Geopolymer composite falls short in flexural strength, modulus, and cost but the temperature capability is superior. Consequently in applications requiring fire endurance, replacement cost or the added cost of a fire barrier must be figured into the material cost for metallic structures.

Aircraft manufacturers and operators are sensitive to fuel costs so that the figure of merit for this application remains specific strength (strength/density). The high specific flexural strength, flexural modulus, temperature capability, and non-combustibility of the Geopolymer composite make it ideally suited for fire resistant aircraft components. The capability for hand layup or filament winding and low temperature curing suggests applications in seismic retrofit of bridge and building interior columns where upgraded fire resistance and good adhesion to concrete is required. Load bearing capability during severe fire exposure, where temperatures reach several hundred degrees Centigrade, will be significantly higher than organic resin composites, steel, and aluminum

which soften and lose nearly all of their compressive and flexural strengths well below these temperatures. Consequently, applications in the chemical industry for fireproof pipe, tanks, and decking are also being considered.

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