Effects of Temperature and Moisture on Sheet Molding Compounds

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SUMMARY

A summary is given on the effects of moisture and temperature on the properties of chopped fiber reinforced sheet molding compounds. The properties surveyed include tensile strength and modulus, compression strength and modulus, shear strength and modulus, flexural strength and modulus, fatigue, creep, vibration damping, moisture absorption characteristics, and thermal expansion.

INTRODUCTION

OWING TO THEIR FAVORABLE PERFORMANCE CHARACTERISTICS, LIGHT weight composite materials have been gaining wide applications in commercial, space, and military applications. For this reason, in recent years several investigators have measured the properties of glass fiber reinforced sheet molding compounds (SMC). In this report a summary is given of the effects of temperature and moisture on the engineering properties of SMC materials. In presenting the results emphasis is placed on the main features and characteristics of the data. Readers interested in details of the material behavior are referred to the appropriate references quoted in the text, figure captions, and table headings. A brief summary of static properties at room temperature is given in Table 1. Further information regarding room temperature properties may be found in reference 1.

Sheet molding compounds consist of polyester (or, less frequently, vinylester or epoxy) resins reinforced with glass fibers. The fibers may be randomly oriented (designated as SMC-R) or may be continuous (SMC-C and XMC). A material may also contain a combination of chopped and continuous fibers (SMC-C/R and XMC-3). Numbers added after the letters R and C indicate the weight percent of chopped and continuous fibers, respectively. XMC contains 75% glass fibers by weight. Typical formulations and densities of different types of materials are given in Tables 2 and 3.

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Table 1. Room temperature tensile strength and modulus (S_t and E_t), Poisson's ratio (ν), compressive strength and modulus (S_c and E_c), flexural strength and modulus (S_f and E_f), in plane shear strength and modulus (S_{LT} and E_{LT}), and short beam shear strength and modulus (S_S and G_S). L-longidutinal, T-transverse direction. Strength in MPa and modulus in GPa (refs. 2-7).

Material	S_t	E_t	ν	S_c	E_c	S_f	E_f	S_{LT}	E_{LT}	S_S	G_S
XMC-3(L)	561	35.7	0.31	480	37	973	34.1	91.2	4.47	55	—
XMC-3(T)	70	12.3	0.116	160	14.5	139	6.8				
SMC-C20/R30(L)	289	21.4	0.3	306	20.4	645	25.7	85.4	4.09	41	—
SMC-C20/R30(T)	84	12.4	0.18	166	12.2	165	5.9				
SMC-R25	82	13.3	0.25	183	11.7	220	4.8	79	4.48	30	5
SMC-R50	164	15.8	0.31	225	15.9	314	14.0	62	5.94	25	7
SMC-R57	160	16.5	—	—	—	—	—	—	—	—	—
SMC-R65	227	14.7	0.26	241	17.9	403	5.7	128	5.38	45	—
EA SMC-R30	30	8.7	0.30	—	—	—	—	—	—	—	—
VE-SMC-R50	165	7.0	—	—	—	—	—	—	—	50	4
VE-SMC-C40/R10(L)	426	—	—	—	—	—	—	—	—	—	—
VE-SMC-C40/R10(T)	57	—	—	—	—	—	—	—	—	—	—
VE-XMC-3(L)	648	—	—	—	—	—	—	—	—	—	—
VE-XMC-3(T)	74	—	—	—	—	—	—	—	—	—	—

Table 2. Material formulations and densities of SMC materials. (PPG-PPG Industries, OFC-Owens Corning Fiberglas) (refs. 2,3).

Material	Ingredient	Type	Weight %	Density kg/m³
XMC-3	Continuous Glass Fibers- ± 7.5°, X-Pattern	PPG XMC Strand Type 1064	50	
	2.54 cm Chopped Glass Fibers	PPG XMC Strand Type 1064	25	
	Resin	PPG Selectron RS-50335 Isophthalic Polyester	21.5	1970
	Monomer	Styrene	2.4	
	Thickener	PPG Selectron RS-5988	0.8	
	Catalyst	TBPB	0.2	
	Mold Release	Zinc Stearate	0.1	
SMC-C20/R30	Continuous Glass Fibers—Aligned	OCF 433AB Roving	20	
	2.54 cm Chopped Glass Fibers	OCF 433AB Roving	30	
	Resin	OCF-E980 Polyester	32.3	
	Filler	Calcium Carbonate	16.1	1810
	Mold Release	Zinc Stearate	0.8	
	Thickener	Magnesium Oxide	0.5	
	Catalyst	TBP	0.3	
	Inhibitor	Benzoquinone	Trace	

(Continued)

Table 2. (Continued)

Material	Ingredient	Type	Weight %	Density kg/m³
SMC-R25	2.54 cm Chopped Glass Fibers	E-Glass (OCF 951 AB)	25	
	Resin	Polyester (OCF E-920-1)	29.4	
	Filler	Calcium Carbonate	41.8	
	Internal Release	Zinc Stearate	1.1	
	Catalyst	Tertiary Butyl Perbenzoate	0.3	1830
	Thickener	Magnesium Hydroxide	1.5	
	Pigment	Mapico Black	0.8	
SMC-R50	2.54 cm Chopped Glass Fibers	OCF 433AB	50	
	Resin	OCF-E980 Polyester	32.3	
	Filler	Calcium Carbonate	16.1	
	Mold Release	Zinc Stearate	0.8	1870
	Thickener	Magnesium Oxide	0.5	
	Catalyst	TBP	0.3	
	Inhibitor	Benzoquinone	Trace	
SMC-R57	Formulated Epoxy Resin	Epoxy Sheet Molding Compound (Gulf 1057)	43	
	1.27 cm Chopped Glass Fibers	E-Glass (OCF-495)	57	1740
SMC-R65	2.54 cm Chopped Glass Fibers	E-Glass (PPG 518)	65	
	Rigid Resin	Polyester (PPG 50271)	16	
	Flexible Resin	Polyester (PPG 50161)	16	1820
	Thickener, etc.			
EA-SMC-R30	2.54 cm Chopped Glass Fibers	E-Glass (OCF 956)	28	
	Resin	Polyester	19.9	
	Filler	Calcium Carbonate	41	1830
	Thickener	Balance	11.1	

STATIC PROPERTIES

Tensile Strength and Modulus. The environment has a marked effect on the tensile strength and modulus. Generally, both the ultimate tensile strength and the tensile modulus decrease at elevated temperatures (Figure 1) and during exposure to different types of fluids (Tables 4–5). The decrease in properties depends on the temperature, the type of fluid, and the length of exposure. Interestingly, under some conditions there is a slight ($\sim$10%) increase in both the tensile strength and the tensile modulus. The increase is probably due to plasticization of the material.

Compressive Strength and Modulus. Both the compressive strength and modulus depend on the material composition, on the fiber orientation, and on the temperature, as shown in Figure 2. As expected, the strength and the

Table 3. VE-SMC-R50 paste formulation.

Component	Parts
A-SIDE	
XD-9013.03	10
TBPB	1
Camelwite	92
Zinc Stearate	3
B-SIDE	
Derakane* 470-45	100
Maglite D	50
Camelwite	100
Pump 10-14/1 by weight A/B	
Max viscosity = 6000 cps	
(90F, RVT, # 4 Spindle, 20 rpm)	

*Registered Trademark of Dow Chemical Company.

modulus are highest along the fiber direction of composites containing continuous fibers (XMC-3 and SMC-C20/R30).

Shear Strength and Modulus. In most cases there is a significant decrease in the shear strength and in the shear modulus at elevated temperature (Table 6) and during exposure to humid air and to different types of liquids

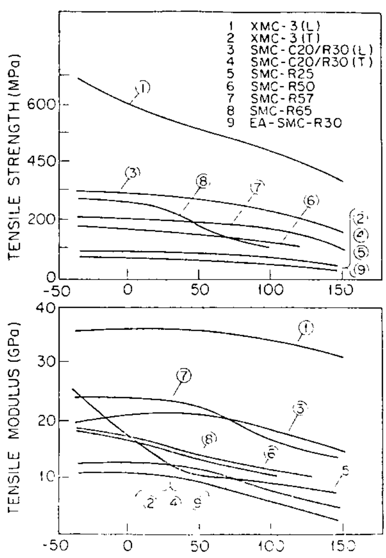

***Figure 1.** The effect of the amount of chopped fibers on the tensile strength of XMC-3 composites. Total fiber content by weight = 75 percent (ref. 8).*

Table 4. Tensile strength retained (percent) after immersion in different fluids for 30 and 180 days. (L-longitudinal, T-transverse direction) (refs. 3,4).

	XMC-3	SMC-C20/R30	SMC-R25		SMC-R50		VE-SMC-R50	
Fluid	30 days	30 days	30 days	180 days	30 days	180 days	30 days	180 days
Water, 23C	89 (L) 107 (T)	103 (L) 73 (T)	–	–	–	–	–	–
Humid Air, 23C, 50% r.h	–	–	100	90	100	100	100	105
Humid Air, 93C, 50% r.h	–	–	95	95	100	90	105	102
Humid Air, 23C, 100% r.h	–	–	90	80	95	80	105	75
Humid Air, 93C, 100%, r.h	–	–	95	55	95	65	95	55
Salt Water 23C	95 (L) 107 (T)	90 (L) 87 (T)	95	65	105	80	102	80
Salt Water, 93C	–	–	70	45	105	50	85	53
No. 2 Diesel, 23C	–	–	90	90	98	98	103	105
No. 2 Diesel, 93C	–	–	95	90	98	98	101	102
Motor Oil, 23C	95 (L) 110 (T)	100 (L) 108 (T)	95	80	95	95	95	102
Motor Oil 93C	–	–	90	80	90	97	105	102
Antifreeze, 23C	95 (L) 110 (T)	78 (L) 108 (T)	95	80	95	95	95	105
Antifreeze, 93C	–	–	75	30	85	30	105	45
Gasoline, 23C	97 (L) 108 (T)	101 (L) 96 (T)	90	90	100	100	100	95
Gasoline, 93C	–	–	75	70	95	70	105	85
Transmission Fluid, 23C	99 (L) 120 (T)	82 (L) 110 (T)	–	–	–	–	–	–
Break Fluid, 23C	97 (L) 93 (T)	97 (L) 109 (T)	–	–	–	–	–	–

(Tables 7,8). As in the case of tensile properties, shear properties also increase slightly under some conditions. Again, this increase is caused by plasticization on the material.

Flexural Strength and Modulus. The flexural strength and modulus decrease with increasing temperature, as illustrated in Figure 3.

FATIGUE

The effect of temperature on tension—tension fatigue life is illustrated in Figures 4 and 5. For chopped fiber composites (SMC-R25 and SMC-R65)

Table 5. Tensile modulus retained (percent) after immersion in different fluids for 30 and 180 days (ref. 4).

	SMC-R25		SMC-R50		VE-SMC-R50	
Fluid	**30 days**	**180 days**	**30 days**	**180 days**	**30 days**	**180 days**
Humid Air, 23C, 50% r.h	105	110	100	90	98	95
Humid Air, 93C, 50% r.h	120	110	90	80	95	90
Humid Air, 23C, 100% r.h	100	95	90	80	95	90
Humid Air, 93C, 100% r.h	120	110	85	80	90	90
Salt Water, 23C	90	95	90	80	95	90
Salt Water, 93C	110	90	85	65	90	85
No. 2 Diesel, 23C	110	115	90	90	95	95
No. 2 Diesel, 93C	120	95	95	90	90	90
Motor Oil, 23C	95	110	80	90	90	95
Motor Oil, 93C	110	115	90	90	95	95
Antifreeze, 23C	90	110	85	80	90	95
Antifreeze, 93C	85	85	80	50	90	75
Gasoline, 23C	95	90	85	85	95	90
Gasoline, 93C	80	80	88	60	85	75

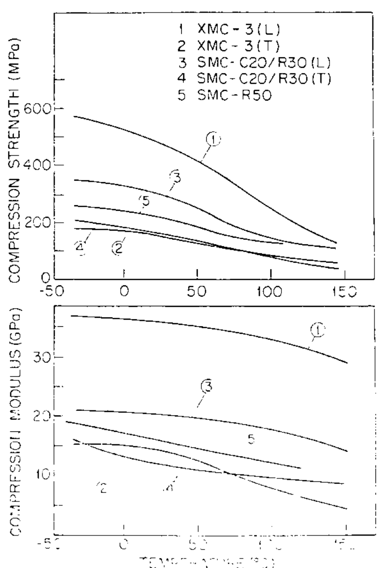

Figure 2. The effect of temperature on the compression strength and compression modulus. (L-longitudinal, T-transverse direction) (ref. 3).

Table 6. Losses in in-plane shear strength (S_{LT}), shear modulus (E_{LT}), and ultimate shear strain (ε_{LT}) when the temperature is raised from 23C to 93C (ref. 3).

	LOSS (Percent)		
	S_{LT}	E_{LT}	ε_{LT}
XMC-3	38	48	13
SMC-C20/R30	40	44	0.7
SMC-R50	–	22	–

an increase in temperature from 23C to 93C results in about a two-fold decrease in fatigue strength of the material. The fatigue strengths of materials containing continuous fibers (XMC-3 and SMC-C20/R30) seem to be affected less by changes in temperature than by the orientation of the fibers.

CREEP

The results of static creep tests are presented in Figures 6–12. The curves are average values. There is considerable scatter in the actual data. An arrow at the end of a curve indicates that the specimen did not fail at the end of the test, while a cross indicates specimen failure.

As expected, the strain increases with load, temperature, relative hu-

Table 7. Short beam shear strength retained (percent) after immersion in different fluids for 30 and 180 days (ref. 4).

	SMC-R25		SMC-R50		VE-SMC-R50	
Fluid	30 days	180 days	30 days	180 days	30 days	180 days
Humid Air 23C, 50% r.h	105	120	110	110	100	103
Humid Air 93C, 50% r.h	120	110	98	110	105	120
Humid Air 23C, 100% r.h	110	110	90	95	95	95
Humid Air 93C, 100% r.h	102	95	92	85	95	95
Salt Water 23C	110	100	95	95	99	98
Salt Water 93C	95	65	80	35	95	75
No. 2 Diesel 23C	115	120	90	75	95	110
No. 2 Diesel 93C	125	125	103	110	100	105
Motor Oil 23C	100	125	85	95	90	115
Motor Oil 93C	110	120	90	110	95	120
Antifreeze 23C	105	110	90	100	95	105
Antifreeze 93C	75	55	50	15	85	50
Gasoline 23C	95	95	80	95	98	99
Gasoline 93C	70	75	85	85	75	75

Table 8. Short beam shear modulus retained (percent) after immersion in different fluids for 30 and 180 days (ref. 4).

	SMC-R25		SMC-R50		VE-SMC-R50	
Fluid	**30 days**	**180 days**	**30 days**	**180 days**	**30 days**	**180 days**
Humid Air 23C, 50% r.h	110	125	105	100	105	115
Humid Air 93C, 50% r.h	125	115	95	95	110	120
Humid Air 23C, 100% r.h	100	115	85	85	90	95
Humid Air 93C, 100% r.h	115	120	95	85	105	105
Salt Water 23C	110	100	85	90	100	95
Salt Water 93C	85	80	65	50	90	95
No. 2 Diesel 23C	125	120	95	95	105	115
No. 2 Diesel 93C	110	115	95	95	110	110
Motor Oil 23C	105	125	75	90	90	110
Motor Oil 93C	105	125	85	95	90	115
Antifreeze 23C	105	115	75	90	90	110
Antifreeze 93C	80	75	54	15	85	55
Gasoline 23C	95	90	80	95	105	110
Gasoline 93C	60	85	70	70	80	75

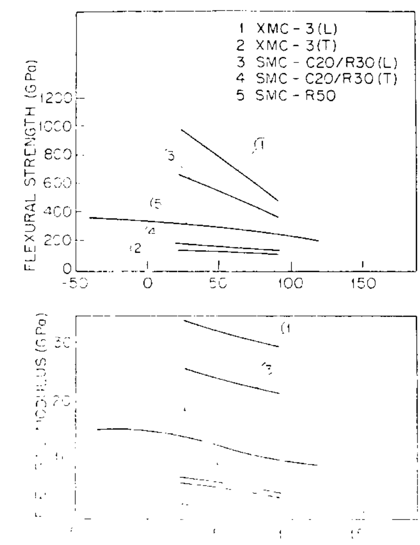

Figure 3. The effect of temperature on the flexural strength and flexural modulus. (L-longitude, T-transverse direction) (ref. 3).

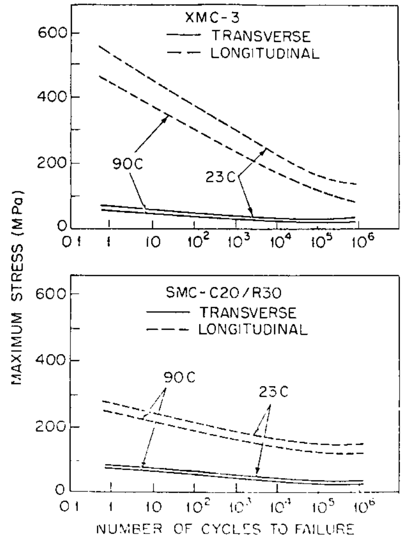

Figure 4. Tension-tension fatigue results. R = 0.05 (ref. 3).

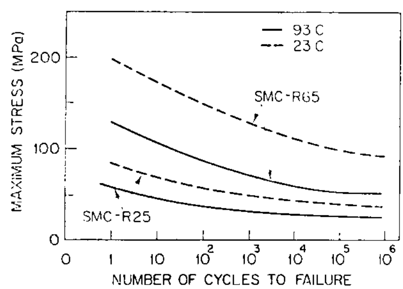

Figure 5. Tension-tension fatigue results. R = 0.05 (ref. 2).

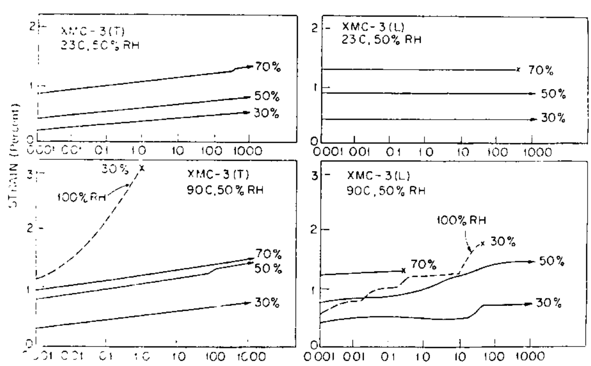

Figure 6. Creep of XMC-3 at 70, 50, and 30 percent of static ultimate tensile strength (L-longitudinal, T-transverse direction) (ref 3).

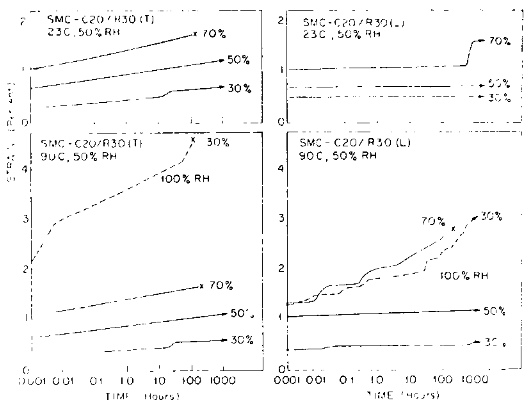

Figure 7. ***Creep of SMC-C20/R30 at 70, 50 and 30 percent of static ultimate tensile strength. (L-longitudinal, T-transverse direction) (ref. 3).***

midity, and time. The increase in strain with time is not uniform. Step "jumps" occur in strain at random times. Because of these unpredictable jumps, the strain cannot be described by simple viscoelastic models.

Heimbuch and Sanders [2] investigated the stress rupture of SMC-R25, SMC-R57 and SMC-R65 composites in air at 23, 60, 90C and at 50% and 100% relative humidities. Owing to the large scatter in the data, the effect of the environment on stress rupture cannot be ascertained from the results of these tests.

ADHESIVE BONDED SINGLE LAP JOINTS

The results presented in this section were obtained with single lap joints

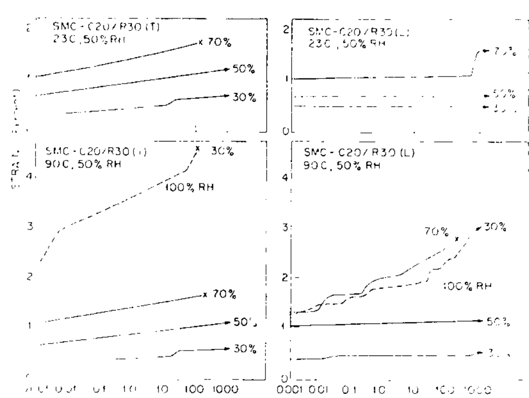

Figure 8. ***Creep of SMC-C20/R30 at 70, 50 and 30 percent of static ultimate tensile strength. (L-longitudinal, T-transverse direction) (ref. 3).***

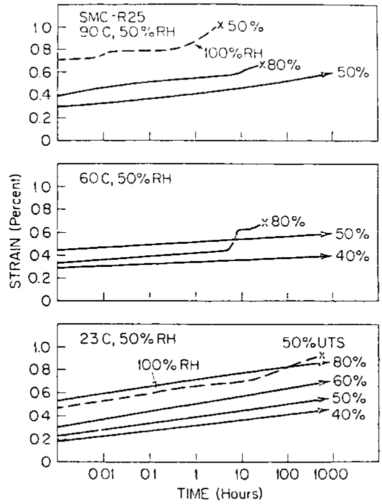

Figure 9. Creep of SMC-R25 under different loads (percent of static ultimate tensile strength) (ref. 2).

bonded with a two part urethane adhesive, characterized in detail in reference [9].

Moisture Absorption Characteristics. Typical moisture absorption data obtained with XMC-3 to SMC-R50 joints are given in Figure 13. Data for SMC-R50 to SMC-R50 joints exhibit similar trends. At 23C both XMC-3 to SMC-R50 and SMC-R50 to SMC-R50 joints seem to approach asymptotically the same maximum moisture content (Mm) when immersed in the same fluid. During a two month test period Mm is reached only in air. In water and in 5% NaCl-water mixture the maximum moisture contents are not attained. The Mm values can be estimated by extrapolating the data,

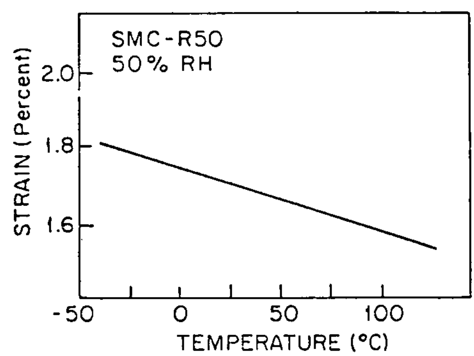

Figure 10. Strain (elongation) of SMC-R50 at failure as a function of temperature (ref. 5).

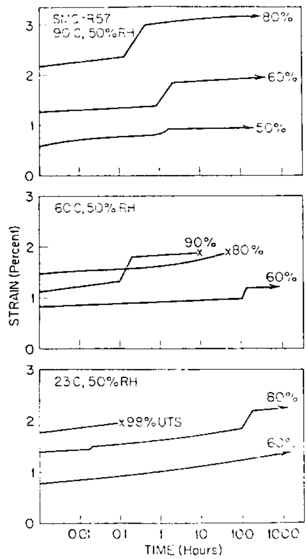

Figure 11. ***Creep of SMC-R57 under different loads (percent of static ultimate tensile strength) (ref. 2).***

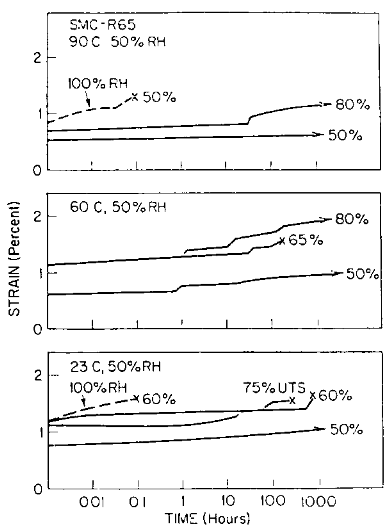

Figure 12. ***Creep of SMC-R65 under different loads (percent of static ultimate tensile strength (ref. 2).***

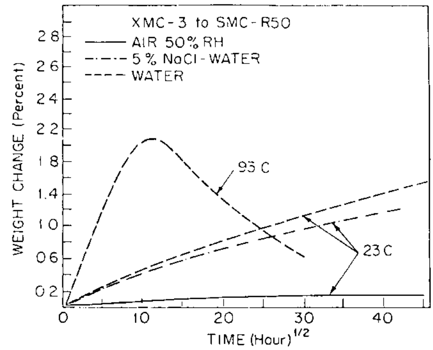

Figure 13. Moisture absorption of adhesive bonded XMC-3 to SMC-R50 single lap joints.

giving 0.18, 1.5 and 2.0 percent for air, salt water, and water, respectively.

At 93C (immersion in water) the maximum moisture level is not approached asymptotically. Here the weight increases for about the first 100 hours and then decreases at a rapid rate. This indicates that the material deteriorates during exposure. At 93C both bonded and unbonded test specimens behave similarly, suggesting that degradation is mostly in the composite and not in the adhesive.

Joints loaded up to 30 percent of their strength did not show appreciable change in their moisture absorption characteristics.

Lap Shear Strength. Lap shear strengths of adhesive bonded single lap joints are given in Table 9. Changes in baseline strength and modulus during environmental exposure are illustrated in Table 10. Neither the strengths nor the moduli change significantly when the joints are exposed to room temperature fluids. In some cases the strength improves slightly (10–15%) during environmental conditioning. The beneficial effects of fluid and temperature are likely due to plasticization. The strength of joints immersed in hot (93C) water and in salt water for 30 days decrease by a factor of two. Loading (up to 30 percent of the baseline strength) during exposure does not seem to affect the strength.

The joints may fail by delamination of the composite or by separation of

Table 9. Baseline ("as received") lap shear strengths of adhesive bonded single lap joints.

	Strength (MPa)	
	23C	93C
XMC to SMC-R50	6.55	3.89
SMC-R50 to SMC-R50	6.11	2.12
SMC-R25 to SMC-R25	3.83	–

Table 10. Changes in lap shear strength (S/S_B) and modulus (E/E_B) of adhesive bonded single lap joints after 30 days of environmental exposure at 23C (B-baseline value) (ref. 9).

	SMC-R25 to SMC-R25		SMC-R50 to SMC-R50	
Fluid	S/S_B	E/E_B	S/S_B	E/E_B
Air	1.00	1.00	1.00	1.00
Motor Oil	0.89	1.05	0.85	0.92
Transmission Fluid	0.92	1.01	0.91	0.91
Gasoline	0.95	0.80	1.20	0.77
Salt Water	0.97	0.72	0.98	0.78
Brake Fluid	0.95	0.87	0.96	0.85
Antifreeze	0.96	1.15	0.81	0.81

the adherent. In these tests, most failures occurred by delamination of the adherent. Separation of the adhesive was predominant only at higher (93C) temperatures.

Fatigue. Wang et al [9] conducted fatigue life tests on SMC-R25 to SMC-R25 and SMC-R50 to SMC-R50 single lap joints. During the tests the stress levels were 30, 50, 70 and 90 percent of the static shear strength. Prior to the fatigue tests the specimens were soaked for 30 days at room temperature in the following liquids: 50% by weight salt water, motor oil, transmission fluid, and gasoline. The ranges of data are shown in Figure 14. The data are not shown separately for specimens immersed in the different fluids because the fluids did not have a significant effect on the fatigue life.

The residual strengths and moduli were also measured for specimens surviving for one million cycles [9]. Cyclic stressing at 30 percent of ultimate strength does not degrade appreciably either the strength or the modulus; in general, both the strength and the modulus retained at least 80 percent of their initial value.

Creep. Creep deformations of adhesive bonded single lap joints under

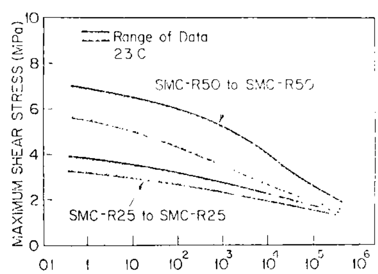

***Figure 14.** Maximum shear stress of adhesive bonded single lap joints (SMC-R50 to SMC-R50 and SMC-R25 to SMC-R25) during tension—tension fatigue (ref. 11).*

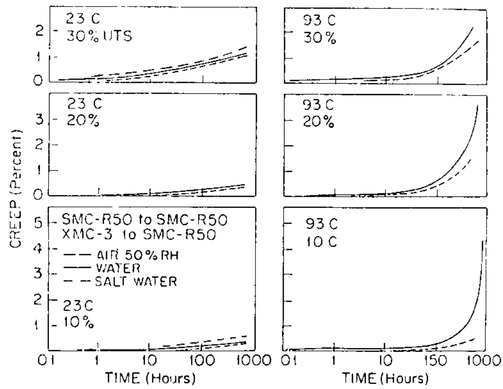

Figure 15. Creep of adhesive bonded single lap joints (SMC-R50 to SMC-R50 and XMC-3 to SMC-R50) immersed in air, water, and 5% NaCl-water mixture under different loads (percent of static ultimate tensile strength).

static and cyclic loadings are shown in Figures 15 and 16. These figures illustrate the effects of material, fluid, temperature, and applied load on creep behavior. The type of material used in forming the joints has smaller effect on creep than does the type of fluid, the temperature, and the applied load. The creep is lowest in air, and is higher in water, in salt water, and in hydrocarbons. The creep also increases with temperature and with applied load. For example, at 23C none of the XMC-3 to SMC-R50 or SMC-R50 to SMC-R50 joints failed during static creep. In air at 93C only one of the

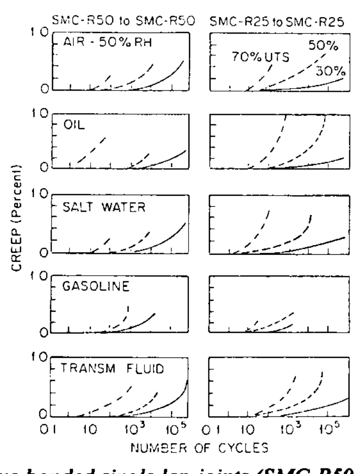

Figure 16. Creep of adhesive bonded single lap joints (SMC-R50 to SMC-R50 and SMC-R25 to SMC-R25) during tension-tension fatigue under different loads (—30% UTS, —50% UTS, —70% UTS) (ref. 9).

joints failed, this occurring at 30 percent load level. During water immersion (at 93C) all but 3 coupons failed before the end of the 715 hours test. During cyclic creep, only joints with 30 percent load survived for one million cycles. At higher loads none of the joints survived for one million cycles.

VIBRATION DAMPING

The vibration damping properties may be characterized by two parameters (the loss factor and the storage modulus) obtained by exciting the material with forced sinusoidal oscillations and by measuring the input stress and output strain [3]. The loss factor is the tangent of the phase angle between the stress and the strain, and is equal to the ratio between the energy dissipated and the energy stored in the material. The storage modulus is the in-phase component of the ratio of input stress to output strain.

The effects of temperature and soaking in different types of liquids are illustrated in Tables 11 and 12. An increase in temperature (from 23C to 120C) increases the damping and reduces the stiffness. Soaking in liquids has similar effects. Soaking for 1000 hours considerably increased the damping of chopped fiber composites (SMC-R25 and SMC-R60), while their stiffness decreased slightly. The damping characteristics of continuous fiber composites (XMC-3 and SMC-C20/R30) change little in the fiber direction. It is noteworthy that both temperature and moisture-induced changes in the vibration properties appear to be reversible [11].

MOISTURE ABSORPTION

Glass fiber reinforced organic matrix composites absorb moisture when exposed to humid air or to liquids. The weight changes of different types of SMC composites exposed to different types of fluids are presented in Figures 17–19. The weight change (M) is defined as

Table 11. Loss factor and storage modulus at 23C, and maximum changes in these parameters when the temperature is increased from 23C to 120C (L-longitudinal, T-transverse direction) (refs. 3,10).

Material	Loss Factor at 23C 0.1 Hz	Loss Factor at 23C 10 Hz	Storage Modulus at 23C (GPa)	Max. Change Percent Loss Factor	Max. Change Percent Storage Modulus
XMC-3(L)	0.028	0.025	36	+129	−7
XMC-3(T)	0.063	0.053	—	+355	−54
SMC-C20/R30(L)	0.034	0.029	—	+ 80	−5
SMC-C20/R30(T)	0.051	0.049	—	+204	−44
SMC-R25	0.037	0.035	4	+471	−48
SMC-R65	0.039	0.034	8	+241	−30
Steel	~0.001				

$$M = \frac{\text{wet weight-dry weight}}{\text{dry weight}} \times 100 \text{ percent}$$

The data show that, in general, when the dry material is submerged in the fluid the weight at first increases then levels off for some length of time. Both the initial rate of weight increase and the value at which the weights level off depend on a) the material, b) the temperature, and c) the environment (relative humidity of air or the type of liquid used). The data also show that in some instances the weight does not remain constant after it reaches a level value but keeps either increasing or decreasing. This suggests that under some conditions the moisture transport is by a non-Fickian process. One reason for the non-Fickian behavior may be that moisture transfer through the resin does not proceed by a process that can be described by Fick's law. Another plausible explanation of the observed non-Fickian absorption process is as

Table 12. Maximum changes in dynamic properties during 1000 hours of soak (L-longitudinal, T-transverse direction) (ref. 11).

		Maximum Change (percent)	
Fluid	**Material**	**Loss Factor**	**Storage Modulus**
Distilled Water 22C	XMC-3(L)	+ 53	0
	SMC-C20/R30(L)	+ 38	0
	SMC-R25	+193	−20
	SMC-R65	+180	− 7
Distilled Water 50C	XMC-3(L)	+ 88	0
	SMC-C20/R30(L)	+112	0
	SMC-R25	+210	−10
	SMC-R65	+247	−12
Salt Water 23C	XMC-3(L)	+ 55	0
	SMC-C20/R30(L)	+ 50	0
	SMC-R25	+117	− 4
	SMC-R65	+178	− 7
Motor Oil 23C	XMC-3(L)	0	0
	SMC-C20/R30(L)	0	0
	SMC-R25	+ 25	0
	SMC-R65	+ 24	0
Antifreeze	XMC-3(L)	0	0
	SMC-C20/R30(L)	0	0
	SMC-R25	+ 29	0
	SMC-R65	+ 22	0
Gasoline 22C	XMC-3(L)	0	0
	SMC-C20/R30(L)	0	0
	SMC-R25	178	−15
	SMC-R65	30	0

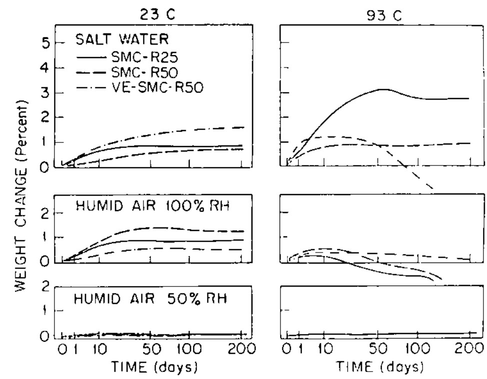

***Figure 17.** Weight change during immersion in humid air and in saturated salt water (ref. 4).*

follows. Owing to the moist, high temperature environment, microcracks develop on the surface and inside the material. Moisture rapidly enters the material, causing an increase in weight. As the cracks grow larger, material, most likely in the form of resin particles, is actually lost. In fact, such material loss is frequently observed after a few hours of exposure to the moist environment. As long as the moisture gain is greater than the material loss, the weight of the specimen increases. Once the weight of the lost material exceeds the weight of the absorbed moisture, the weight of the specimen

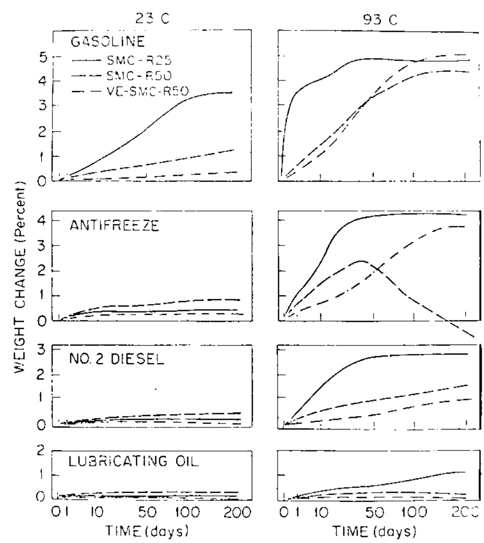

***Figure 18.** Weight change during immersion in different types of hydrocarbons (refs. 4, 12).*

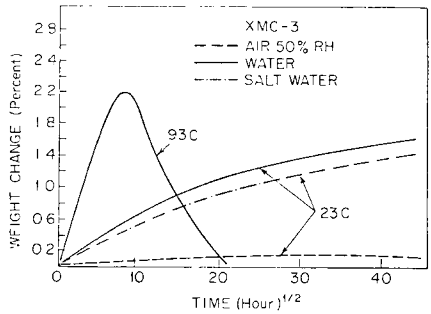

Figure 19. Weight change of XMC-3 immersed in humid air, water, and in 5% NaCl-water mixture (ref. 4).

decreases. Of course, when the material is lost, the measured weight change no longer corresponds to the moisture content of the material.

The foregoing results were all obtained with unstressed specimens. However, the moisture absorption characteristics of stressed and unstressed SMC materials do not differ appreciably.

THERMAL EXPANSION

The dimensional changes of the material during temperature cycles must be taken into account in the design process. The thermal expansion coefficient values reported by Heimbuch and Sanders [2] and by Riegner and Sanders [3] are reproduced in Table 13. As expected, the thermal expansion coefficients are lowest along the fiber direction of composites containing continuous fibers (XMC-3 and SMC-C20/R30). The coefficient is high in the transverse direction of these materials and also for SMC-R25 composites. More com-

Table 13. Thermal expansion coefficient α at room temperature (L-longitudinal, T-transverse direction) (refs. 2,3).

Material	α(μm/m °C)
XMC-3(L)	8.7
XMC-3(T)	28.6
SMC-C20/R30(L)	11.3
SMC-C20/R30(T)	24.6
SMC-R25	23.2
SMC-R50	14.8
SMC-R65	13.7

prehensive data on the variation of the thermal expansion coefficient with temperature are not yet available.

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