Effect of Reinforcement Type and Length on Physical Properties, Surface Quality, and Cycle Time for Sheet Molding Compound (SMC) Compression Molded Parts

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ABSTRACT: One of the fastest growing applications of sheet molding compound (SMC) compression molding is the manufacture of truck body panels. The trucking industry requires parts with high strength and stiffness, but the surface quality is also important. In this study, the effect of reinforcement type and length on physical properties, surface quality, and cycle time are evaluated. In particular, the effect of different lengths of carbon fibers and glass fibers with different sizing are studied. It was found that for the same volume percent, carbon fibers greatly improve the stiffness of the SMC at the sacrifice of strength and surface quality and also require larger fill times for the same molding force, as compared to glass fibers. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 90: 2557–2571, 2003

Key words: composites; compression; molding; fibers; mechanical properties

INTRODUCTION

Sheet molding compound, or SMC, had its early beginnings in the fiberglass reinforced polymeric composite body panels that were used to make the Corvette. These body panels were first produced in 1954 using preform molding. In this process, woven glass mats were first placed in the mold cavity and the resin then poured on them.[1] Several advances in the late 1960s revolutionized the above process to create the product that is today known as SMC. Currently, the surface finish of SMC is equivalent to that of steel and can be classified as a Class A surface. (A Class A surface is defined as a perfectly polished, high luster surface, free of porosity and scratches of any kind. It is the visible surface that consumers see on a product.) SMC is not only competitive with steel based on its surface quality, but also boasts mechanical properties that are equivalent to or in many cases superior to those of steel. For example, the coefficient of thermal expansion is the same for both steel and SMC, but SMC has a higher strength to weight ratio.[3] This is especially important in the automotive industry where the less that a car weighs the less energy it consumes. For example, an SMC part of 0.1-inch [0.254 cm] thickness weighs 25% less than a steel part of 0.03-inch [0.08 cm] thickness, but provides the same stiffness.[2] In addition, as compared to steel, SMC has better resistance to "dings," is more corrosion resistant, and has lower tooling costs.[2] Due to these properties SMC is now used in several industries for many different applications with the heavy trucking industry showing the largest growth potential.

SMC consists of resin, reinforcement fibers, filler, and various additives. Selection of the resin type, from the several available commercially, depends on the application of the finished products. Polyester resin is the most frequently used in SMC applications as it offers fast reaction times, low cost, and good mechanical properties. The proper selection of initiators and inhibitors is essential to control the reactivity of the resin system.[4]

Glass fibers, specifically E-type glass fibers, are the most common type of reinforcement used in the SMC industry. They provide dimensional stability and good mechanical properties. Typically the glass fibers, which are bundles of individual filaments, occupy 25–35% by weight of the SMC composition and are randomly oriented in the plane of the sheet.[4] Glass fibers are also characterized by the sizing chemistry—either hard or soft fibers. Hard fibers have a higher degree of integrity throughout the SMC process and are used for Class A surfaces and for parts requiring high impact resistance. Soft fibers are coated with a soluble binder, thus they have a high degree of filamentation during the molding process and provide superior mechanical properties. They are typically used in applications where the geometry is complex and is more easily filled with filaments than with fiber bundles.[4] If a large

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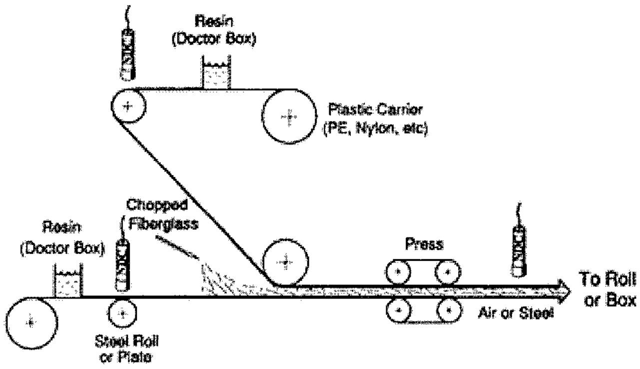


Figure 1 Schematic of a typical SMC machine.

stiffness is desired, carbon fibers can also be used as reinforcements.

To begin the process of producing the SMC all the ingredients, except the fibers, are mixed batch mixed prior to processing. The resulting paste is then poured into two doctor boxes on the SMC machine (see Fig. 1). The doctor boxes apply a thin layer of paste onto two separate polyethylene/nylon films. One film with a layer of paste is brought underneath a rotating cylinder with blades used to chop glass roving into lengths of 0.5, 1, 2 inch [1.27, 2.54, 5.08 cm] or a combination of any of these lengths. The chopped fibers then randomly fall onto the paste. From there the second layer of polyethylene film with paste is brought into contact with the chopped fiber/paste mixture, creating a sandwich with the film on the outside and the fiber/paste mixture in between. At this point, the sandwich is then fed into a series of compaction rolls that help to improve wetting of the glass by removing the air within the sheet. This product is known as SMC. The SMC is stored for a period of 2–3 days in order to give the paste time to thicken, or mature, after which it is ready to be molded.

When the SMC has matured sufficiently for molding it is cut into pieces, called plies. Three or four plies are then stacked, creating a charge, weighed and placed in a mold, which is typically heated to 300°F (150°C). To allow for enough flow and in order to eliminate air voids trapped in the SMC, the charge covers 50% or less of the mold surface.[1] Once the charge has been placed in the mold, the press is closed. This brings the two mold halves together and a pressure of approximately 800 lbs/inch^2 (5.52 MPa) is exerted over the projected part area.[2] The mold then remains closed for about 45 s to 1 min, until the cure of the part is complete and it can be removed from the mold.[2]

RESEARCH BACKGROUND AND OBJECTIVES

As previously mentioned, heavy truck body panels are the area of largest growth potential for SMC. The trucking industry requires parts with high strength and stiffness, yet surface quality is also important. By increasing the length of the reinforcement, the physical properties of molded parts can be tailored to the desired application. Additionally, if higher stiffness is desired, carbon fibers can be used as reinforcements. However, since surface quality is important, how it is affected by reinforcement length and type needs to be determined. Furthermore, since the SMC industry is cost driven, the effect on fill time and, consequently, economics needs to be understood. Therefore, this study was undertaken to determine how the use of different reinforcement types and lengths would affect the physical properties, surface quality, and cycle time for SMC compression molded parts. Specifically, hard and soft E-glass fibers, as well as, carbon fibers were tested in four different fiber length combinations: 0.5, 1, 2 inch (1.27, 2.54, 5.08 cm) and a combination of 0.5 and 1 inch (1.27 and 2.54 cm).

EXPERIMENTAL

With the assistance of Ashland Chemical (Dublin, OH) 12 different types of SMC were produced. Each SMC was 36 inch wide, was compacted at 450 g/ft^2 and utilized the same paste make-up (see Table I). However, the type and length of fibers that were added to the paste differed for each of the 12 SMC combinations. Table II provides the type and length of fibers that were contained in each of the 12 SMCs.

From the 12 SMCs produced two sets of moldings were made. For the first set, with the cooperation of Omnova Solutions (Akron, OH) a 400-ton (363 metric tons) Hoesch press with a flat plate rectangular mold measuring 17 × 22 inch (43.2 × 55.9 cm) was utilized. For each type of SMC described above 12 moldings at 300°F (150°C) were made. Of each set of 12 moldings four moldings each were made using 3, 4, and 6 plies of SMC. The charges were all 17 inch in width; two were placed in the far left side of the mold and the other two in the center of the mold. Thus, the flow for these experiments was one-dimensional in either one (left charges) or two directions (center charges). It

TABLE I
SMC Paste Make-Up

Component	Parts per hundred
Unsaturated polyester and styrene monomer resin (including low profile additive)	100
Mod E (inhibitor)	0.24
TBPB (catalyst)	1.5
PDO (catalyst)	0.2
VR 3 (mold release)	3.0
Calcium stearate (mold release)	1.0
$CaCO_3$ (63% filler of SMC paste)	200
Thickener	10.2

TABLE II
SMC Compositions Tested

Combination	Fiber length (inch) 0.5	1	2	Fiber type
1	W_1	—	—	Hard glass
2	—	W_1	—	Hard glass
3	—	—	W_1	Hard glass
4	$W_1/2$	$W_1/2$	—	Hard glass
5	W_1	—	—	Soft glass
6	—	W_1	—	Soft glass
7	—	—	W_1	Soft glass
8	$W_1/2$	$W_1/2$	—	Soft glass
9	W_2	—	—	Carbon
10	—	W_2	—	Carbon
11	—	—	W_2	Carbon
12	$W_2/2$	$W_2/2$	—	Carbon

W_1 = 28% and W_2 = 21.5%, percentage (by weight) of fiber that the SMC should contain. Although the weight percents of glass fiber and carbon fiber differ, the volume percentage of fibers is the same for each combination, and is equal to 21%. Hard glass: Vetrotex America 239-113, soft glass: PPG 6545, carbon fiber: Zoltek XP3304815R-X19.

should be noted that in each instance it was desired that the volume of the part remains the same, so each charge was weighed prior to molding to ensure that the volume would be consistent. This also ensured that the plaques produced all had an approximate thickness of 0.125 inch (0.32 cm). Given that the mold cavity measured 17 × 22 inch (43.2 × 55.9 cm) the final volume of the parts was approximately 46.75 inch^3 (766 cm^3). In summary, a total of 144 plates were molded: three types of reinforcement (hard glass, soft glass, and carbon) × four reinforcement lengths (0.5 inch, 50–50 combination of 0.5 and 1 inch, 1, and 2 inch) × three different ply set-ups (3, 4, and 6) × two charge locations in the mold (left and center) × two repeats.

The second set of moldings consisted of 48 plaques molded at Ashland Chemical. Four plaques were made for each of the 12 SMC combinations detailed in Table II. All were molded in a square 12 × 12-inch (30.48 × 30.48 cm) mold using centrally located square 3-ply charges measuring 7 × 7 inch (17.8 × 17.8 cm). Therefore, the flow for these square plaques was two-dimensional. The fact that two different flow patterns were used, giving different fiber orientations for the moldings, will aid in the evaluation of the physical properties and surface quality.

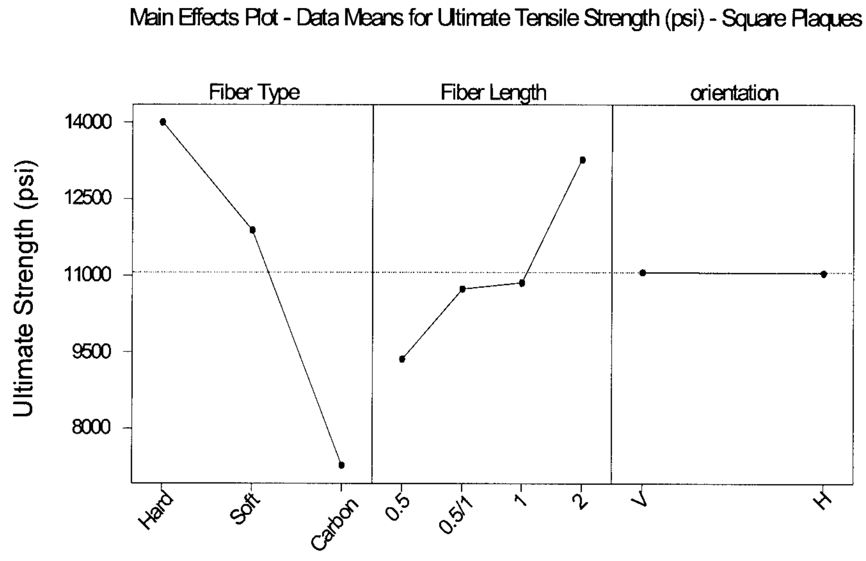
Physical property testing

The physical properties of the plaques were measured after the surface quality data had been obtained, but in order to facilitate the flow of the discussion the physical properties will be discussed first. Due to the nature of the two types of moldings, one-dimensional flow versus two-dimensional flow it was of interest to test specimens in two directions from each group of moldings. In the case of the two-dimensional flow (square plaques molded at Ashland Chemical), it was expected that the orientation of the specimens would have no effect on the physical properties. On the other hand, since the rectangular plaques molded at Omnova Corporation were constrained to one-dimensional flow it was expected that they would have superior physical properties in the direction of flow (0°) than when tested perpendicular to the flow (90°). In fact, Kim and Im[9] have previously documented this effect for glass reinforced SMC.

Four tensile specimens per plaque for the Omnova molded plaques and six for the Ashland molded plaques were cut according to ASTM A 370. Of the specimens cut from each plaque half were taken in the direction of the flow (0°) while the other half were perpendicular to the flow (90°). For the Omnova plaques, only those molded with 1-inch (2.54 cm) fibers and 2-inch (5.08 cm) fibers were tested. Also, only the plaques located in the left side of the mold were used.

An ANOVA analysis was performed on the data, using MINITAB, to see what factors had the largest effect. In Figure 2, the main effects plot and ANOVA table for the ultimate tensile strength for the specimens taken from the square plaques is given. Based on this plot it can be seen that both the fiber type and fiber length have a very large effect on the strength of the SMC (a factor is considered significant if it has P value less than 0.01). It can also be seen that hard glass and fibers 2-inch (5.08 cm) in length offer significant advantages for ultimate tensile strength. In addition, it can be observed that the orientation of the test specimens has no effect on the ultimate tensile strength. This is expected as these plaques were square and were molded using square charges. This causes the flow within the mold to be two-dimensional and the properties of the plaques to be equivalent in both the horizontal and vertical directions. No significant interactions were observed (see ANOVA Table).

The main effects plot and ANOVA table for the modulus of the square plaques can be seen in Figure 3. From this plot it can be observed that both the fiber type and fiber length are, again, the significant factors when examining the modulus. In this case, the carbon fiber is superior to the glass fibers if a high stiffness is desired. The orientation is shown to have no effect on the modulus and, again, the 2-inch (5.08 cm) fibers appear to be significantly better than the other fiber lengths. However, if the interaction plot for the modulus is examined (see Fig. 4) along with the ANOVA table in Figure 3 it can be seen that there is a significant interaction between the fiber length and fiber type. This interaction appears because there is a very dramatic increase in the modulus from 1-inch (2.54 cm) to 2-inch (5.08 cm) carbon fibers. This makes it appear in



Analysis of Variance for **Ultimate Tensile Strength**, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Fiber Type	2	570773001	570773001	285386501	181.35	0.000
Fiber Length	3	142922324	142922324	47640775	30.27	0.000
Orientation	1	6747	6747	6747	0.00	0.948
Fiber Type*Fiber Length	6	27154084	27154084	4525681	2.88	0.018
Fiber Type*orientation	2	1554765	1554765	777382	0.49	0.613
Fiber Length*orientation	3	15589413	15589413	5196471	3.30	0.028
Fiber Type*Fiber Length* orientation	6	26320120	26320120	4386687	2.79	0.021
Error	48	75536470	75536470	1573676		
Total	71	859856924				

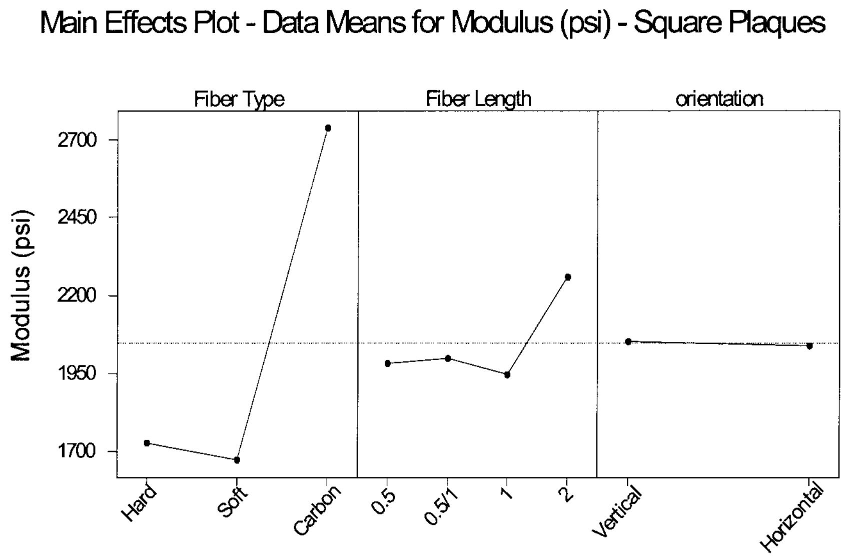
Figure 2 Main effects plot and ANOVA table for ultimate tensile strength—square plaques.

the main effects plot as if 2-inch (5.08 cm) fibers would be beneficial when using any type of fiber. However, the interaction plot reveals that this result is mainly due to the carbon fiber. Therefore, it does appear that 2-inch (5.08 cm) carbon fibers would provide the highest modulus, but in the case of the hard and soft glass increasing the fiber length does not appear to increase the modulus of the final SMC part.

For the rectangular plaques, several of the results found were similar to those of the square plaques. Therefore, results will be presented only if it adds additional information to the discussion (all testing results can be found in Ref. 5). A group of 72 specimens: two reinforcement length (1 and 2-inch) × three different types of reinforcement (hard glass, soft glass, and carbon) × three different ply set ups (3, 4, and 6) × two sample orientation (flow direction and cross flow direction) × two repeats, were tested.

As expected, the analysis showed that the same factors were significant for both types of plaques (rectangular and square). For example, when the data was analyzed the main effects plot and ANOVA table for ultimate tensile strength (see Fig. 5) showed that the fiber type and fiber length were significant, just as they had been in the case of the square plaques. Once again, as can be seen from the plot, hard glass provides the highest ultimate tensile strength followed by soft glass, and finally carbon fiber. Two-inch (5.08 cm) fibers were also seen to have superior strength properties over 1-inch (2.54 cm) fibers. Two other notable items in this figure are the fact that the number of plies appears to have no significant impact on the ultimate strength and that the direction in which the sample was taken is significant.

The fact that the number of plies appears to have no significant effect on the ultimate strength merits further discussion because the more the plies that are used the more the flow that has taken place. Therefore, it is expected that these specimens would have had a higher strength in the direction of the flow. However, the effect of the number of plies is cancelled out by the fact that as the parts become stronger in the direction of the flow, they become weaker in the direction perpendicular to the flow and the main effects plot is unable to show this result. However, if the ratio of the tensile strength or the modulus in the direction parallel (0°) to the one perpendicular (90°) to the flow is taken and an ANOVA analysis is completed, it can be seen that the number of plies does in fact have a significant influence on the ultimate tensile strength,



Analysis of Variance for **Modulus**, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Fiber Type	2	17370677	17370677	8685338	145.80	0.000
Fiber Length	3	1104728	1104728	368243	6.18	0.001
Orientation	1	2854	2854	2854	0.05	0.828
Fiber Type*Fiber Length	6	1277490	1277490	212915	3.57	0.005
Fiber Type*orientation	2	162883	162883	81441	1.37	0.265
Fiber Length*orientation	3	123071	123071	41024	0.69	0.563
Fiber Type*Fiber Length*orientation	6	541624	541624	90271	1.52	0.193
Error	48	2859398	2859398	59571		
Total	71	23442723				

Figure 3 Main effects plot and ANOVA table for modulus—square plaques.

as well as on the modulus, of the parts, see for example Figure 6 for the modulus. This result is expected since, as mentioned before, the more the plies that are used the greater the distance that the SMC must flow to fill the cavity and the larger the fiber orientation. Figure 6 also shows that the ratio of the modulus parallel and perpendicular to the flow is lower for the 2-inch length fibers than for the 1-inch fibers. This indicates that the 2-inch fibers orient less than the 1-inch fibers.

Surface quality testing

A key attribute for SMC compression molded exterior automotive, or truck, body panels is the surface flatness. This refers to surface waviness and orange peel. A surface quality measurement commonly used, and universally accepted in the SMC industry, is the Ashland Index (AI).[10] The LORIA Surface Analyzer obtains this measurement by scanning 21 lines across the surface of the part. Each line is 10 inch in length and is separated by 0.5 inch from the next line. The deviation from a flat part is then measured and manipulated to obtain the AI. The larger the value of the AI, the worse the surface quality is. In the SMC industry, a surface with an AI of less than 100 is considered Class A. The AI was measured for both the rectangular and square plates and the results analyzed using MINITAB.

The main effects plot and ANOVA table for the square plaques can be seen in Figure 7. From this plot and the ANOVA table both the fiber type and fiber length are found to be statistically significant. The hard and soft glass fibers are shown to be better for use if Class A surfaces are desired. It can also be seen that as the fiber length increases the AI increases, indicating a decrease in surface quality. This is likely due to the fact that the smaller fiber lengths move more easily and, therefore, the plaque is more homogeneous than when longer fibers are used.

The main effects plot and ANOVA table for the rectangular plates is shown in Figure 8. From this it can again be concluded that both hard and soft glass fibers are good choices for Class A surfaces, while carbon would be better suited for structural use. This plot also shows that the fiber length is a significant factor in the value of the AI. As can be noted from Figure 8 it appears that for one-dimensional flow 0.5-inch (1.27 cm) and 2-inch (5.08 cm) fiber lengths are the most likely to produce Class A surfaces. It is believed that the reason that the AI for the 2-inch (5.08

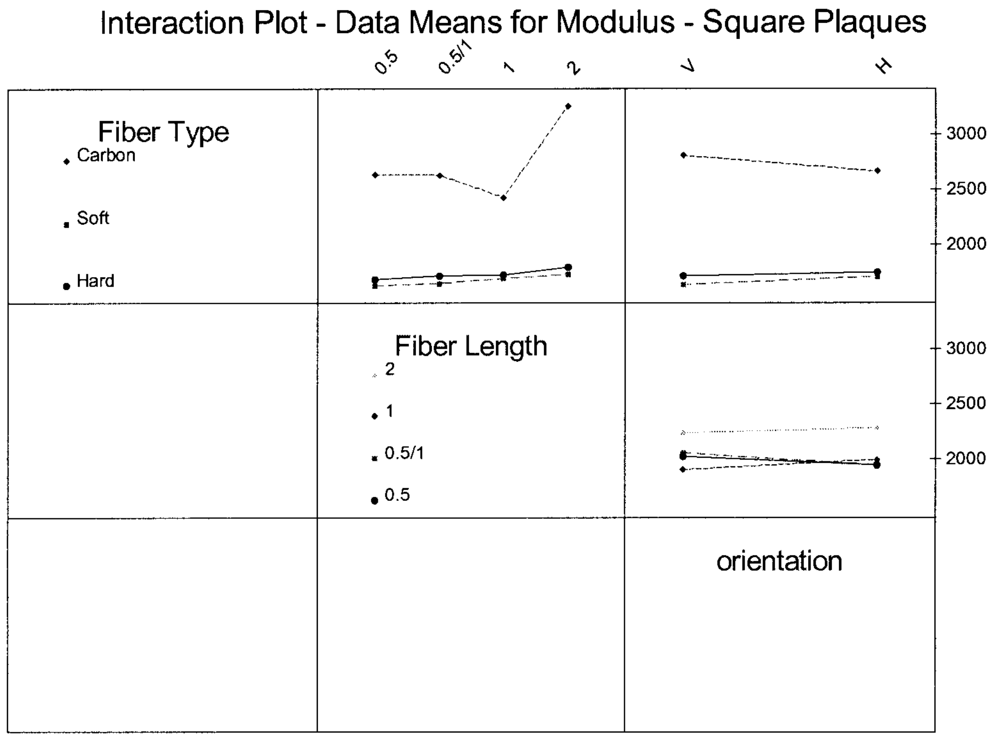


Figure 4 Interaction plot for modulus—square plaques.

cm) fibers is improved over that of the 1-inch (2.54 cm) fibers is that the 2-inch (5.08 cm) fibers are less oriented in the direction of the flow. This is reinforced by examining Figure 6, where the main effects plot for the ratio of the modulus for the samples in the flow direction with respect to the samples taken perpendicular to the flow direction is given. This plot seems to indicate that the 2-inch (5.08 cm) fibers are more difficult to align in the flow direction than the 1-inch (2.54 cm) fibers, creating a more homogeneous SMC; and leading to a better surface quality.

The main effects plot in Figure 8 also shows that the number of plies has a significant effect on the AI. The fewer the number of plies used the better the surface quality, that is, the lower the AI. This is expected because the more the plies that are used the lesser the mold surface area covered by the charge. This implies a greater amount of flow has taken place, thus causing the fibers to orient more and the AI to increase.

PREDICTION OF CLOSING SPEED AND FILL TIME

As discussed in the Introduction section, the SMC industry is extremely price sensitive, thus the effect of SMC type on cycle time is a key part of process optimization. Typically in an industry a company will have a press with a given capacity (tonnage), but is unsure how short the compression time can be in order to completely fill the mold cavity. This is important due to the fact that the faster the mold cavity is filled, the more reactive the SMC can be, leading to a shorter cure time and, in turn, a shorter cycle time. Therefore, in the discussion that follows a method to determine the minimum fill time for an available molding force will be detailed.

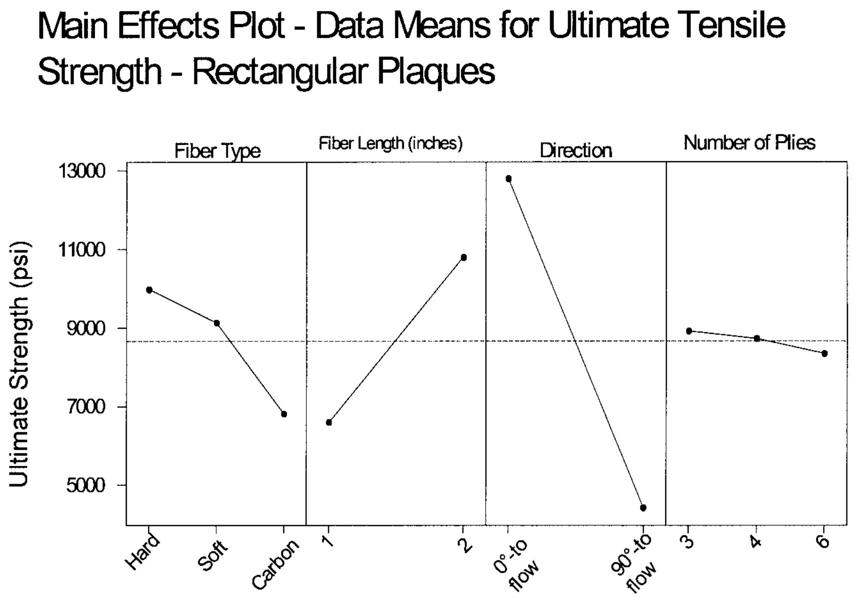
In a previous research,[3] a model was presented to predict the force to mold during the SMC compression molding step given a constant closing speed. In addition, a simple procedure to measure the SMC rheological parameters needed to predict molding forces was developed.[5] The following equations, derived in Ref. 3, are used to predict the molding force for one-dimensional flow as a function of the instantaneous cavity thickness, h, for an SMC charge located in the left side of the mold (F_L) or the center of the mold (F_C).

$$F_L = \frac{4f_C VU}{h^2} + f_L \frac{2U^n V^{n+2}}{h^{2n+3} W^{n+1}(n+2)} \quad (1)$$

$$F_C = \frac{4f_C VU}{h^2} + f_L \frac{2U^n V^{n+2}}{h^{2n+3} W^{n+1}(n+2)(2^{n+1})} \quad (2)$$

where,

f_C = coefficient of extension in the core, (tons s/in^2) [N s/cm^2]
V = volume of part, inch^3 [cm^3]
U = closing speed, inch/s [cm/s]
h = cavity thickness, inch [cm]
n = power law exponent, dimensionless



Analysis of Variance for **Ultimate Strength**, using Adjusted SS for Tests

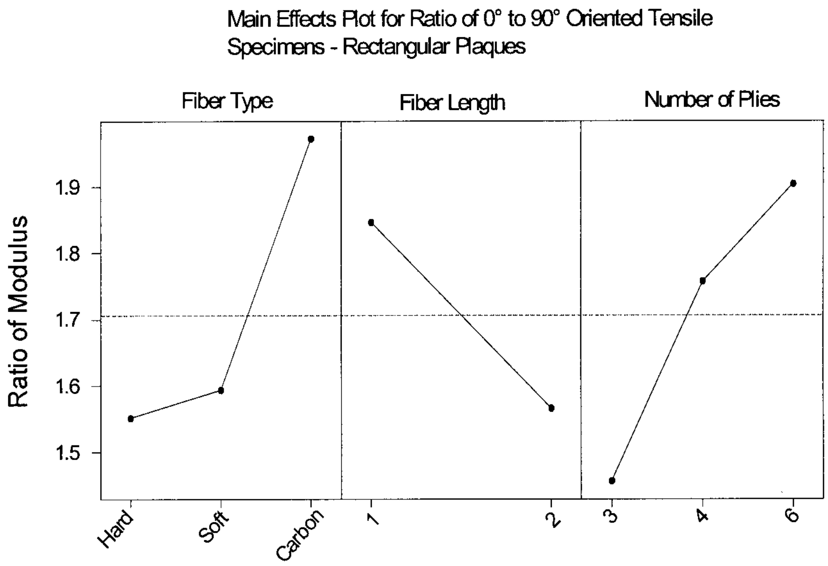
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Fiber Type	2	126359498	118022594	59011297	32.87	0.000
Fiber Length	1	306050834	268947148	268947148	149.82	0.000
Direction	1	1244642605	1229496442	1229496442	684.89	0.000
Number of Plies	2	2957041	4534391	2267196	1.26	0.295
Fiber Type*Fiber Length	2	9767044	8277392	4138696	2.31	0.115
Fiber Type*Direction	2	55064508	52317673	26158837	14.57	0.000
Fiber Type*Number of Plies	4	10121376	7710995	1927749	1.07	0.384
Fiber Length*Direction	1	35043468	38849190	38849190	21.64	0.000
Fiber Length*No. of Plies	2	3191745	4382871	2191436	1.22	0.307
Direction*No. of Plies	2	16087284	15753102	7876551	4.39	0.020
Fiber Type*Fiber Length* Direction	2	1065546	1511133	755567	0.42	0.660
Fiber Type*Fiber Length* Number of Plies	4	2738871	2051035	512759	0.29	0.885
Fiber Type*Direction* Number of Plies	4	29859313	30844077	7711019	4.30	0.006
Fiber Length*Direction* Number of Plies	2	1976355	1691681	845841	0.47	0.628
Fiber Type*Fiber Length* Direction*No. of Plies	4	16035312	16035312	4008828	2.23	0.085
Error	35	62831531	62831531	1795187		
Total	70	1923792330				

Figure 5 Main effects plot—ultimate strength—rectangular plaques.

f_L = lubricating layer coefficient, (tons s^n/in^{n+2}) [N s^n/cm^{n+2}]
W = width of mold, inch [cm]

These equations can also be used to predict the closing speed, U, for a limiting available molding force (F_C or F_L), which, in turn, can be used to find the fill time, t. To do so, several material constants must be known. These constants are the lubricating layer coefficient, f_L, the power law exponent, n, and the coefficient of extension in the core, f_C. These constants for the SMCs discussed here were measured and are given in Table III.[7]

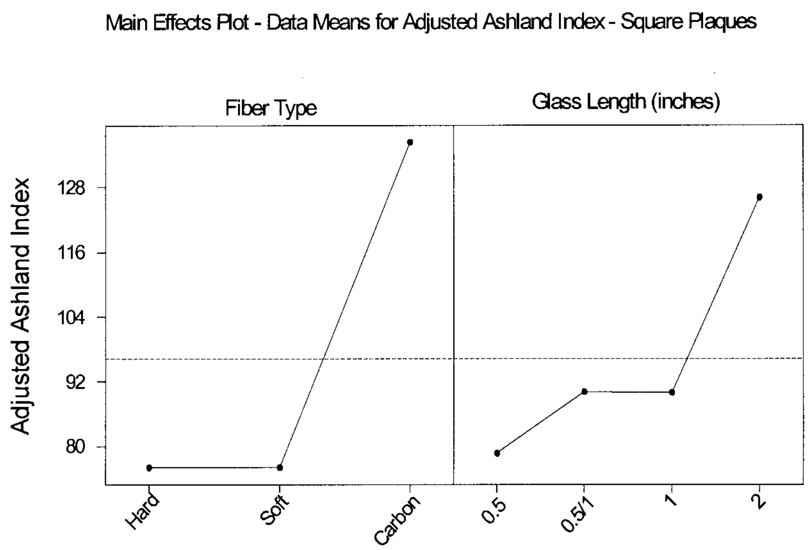
Integrating the closing speed, $U = -(dh/dt)$ the following equation is obtained: $h_{new} = h_{old} - U\Delta t$, where h_{new} designates the cavity thickness after a time increment of Δt has passed, while h_{old} designates the cavity thickness before this time increment has passed. The value h_{new} can then be inserted into either eq. 1 or 2 and the value of U solved for. Iteration is necessary to solve eq. 1 or 2 for U; therefore, MATLAB was utilized in order to write two programs (one for a center placed charge and one for a left hand placed charge) that could iterate the equations until the correct value was found. The programs begin by calculating the closing speed based on the initial thickness of the charge. This value of the closing speed, U, is then used to calculate the new cavity thickness, h_{new}, after a time interval, Δt. This new value of cavity



Analysis of Variance for **Modulus**, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Fiber Type	2	3.1794	2.3975	1.1987	9.60	0.000
Number of Plies	2	2.4668	2.3649	1.1825	9.47	0.000
Fiber Length	1	1.3633	1.3633	1.3633	10.92	0.002
Error	64	7.9879	7.9879	0.1248		
Total	69	14.9974				

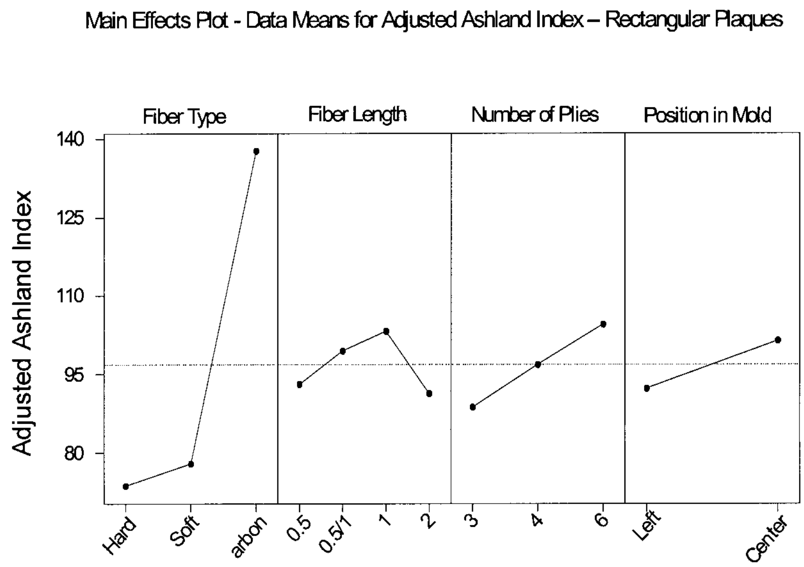
Figure 6 Ratio of modulus parallel and perpendicular to the flow—rectangular plaques.



Analysis of Variance for **Adjusted Ashland Index**, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Fiber Type	2	38600.3	38600.3	19300.1	64.54	0.000
Fiber Length	3	15220.8	15220.8	5073.6	16.97	0.000
Fiber Type*Fiber Length	6	1839.9	1839.9	306.6	1.03	0.425
Error	36	10765.0	10765.0	299.0		
Total	47	66425.9				

Figure 7 Main effects plot for Ashland Index (AI)—2-dimensional flow.



Analysis of Variance for **Adjusted Ashland Index**, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Fiber Type	2	122106.4	120781.2	60390.6	791.49	0.000
Fiber Length	3	3394.7	3411.8	1137.3	14.91	0.000
Number of Plies	2	6243.1	5852.9	2926.5	38.35	0.000
Position	1	2484.7	2563.9	2563.9	33.60	0.000
Fiber Type*Fiber Length	6	462.7	449.8	75.0	0.98	0.444
Fiber Type*No. of Plies	4	5108.7	5196.8	1299.2	17.03	0.000
Fiber Type*Position	2	129.6	124.3	62.1	0.81	0.447
Fiber Length*No. of Plies	6	411.3	438.5	73.1	0.96	0.460
Fiber Length*Position	3	369.4	366.7	122.2	1.60	0.197
Number of Plies*Position	2	555.1	520.5	260.3	3.41	0.039
Fiber Type*Fiber Length* Number of Plies	12	1018.6	947.4	78.9	1.03	0.428
Fiber Type*Fiber Length* Position	6	859.2	881.6	146.9	1.93	0.089
Fiber Type*Number of Plies* Position	4	171.9	176.7	44.2	0.58	0.679
Fiber Length*Number of Plies* Position	6	646.1	660.4	110.1	1.44	0.211
Fiber Type*Fiber Length* No. of Plies*Position	12	752.2	752.2	62.7	0.82	0.628
Error	70	5341.0	5341.0	76.3		
Total	141	150054.9				

Figure 8 Main effects plot for AI—1-dimensional flow.

TABLE III
Rheological Parameters for the SMC Compositions Tested

Fiber type	Fiber length inch (cm)	f_C (lbs*s/inch^2)	f_C (N*s/cm^2)	f_L (lbs*s$^{0.33}$/inch$^{2.33}$)	f_L (N*s$^{0.33}$/cm$^{2.33}$)
Hard glass	0.5 (1.27)	79.70	54.95	3.69	1.86
	1 (2.54)	218.80	150.85	3.66	1.85
	2 (5.08)	446.65	307.94	4.11	2.08
Soft glass	0.5 (1.27)	73.15	50.43	3.79	1.92
	1 (2.54)	179.85	124.00	3.83	1.94
	2 (5.08)	382.75	263.88	3.07	1.56
Carbon	0.5 (1.27)	76.65	52.85	5.50	2.79
	1 (2.54)	143.05	98.62	5.16	2.61
	2 (5.08)	420.20	289.70	5.79	2.93

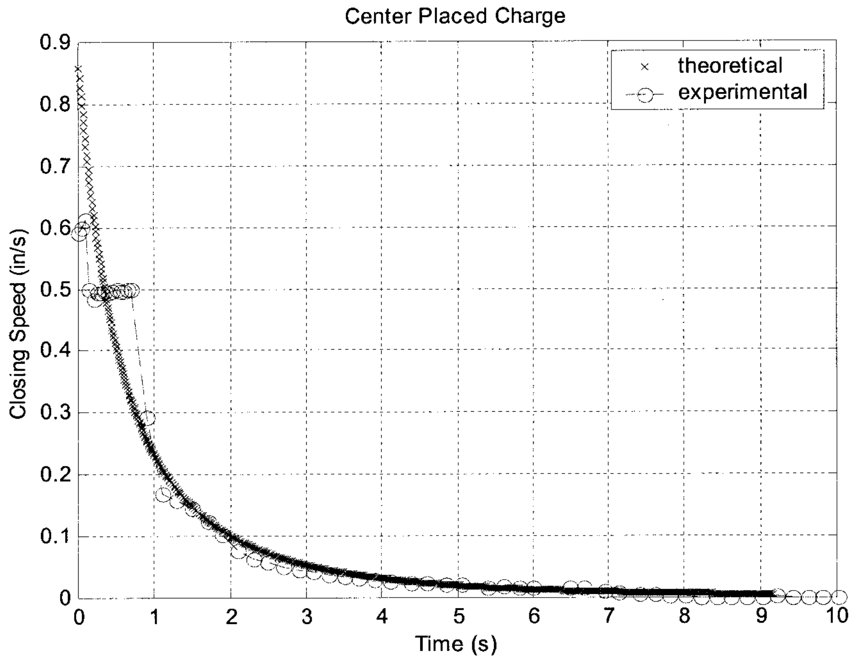


Figure 9 Predicted closing speed versus actual closing speed for a center placed charge—50 tons, 0.165 inch thick plaque.

thickness is then put into the equations until another value of U is found. This process is repeated until the thickness of the cavity is equal to the predetermined final part thickness.

It has previously been shown [see Ref. 7] that the above equations do a good job predicting the molding forces for a given closing speed, and here it will be shown that this model also efficiently predicts the closing speed given a limiting tonnage. In order to determine if this model gave appropriate results, experiments were conducted to compare the results from the theoretical model to the results of actual tests. For this experiment, parts with two different final volumes were produced, 43.01 inch^3 [704.81 cm^3] for a final part thickness of 0.115 inch [0.29 cm] and 61.71 inch^3 [1011.25 cm^3] for a final part thickness of 0.165 inch [0.42 cm]. For these experiments the rectangular mold previously discussed was utilized and SMC with 28% by weight 1-inch long hard glass fibers was used. The press was set to close as fast as possible with the maximum compression force set at 50 tons (45.36 metric tons). The details of the experiments can be found in Ref. 5. Here for brevity, we only show the results for one case, in Figure 9 for the closing speed and in Figure 10 for the cavity thickness. As can be seen from the figures the experimental and theoretical results correlate quite well, showing that the program can, in fact, be used to predict the closing speed for a press with a known tonnage. A more complete comparison with experimental results can be found in Ref. 5.

Based on the good agreement with experimental results it can be concluded that this program can be used with parameters for the SMCs given previously[5,7] and summarized here in Table III, to predict the minimum closing time for the SMCs discussed here. Figure 11 shows the effect of fiber length and type on the minimum fill time for molding a rectangular plaque measuring 22 inch × 17 inch using a centrally placed charge in a 50-ton press. The graph would be different for parts with different volumes and press tonnages, however, the trends would remain the same. From the figure we can see that the dominant effect is the reinforcement length. For the same reinforcement length there is little difference if one uses hard or soft glass, however, carbon fibers do show a larger minimum fill time.

Figure 12 shows the effect of available molding force on the minimum fill time, where the initial SMC thickness is 0.45 inch, the final thickness is 0.125 inch, the volume of the part is 46.75 cubic inch, and the charge is located in the center of the mold. This graph is for hard glass fibers of several fiber lengths. An equivalent graph could be obtained for other reinforcement types or part volumes. Once a plot such as the one in Figure 12 has been obtained, it is then possible to find the fill time for a press with a limited tonnage. For example, if a press with a capacity of 50 tons [45.36 metric tons] was available the graph in Figure 12 gives fill times of 1.6 s for 0.5-inch fibers (1.27 cm), 3.2 s for 1-inch (2.54 cm) fibers, and 6.2 s for 2-inch (5.08 cm) fibers.

The faster the press is closed, the more reactive the SMC that can be used. Thus, by having a larger molding force available, not only can time be saved on closing, but also during the cure cycle. It has been found that to obtain a defect-free part, the SMC needs to

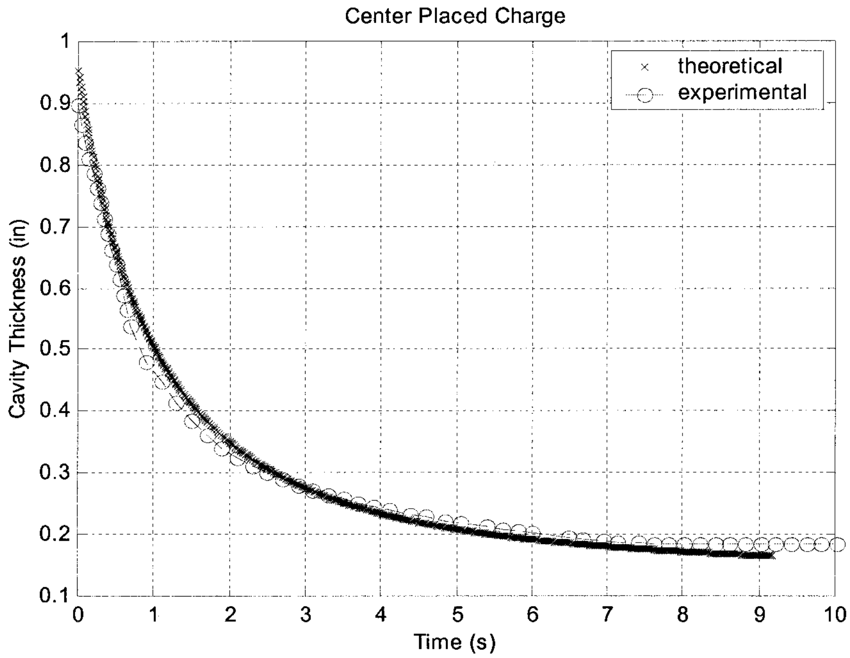


Figure 10 Predicted cavity thickness versus actual cavity thickness for a center placed charge—50 tons, 0.165 inch thick plaque.

be formulated with enough inhibitor such that the inhibition time is twice the fill time.[8] Continuing with the above case, Figure 13 gives a plot of cure time versus inhibition time for an SMC with 63% filler of paste by weight and 28% hard glass by weight of SMC.[8] Using Figure 13 one can estimate the total cycle time for the SMC. Thus, the fill time found in Figure 12 can be doubled and then the cure time determined from Figure 13. The total cycle time can then be calculated as the fill time plus the cure time. For example, the cure times at 50 tons for 0.5-, 1-, and 2-inch fibers are, respectively, 18, 23, and 30 s. This gives total cycles times of 19.6, 26.2, and 36.2 s, for 0.5-, 1-, and 2-inch fibers, respectively. If a larger press were available, say 100 tons [90.7 metric

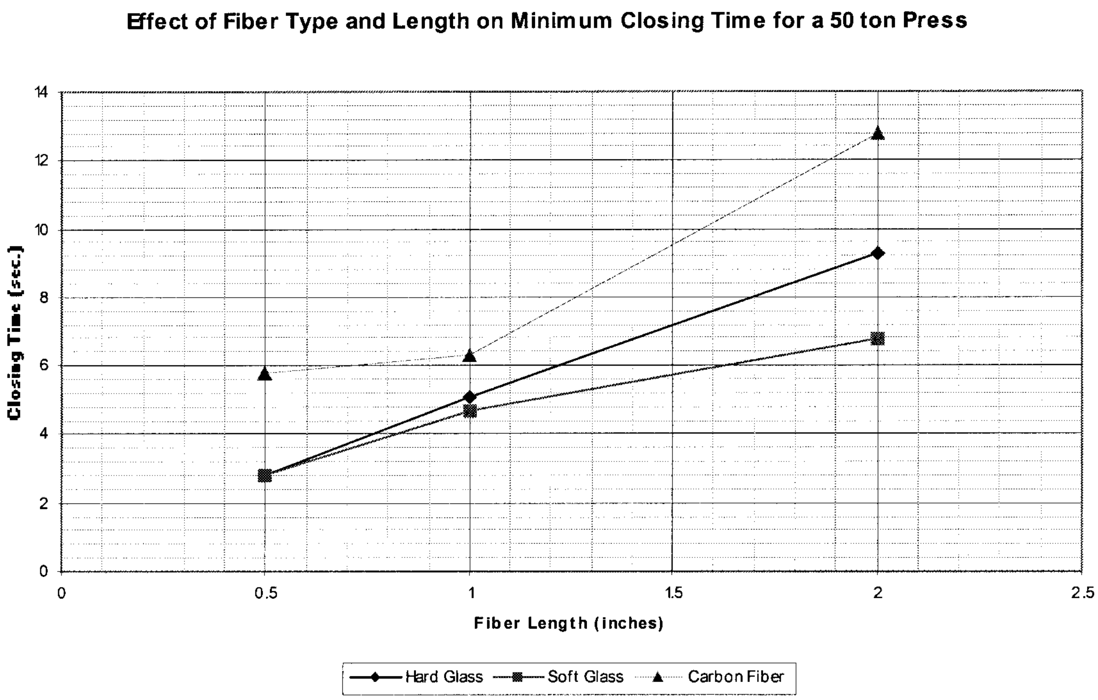


Figure 11 Effect of fiber length and type on minimum closing time for a press of 50 tons.

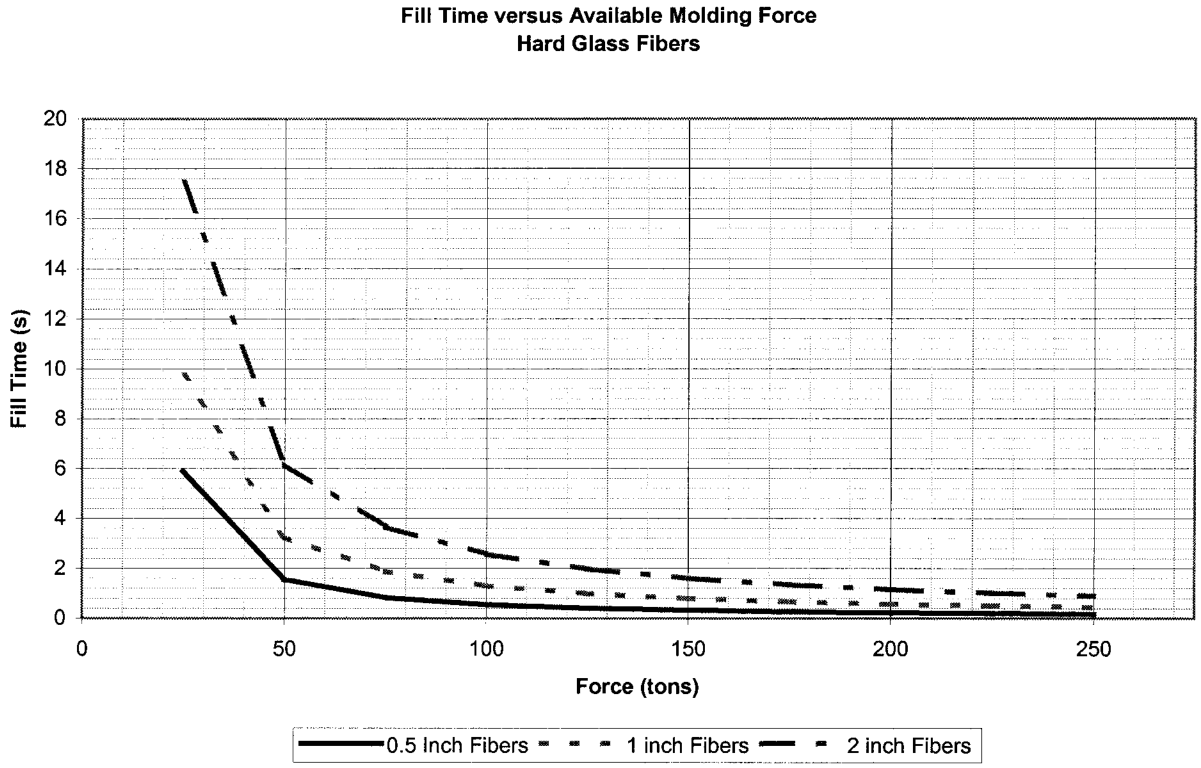


Figure 12 Fill time versus available molding force for hard glass fibers.

tons], the fill times would be 0.5, 1.3, and 2.6 s for 0.5, 1, and 2 inch length fibers, respectively, and the cure times from Figure 19 would be 14, 18, and 20 s, thus giving cycle times of 14.5, 19.3, and 22.6 s. The molder then would decide if the decrease in cycle time merits the increased investment on a larger press.

SELECTION OF REINFORCEMENT TYPE WHEN CLASS A SURFACE QUALITY IS DESIRED

This section summarizes the results of this paper by providing a practical application for SMC processing

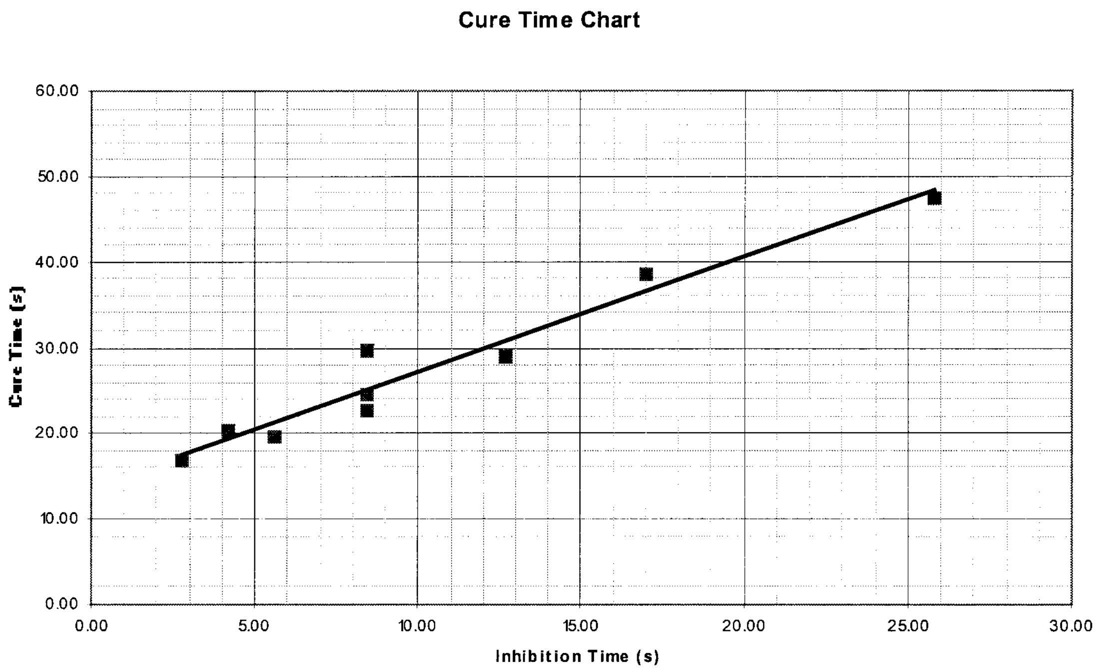


Figure 13 Cure time chart.

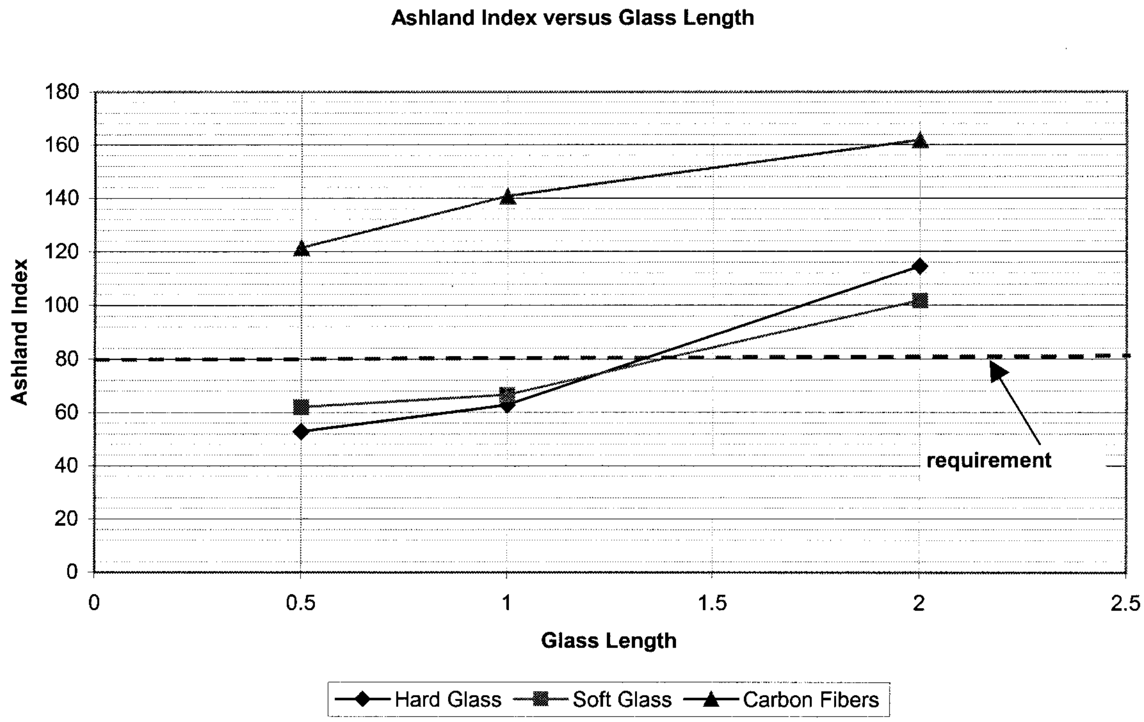


Figure 14 AI versus glass length.

where it is assumed that the amount of glass fiber and filler to be used is known. Several figures are then provided to help in the selection of the fiber type and fiber length that will be used.

This case focuses specifically on an SMC formulation in which 28% fiber by weight of SMC and 63% of filler by weight of paste will be used, but the fiber length and fiber type are to be selected. It should be noted that the following figures are applicable only to the specific case, in which 28% fiber by weight and 63% filler by weight of paste will be used in a square mold with the charge placed centrally. However, with a small amount of testing, similar plots could be produced for any SMC.

The choice of fiber type and length is dependent on the surface quality and physical properties. Therefore, it is necessary to choose the type of fiber to be used based upon the desired surface quality, as well as, the physical property specifications, such as ultimate tensile strength and modulus. Figure 14 provides a plot of the AI versus fiber length for hard glass, soft glass, and carbon fiber (these data represent the averages taken from the square plaques molded at Ashland Chemical). Using this plot it can be seen that if a high quality surface (AI < 100) is desired, hard or soft glass of 0.5 inch (1.27 cm) or 1 inch (2.54 cm) length can be used.

Figure 15 provides a plot of the tensile strength and modulus versus fiber length for hard glass, soft glass, and carbon fiber. Again the data from the plaques molded at Ashland Chemical is used. By using this plot a decision can be made on the best fiber type and fiber length combination for the required physical properties.

As an illustration of how these plots can be utilized assume that a part with the following requirements is to be produced: ultimate tensile strength $\geq$ 10,500 psi [72.4 MPa], modulus $\geq$ 14 ksi [96.5 MPa], Ashland index (AI) $\leq$ 80.

To begin the determination of the fiber type to be used, Figure 14 for the AI is examined, where it is immediately seen that carbon fiber cannot be used, as the AI for the carbon fibers never falls below 120. Examining the figure more closely, it is found that only 0.5 inch (1.27 cm) or 1 inch (2.54 cm) hard or soft glass will give an AI below 80.

Next, in order to restrict the choice even further, Figure 15 can be used. When the requirement of an ultimate tensile strength greater than 10,500 psi [72.4 MPa] is investigated it is found that 0.5 inch (1.27 cm) soft glass does not meet this requirement and, therefore, cannot be used. However, the remaining three choices meet all ultimate tensile strength and modulus requirements. Therefore, the choice has been narrowed down to either 0.5 inch (1.27 cm) or 1 inch (2.54 cm) hard glass, or 1 inch (2.54 cm) soft glass fibers. Then based on the results of the previous section and assuming that as the fiber length increases for square plaques the cycle time will increase similarly to the rectangular plaques, it would be recommended that 0.5 inch hard glass be used.

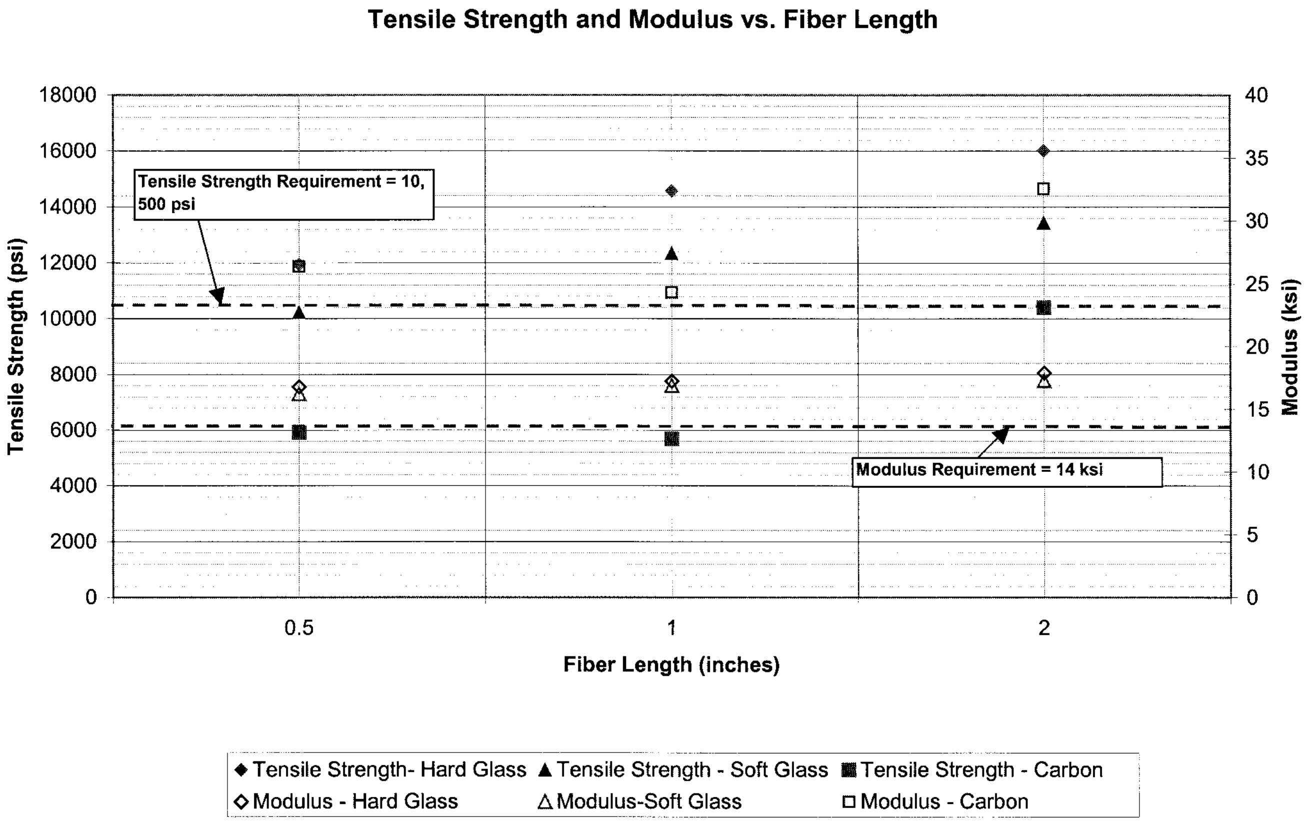


Figure 15 Tensile strength and modulus versus fiber length.

CONCLUSIONS

The major results and conclusions of this research are as follows:

- Overall the tensile strength of SMC increases as the fiber length increases. However, the tensile strength of carbon fiber SMC is less than that of either hard or soft glass fibers.
- On the other hand, the modulus of elasticity is found to be greater for carbon fiber SMC than for either hard or soft glass. In addition, there is little effect on the modulus for any fiber type when the length of the fibers is increased for 0.5–1 inch; however, when the length of the fibers increases from 1 to 2 inch the modulus experiences a much larger increase for all fiber types.
- The fiber length had very little effect on the percent elongation for SMC with any fiber type. However, the percent elongation was less for the carbon fiber SMC, than for either hard or soft glass SMC.
- The placement and shape of the charge in the mold has a large effect on the flow and fiber orientation.
- The ratio of the maximum tensile strength to the minimum tensile strength decreased as the fiber length increased from 1 to 2 inch, but increased as the number of plies increased. The same holds true for the modulus. However, for the percent elongation, the ratio of the maximum to minimum decreased from 1 to 2 inch, but there was no change as the number of plies increased.
- For 1-D flow SMC made with 2 inch fibers gave a lower AI than SMC made with 1 inch fibers, indicating a better surface quality could be achieved with 2 inch fibers, however, for 2-D flow as the fiber length increased so too did the AI.
- Carbon fibers could not achieve Class A surfaces (AI < 100).
- Increasing the reinforcement length increases the cycle time for the same available molding force.
- Carbon fibers require larger fill times than glass fibers.

Future research will include:

- Investigate the different types of carbon fibers that are available and determine if any of these could be used to improve the wetting of the carbon fibers. Improved wetting could help to achieve better surface quality parts, leading to the use of carbon fiber SMC for Class A surfaces.
- Experiment with different filler compounds to determine their effect on the surface quality, physical properties, and cycle time of SMC.

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