AMPHLET AMCP 706-313

A015181

ENGINEERING DESIGN HANDBOOK

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SHORT FIBER PLASTIC BASE COMPOSITES

HEADQUARTERS, US ARMY MATERIEL COMMAND

JULY 1975

DEPARTMENT OF THE ARMY
HEADQUARTERS UNITED STATES *ARMY* MATERIEL COMMAND
5001 Eisenhower Ave., Alexandria. VA 22333

AMC PAMPHLET
No. 706-313 31 July 1975

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PREFACE

The Engineering Design Handbook Series of the US Army Materiel Command is a coordinated group of handbooks containing basic information and fundamental data useful in the design and development of Army materiel and systems. The handbooks are prepared for the special use of the design engineers and scientific personnel in the Government and industry engaged in the design, development, and upgrading of Army equipment, materiel, components, and techniques.

This handbook deals with a specific class of fiber reinforced plastics/composites. The fibrous composites, in general, constitute one of the major groups of nonmetallic structural materials. Their performance has been demonstrated effectively in a variety of military applications. Increased usage is anticipated as new weapon systems and other items of military equipment are introduced or redesigned. The composites cover a broad range of physical properties. They include the continuous fiber reinforced materials that have exceptionally high strengths and moduli of elasticity. The short discontinuous fiber reinforced composites, which comprise the subject matter of this handbook, are at a lower strength level. It is believed that this material group – which is easier to process and less costly – offers numerous opportunities for design simplification, innovations in design, and improvements in maintenance and producibility. It is the purpose of the handbook to acquaint Army personnel with the characteristics of these materials. Emphasis is placed on the close relationship between material properties and the associated processes for fabricating these materials.

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CHAPTER 1

INTRODUCTION

1-1 SHORT FIBER COMPOUNDS DEFINED

The reinforced plastics, which are the subject matter of the handbook, are identified conveniently as short fiber molding compounds in contrast to other materials with continuous or particulate reinforcements. They are defined, in simplest terms, as composites in which randomly distributed discontinuous fibers form a reinforcement phase and a thermoset resin serves as the matrix or binder. A dispersion of inert fillers may or may not be incorporated within the resin system. The fiber length is variable and may range from 1/8 in. or less to 3 in. or greater. Mechanically, the load transfer mechanisms and stress distribution are unique for the short fiber reinforcement. Strength properties cover a range between the continuous reinforced at a higher level, and the particulates at a lower level.

In terms of specific commercial types, the short fiber compounds included in the handbook are the relatively new sheet molding compounds (SMC) and the bulk molding compounds (BMC). To these are added the older preform wet molding systems and a group of compounds made from resin impregnated chopped reinforcements. SMC, BMC, and preform moldings are based on polyester resin systems with fiberglass reinforcements. The chopped roving materials most frequently use an epoxy binder and either fiberglass or graphite fibers as the reinforcing phase.

Commercially, the more important materials are SMC and BMC. These two material types comprise a major portion of the output in the reinforced plastics industry. SMC and BMC are natural outgrowths of industrial efforts to provide a class of materials which possess a desirable balance of physical properties, are easy to process in automated production equipment, and which remain competitive with traditional metals and metal manufacturing technology. The combination of fiberglass and polyester represents an optimum choice consistent with maximum mechanical properties and low production costs. The fillers are added to reduce raw material costs and in certain instances yield compounds with improved electrical, flame retardant, or corrosion resistant properties.

The fabrication, molding characteristics, design features, and finished material properties of SMC and BMC are the basic elements treated in the handbook. Preform molding, which is steadily being replaced by more efficient SMC systems, is also considered since it produces parts with somewhat higher mechanical properties. The preimpregnated roving compounds, representing a minor segment of the reinforced plastics, are of significance in military applications. These compounds have been used to attain superior mechanical properties and are a convenient means for combining specific reinforcements and resins. Their preparation and properties therefore are included.

A number of materials which, strictly speaking, can be classified as short fiber thermosets are not treated. These are special purpose composites formulated for specific thermal, ablative electrical, or chemical applications and the class of materials fabricated by spray-up or hand lay-up techniques in open molds. (For a listing of these materials and references to information sources, see Table 2-1.)

1-2 SIGNIFICANCE OF FABRICATION AND MOLDING PROCESSES

1-2.1 GENERAL

Attention is focused on the processing of the resin-fiber mixture preparatory to molding and on the final molding operation. Close process controls are essential at all manufacturing stages from raw materials to finished moldings if anticipated properties, product uniformity, and reproducibility are to be attained. Manufacture of the short fiber compounds is unique in that it is most frequently carried out by molders using in-plant compounding or mixing equipment, rather than purchasing directly from commercial material suppliers. The major stages of formulating and material processing as well as the molding are thus controlled at one source. The obvious advantage of this practice is a reduction in production costs, but on occasion it may lead to a deterioration in molded quality. An understanding of process requirements will assist the materials engineer and designer in devising safeguards to insure the maintenance of formulation and property standards.

1-2.2 MOLDING SHORT FIBER COMPOUNDS

The basic method for the cure of short fiber compounds is compression molding, i.e., in press operated matched metal dies under heat and pressure. Formulation modifications, which are essentially reductions in fiber content or length, permit the use of injection or transfer molding.

Selection of either of these methods depends on part size and strength requirements. Straight compression molding is suited to large as well as small moldings and results in finished parts with superior mechanical properties. Injection or transfer moldings, within current capabilities, are more satisfactory with relatively small moldings and, due to the limitations on fiber content and length, produce parts with reduced strengths. The advantage of injection or transfer molding is that machines for this purpose are operated by automatic controls and do not require manual loading or unloading.

Innovations in compression molding techniques, concurrent with the increased use of SMC and BMC, have resulted in fully automated production lines. The in-plant material fabrication systems are integrated with the molding process so that inventories are maintained at a minimum. Faster acting presses have been installed and mold charging, press cycling, and part removal are automatic operations.

Economic use of automated lines is geared to long production runs at high production rates and is feasible only in a limited number of military applications. Partial use of features, such as automatic preforming of SMC or BMC and semiautomatic press cycling, is more likely. The molding of the short fiber composites, SMC or BMC, is best compared with the earlier preform, spray-up, and hand lay-up methods. From this viewpoint, current techniques offer improvements in efficiency and uniformity of product.

1-3 CLASSIFICATION OF POLYMER BASED COMPOSITES

The efforts of the reinforced plastics industry to upgrade material properties, improve fabrication, and reduce production costs have led to a high degree of product diversification and have resulted in a number of distinct material classes and subclasses. Systems for classifying materials become useful in distinguishing properties and moldability of a particular polymer reinforcement combination and for comparative purposes. Several methods for classifying polymer based composites have been proposed. Of particular interest are systems based on the physical form of the reinforcing media or fillers. Fig. 1-1 depicts such a classification scheme. The manufactur-

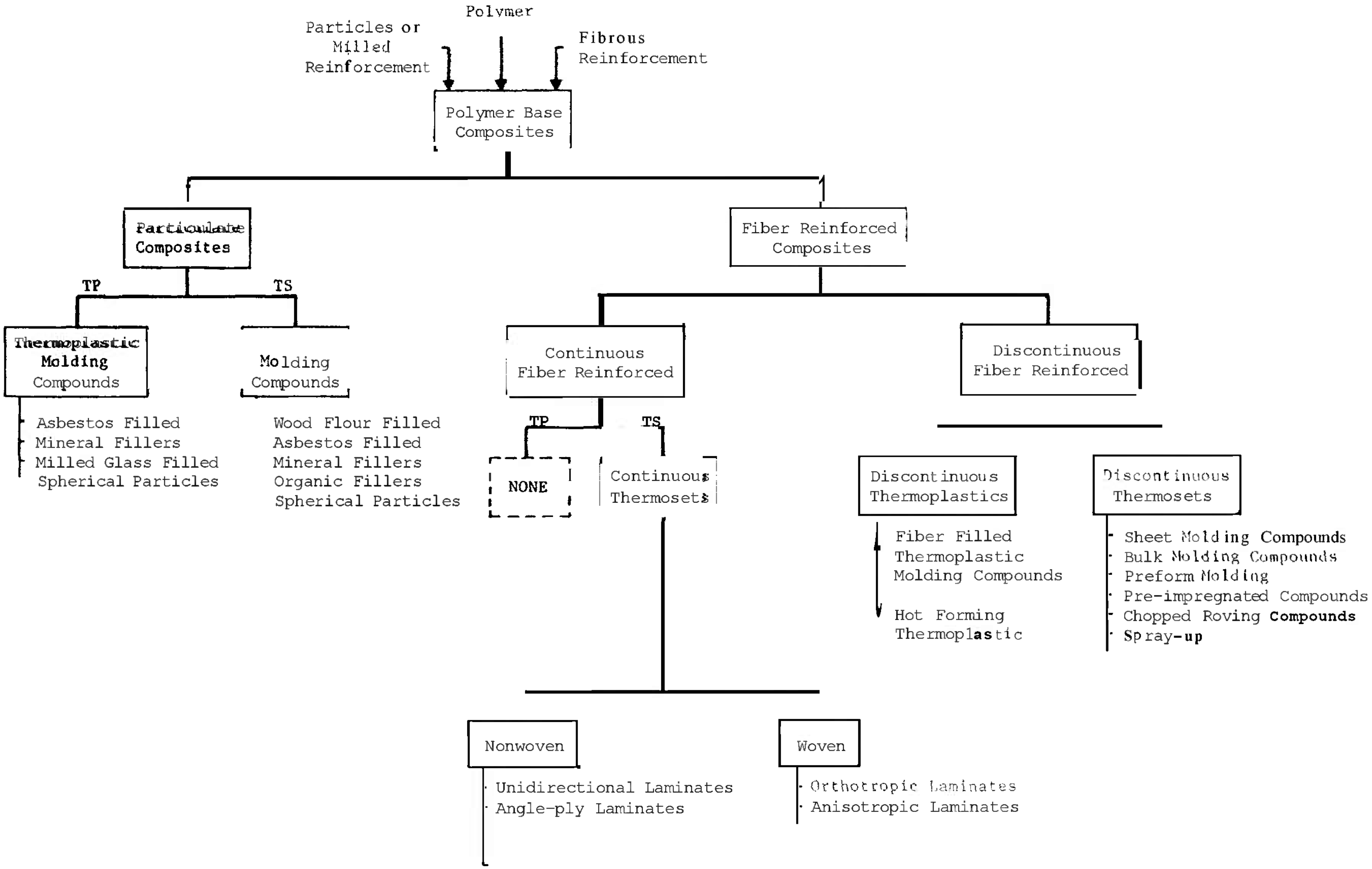


Figure 1-1. Classification System for Polymer Based Composites

TABLE 1-1
MANUFACTURING PROCESSES FOR POLYMER BASED COMPOSITES

PROCESS	Short Fiber Thermosets	Fiber Reinforced Thermoplastics	Woven Laminates	Nonwoven Laminates	Filament Winding	Pultrusion	Thermoset Molding Compounds	Filled Thermoplastics
Compression Molding	X		X	X			X	
Transfer Molding	X						X	
Injection Molding	X	X					X	X
Open Mold Spray-up	X							
Open Mold Hand Lay-up	X		X					
Autoclave Molding			X	X				
Vacuum Bay Molding			X	X				
Vacuum Impregnation	X		X					
Pressure Forming		X						
Filament Winding					X			
Pultrusion						X		
Extrusion		X						X
Centrifugal Casting	X							
Rotational Molding								X

ing methods corresponding to the various material subdivisions are listed in Table 1-1. The close interrelation between the reinforcement form and applicable molding techniques is noted here and is described more fully in later chapters.

The major groups in the system shown are the ***particulates, continuous fiber,*** and ***discontinous fiber*** composites. The latter two comprise the area of fiber reinforced plastics, although in some instances the particulates may be *so* classified. The general characteristics of each type are reviewed in the, paragraphs that follow.

1-3.1 PARTICULATES

Additives used with the particulates may be fibrous, spherical, or platelets and their sources natural organics, synthetic organics, or minerals. Platelets and spheres usually are in a *5-60* micron range and follow size distribution patterns. An arbitrary limitation on the fibrous fillers is set as 1/32 in. maximum length. Typical fillers include wood flour, asbestos, calcium carbonate, mica, clay, glass spheres, and milled glass.

The thermoset resins, it is noted, are not used as molding compounds without the addition of fillers. This is not the case with thermoplastics. The distinction between "particulate thermoplastics" and "discontinuous fiber thermoplastics" is minor and is only apparent as a difference in mechanical properties.

The effect of fillers on composite properties depends on factors such as the volume fraction included,. particle geometry, size distribution, filler wet-out by the resin, and the degree of chemical bonding between filler and resin. In the case of a simple inclusion of the filler, a weakening of the composite is to be expected. As wetting and bonding increase, strengthening effects will occur, marked by an increased stiffness and a decrease in ultimate elongation. Judicious use of fillers also will lead to improved impact resistance, electrical properties, and dimensional stability. Heat distortion temperatures are raised while shrinkage during molding is decreased.

Filler volume loadings are variable and are influenced by the absorptive capacity and exposed surface area of the filler. Usually loadings are not in excess of 50 percent; below 5 percent their effects are minimal.

1-3.2 CONTINUOUS FIBER REINFORCED

Continuous fiber composites contain either nonwoven or woven reinforcements. The basic structural unit for the nonwoven laminates is the monolayer – composed of uniaxial parallel aligned filaments. The monolayer is characterized as anisotropic. It develops high strengths in the fiber direction, but is weak in the direction perpendicular to the fibers. The monolayer may be angle-plied, cross-plied, or plied in several directions to yield a quasi-isotropic laminate. Typical reinforcing fibers are E-glass, S-glass, and the high-modulus filaments of boron, graphite, or Kevlar 49 (a duPont synthetic).

Woven fabrics most frequently are of E-glass; occasionally, fabrics of S-glass, graphite, or Kevlar 49 are used. Depending on the number of yarns in the warp and fill direction, fabrics may be orthotropic or contain varying degrees of anisotropy.

The fiber volume fractions in continuously reinforced composites are limited by practical considerations such as the processing conditions and the attainment of optimum property values consistent with maximum reproducibility. Even so, they are higher than is customary with other composites.

Reinforcements are added to increase the tensile strength and modulus of the composite. The principal role of the matrix is to transmit load to the fibers. Strength in transverse loadings, some shear properties, and retention of mechanical properties at elevated temperatures are mainly functions of the resin. Small amounts of fillers may be added to the resin system to control viscosity and flow during processing.

1-3.3 DISCONTINUOUS FIBER REINFORCED

1-3.3.1 FIBER REINFORCED THERMOPLASTICS

The fiber reinforced thermoplastics are one of the two material classes listed as discontinuous fiber composites. Nearly all thermoplastic resins can or have been reinforced, including the so-called "engineering thermoplastics" – nylons, acetals, polycarbonates, polyphenyl oxides, and polysulfones. Glass fibers are the common additives. Asbestos and graphite fibers also are used. Fibers are incorporated into the resin by one of several extrusion-type processes, the resulting product being a molding compound in the form of cylindrical pellets. Maximum fiber lengths, commercially designated as "long glass", are approximately 0.5 in.; chopped fiber in random 0.25 in. lengths is the more usual reinforcement. Fiber breakage occurs during handling, fabrication, and molding so that exact fiber length distribution is not known and is variable. Fiber loadings depend on the base resin. For example, maximum moldable loadings with nylon 12 are 50 percent by weight or 35 percent by volume. More typical volume fractions are in a range of from 15 percent to 20 percent.

The strengthening of the thermoplastic depends on fiber volume, fiber length, and the fiber-resin bond. The principal limitation is the breakdown of fibers during compounding and molding operations. Fiber additions lead to increased tensile strength and modulus, but are accompanied by lower elongations and fracture strains. The effect of fibers on impact resistance is mixed; with some resins the resistance is increased while with the more ductile resins it is decreased. Fibers raise the heat distortion temperature, reduce mold shrinkage, and improve the dimensional stability of the thermoplastic resin.

One of the newer types of reinforced thermoplastics is marketed as a glass filled sheet. Compounding in sheet form permits the use of longer fibers and possibly higher fiber loadings without incurring the fiber damage typical of the extrusion methods of fabrication. The material is converted to a finished molded shape by methods variously described as stamping, hot forming, draping, or compression molding, which are basically similar. Pressure and flow requirements are reduced with these techniques, again with minimum fiber damage. The sheet form appears more readily adapted to the molding of large parts than is the case with conventional injection molding.

1-3.3.2 SHORT FIBER THERMOSETS

The polyester base thermosets (SMC, BMC, and preform molding) use the same resin systems, reinforcements, and fillers. Formulations for SMC and BMC may, in fact, be identical. Preform molding formulations vary from SMC and BMC chiefly in the amount of filler which can be added. Despite these similarities, the mechanical properties and molding flexibilities are distinctive for each type. Differences are attributed to the fabrication method used to prepare each material. Significant deviations are apparent. These include the range of tolerable reinforcements and filler, maximum fiber length, fiber deterioration from processing and molding, bulk density prior to molding, flow properties during molding, pressure requirements for mold filling, and the efficiency of fiber use. Additionally, the materials vary in regard to suitability for automated processing, throughput rates, limitations on molded part size, mold costs, and overall production costs. These factors are elaborated upon in chapters that follow.

The chopped roving compounds in many respects are similar to the continuous unidirectional materials. Resin systems, reinforcements, fiber loadings, Bstaging, and curing are comparable. Resin systems rarely are diluted with fillers. Mechanical properties, in general, are superior to those of the other molding compounds.

As with the fiber reinforced thermoplastics, strength of the thermosets depends on fiber loading, fiber length, and the fiber-resin interfacial bond. Fiber loading is limited by the processibility and moldability of the compound. Strength increases with fiber length, but reaches an optimum due to breakage and/or moldability. Depending on mold flow conditions, fiber orientation or segregation may occur, which also may result in a weakening of the molding. Fiber orientation, on the other hand, may be used effectively under controlled conditions to give higher strengths in specific directions.

1-4 STATUS OF SHORT FIBER THERMOSETS

Military interest in composites has been centered on the development and exploitation of the high-strength, high-modulus filamentary materials. Boron and graphite composites and their application in aircraft structural components are typical examples. The advancements in short fiber technology, on the other hand, have been accomplished within the plastics industry and have been directed mainly to opening new markets in transportation, electrical equipment, appliances, and corrosion resistant products. Military usage has been limited, but is expected to increase as new weapon systems and other items of military equipment are.developed or existing systems are redesigned. Potential applications are anticipated in military vehicles, missile airframes, fuel tanks, water tanks, rifle stocks, electronic housings, shipping containers, leaflet bombs, heat shields, land mines, semipermanent shelters, landing craft, and others.

The capabilities of the short fiber thermosets appear to be best suited for molding large semistructural parts that are not highly stressed. That is to say, the short fiber composites do not attain the strengths and moduli which can be achieved with continuous reinforced materials. Normally, these two material types are not competitive. There may be some instances, if strength to weight is not a prime consideration, when SMC or preform molding may be substituted effectively for woven fabrics.

The mechanical properties are marked by moderate tensile strengths and a high resistance to impact. Maximum tensile strengths are in the order of 25,000 psi which is obtained with chopped roving. Tensile strengths of 20,000 psi have been attained with SMC; a more practical limit is set at 15,000 psi. Impact resistance tests, measured by notched Izod methods, indicate that strengths of over 20 foot-pounds per inch of notch can be attained with SMC and as high as 30 foot-pounds with preform molding. These values are superior to other molding compounds and closely approximate the continuous fiber composites.

Maximum service temperatures for the short fiber compounds are limited by the polyester systems currently in use. They appear to be capable of withstanding heat continuously up to 300°F and in special cases to 350°F. Where greater heat resistance is required, other resin systems must be employed.

One of the principal advantages of the short fiber SMC and BMC is their moldability. They are easy to load into a mold, curing cycles are short, relatively low mold-closing pressures are required, and they can be molded at high speed production rates. Mold construction is flexible and can be readily adapted to prototype molding or low volume preproduction runs. The autoclave, vacuum, or bag molding techniques for the continuously reinforced materials, by comparison, are suited for low production rates and require long curing cycles and post-curing.

Comparisons of the short fiber thermosets with the thermoplastic composites indicate that the thermosets are generally superior in regard to mechanical properties. Properties of glass filled polymers such as the acetals, nylons, polycarbonates, polyphenyl oxides, and polysulfones are approximately equivalent to SMC and BMC. These materials, however, are more expensive. The other thermoplastics (polystyrene, polyolefins, ABS) are inferior in strength, stiffness, and impact resistance. The thermoplastic properties tend to deteriorate under high temperature service conditions. Other shortcomings are a tendency to creep, poor dimensional stability and, with some polymers, stress cracking. The injection molding processes for thermoplastics are favorable to high volume production and offer some advantages over compression molding. Secondary operations such as flash removal, drilling, and threading are at a minimum. Scrap losses are low since the materials can be reprocessed. Different material systems can be run through the same equipment, and molds for different parts are changed more easily. As molded part size increases, processing advantages begin to favor the thermosets. It may be concluded that the short fiber thermoplastics arid thermosets are competitive only in borderline cases. Here property requirements and production cost will be the determining factors in material selection.

On a strength to cost basis the short fiber thermosets, except for the chopped roving/epoxy compounds, have an advantage over other composites. BMC, SMC, and preform molding are relatively low cost materials. Only the wood-flour filled phenolics and some glass-filled thermoplastics are less expensive. Overall cost-effectiveness comparisons – considering factors such as mold costs, durability, repairability, and part replacement –

TABLE 1-2

COMPARISON OF POLYMER BASED COMPOSITES

	Reinforcement[1]		Resin Type	Specific Gravity	Bulk Factor[2]	Tensile Properties			Impact Resistance, Ft-lb/in. notch	Raw Material cost, ¢/Lb[5]
	Length, in.	Wt, %				Ult. ksi	Modulus psi x 10^6	Ult Elong. %		
CONTINUOUS FIBER										
Thermoset										
Nonwoven, uniaxial	cont.	65-75	Epoxy	1.80-2.00	NA	180-220	6-8	3.0-4.0	—	40.3
Nonwoven, quasi-isotropic	cont.	65-75	Epoxy	1.80-2.00	NA	60-80	3.0-4.5	3.0-3.5	—	—
Woven, Orthotropic[3]	cont.	60-70	Epoxy	1.75-2.00	NA	55-75	2.8-4.2	1.7-2.8	10-30	27.4
Woven, Anisotropic[4]	cont.	65-70	Epoxy	1.85-1.90	NA	75-95	4.5-5.5	1.6-2.2	—	—
DISCONTINUOUS FIBER										
Thermoset										
Sheet Molding Compounds	0.5-1	15-30	Polyester	1.7 -2.1	1.1-1.5	8-20	1.6-2.5	0.3-1.5	8-22	2.06
Bulk Molding Compounds	0.25	10-30	Polyester	1.4 -2.0	1.1-3	3-10.0	1.5-2.0	0.3-1.0	2-8	1.56
Preform Molding	1-2	25-45	Polyester	1.5 -1.7	NA	12-20	1.0-1.8	1.0-2.0	5-15	2.02
Chopped Roving	0.5	60-70	Epoxy	1.75-2.00	5-10	20-25	3-4	0.6-0.8	20-30	20.6
Thermoplastic										
Nylon	0.25	33-43	Nylon 6/12	1.30-1.46	2.0-2.5	20-24	1.2-1.5	4-5	2.5-4.0	10.1
Polystyrene	0.25	30	Impact grade	1.3	2.0-2.5	14	1.2	1.1	2.5	2.35
PARTICULATE FILLED										
Thermoset										
Phenolic Wood Flour	NA	35-45	General Purpose	1.35-1.40	2.2-2.5	7.0	1.0-1.4	0.4-0.8	0.30	1.52
Thermoplastic										
Nylon	<1/32	30	Nylon 11	1.25	2.0-2.5	14.0	0.5	5.0	1.5	9.1

[1] E-glass, except phenolic wood flour

[2] Bulk factor = Molded density/apparent density, unmolded

[3] Fabric style 7781, yarn count, 57 warp, 54 fill

[4] Fabric style 7743, yarn count, 120 warp, 20 fill

[5] Estimated as of 1/1/74

tend to favor short fiber thermosets over other material types.

Some of the more general material characteristics are shown in Table 1-2 for a series of glass-filled composites. **A** range of tensile properties, impact resistance, specific gravity, and estimated raw material cost is listed for comparative purposes. Raw material costs per cubic inch are based on prices as of 1 January 1974, but may require revision due to current petrochemical shortages and inflationary trends.

It is not yet known with any degree of certainty whether the relative position of the short fiber material prices will change more drastically than other materials or which types will be most strongly affected. In general, polyester prices have increased by approximately 15 to 20 percent. Specific shortages have been apparent in the supply of styrene monomer, which is used most frequently with polyester resins. Also the manufacture of certain epoxy resins has been discontinued, but this may be due to other causes. Prices of fiber glass reinforcements have increased as a result of increased power costs. Further increases may be expected due to pollution controls placed on the manufacture of fiberglass products.

CHAPTER 2

THERMOSET MOLDING COMPOUNDS

2-1 INTRODUCTION

Information on the formulation and fabrication of four types of short fiber compounds is provided in this chapter. *Sheet molding compounds (SMC)* are combinations of fiberglass, fillers, and polyester resins which are processed into a dry or slightly tacky sheet form ready for molding. The closely related *bulk molding compounds (BMC)* also contain fiberglass and fillers in a polyester binder. It is compounded into a dough-like consistency and may be extruded into simple preformed shapes to facilitate mold loading or is handled in the bulk form. *Preform moldings* are prepared by a two-stage wet processing method in which the fiberglass preform and polyester resin mix are combined during the molding. *Chopped roving compounds* are reinforcement strands coated with resin, either from solution or a hot melt. The continuous reinforcements are dried or B-staged and then cut into desired lengths.

The general features and subdivisions of each group, together with applicable Military Specifications, are shown in Table 2-1. The table also includes a number of other miscellaneous short fiber thermoset compounds for reference purposes.

2-2 SHEET MOLDING COMPOUNDS (SMC)

Sheet molding compounds are resin impregnated fibrous materials that have been processed into a comparatively dry sheet form suitable for matched die molding. The term “sheet molding compound” as used in the plastics industry applies specifically to a system consisting of a *chemically thickened polyester* resin reinforced with chopped fiberglass strands. A third component is an inert filler system or combination of fillers added to reduce cost or to impart special properties. All essential ingredients such as catalysts and release agents are incorporated into the material so that it can be molded without further additions. Conversion to a cured product is accomplished with mold temperatures ranging from 265” to 350°F. Pressures of from 500 to 1500 psi are required. Typical mold conditions are 300°F and 1000 psi.

Cure cycles in the order of from 1 to 2 min are normal for sections of from 1/8 to 1/14 in. nominal thickness.

SMC is a relatively low cost material which is easy to process. Mechanical properties are superior to BMC and approximately equivalent to preform or mat moldings. The sheet form is convenient for handling and for the molding of large parts. The sheets can be trimmed automatically and blanked into the proper sizes for mold loading. When strategically positioned in the mold, charge patterns can be closely controlled. As a result, pressure requirements for mold filling are reduced, deep draws readily are attained, and the finished properties tend to be more uniform. Automatic loading and unloading equipment can be installed at the press to reduce labor costs in handling large parts. Variations in SMC formulations are made to attain low shrinkage, electrical, flame retardant, chemically resistant, and injection molding grades. Glass content varies from a low of 10 percent to a high of 45 percent by weight, but rarely is in excess of *35* percent. Injection molding grades normally are not produced with glass

TABLE 2-1

REINFORCED THERMOSET MOLDING MATERIALS

Types and Grades	Constituents	Form	MIL-Spec
SHEET MOLDING COMPOUNDS			
general purpose, low shrinkage, flame retardant, electrical, corrosion resistant, injection molding	Polyester/fiberglass	Sheet	MIL-P-46169
BULK MOLDING COMPOUNDS			
general purpose, low shrinkage, flame retardant, electrical, corrosion resistant, injection molding	Polyester/fiberglass	Bulk, extruded shapes, fibrous putty	MIL-P-43043 MIL-P-46069
Sisal-filled	Polyester/sisal		
PREFORM MOLDING			
two component wet molding systems	Polyester/fiberglass	Preform	L-P-383
chopped fiber, chopped strand mat			
continuous fiber mat			
two component cold-molding systems			
CHOPPED ROVING PREPREGS			
fiberglass reinforced	Epoxy/fiberglass	Uniform lengths	----------
graphite fiber reinforced	Epoxy/graphite	Uniform lengths	----------
MISCELLANEOUS SYSTEMS			
asbestos base	Phenolic/asbestos	Fibrous wads	MIL-M-14
	Dapon/asbestos	Granular	MIL-M-14
Orlon base	Dapon/Orlon	Granular	MIL-M-14
fiberglass base	Phenolic/fiberglass	Sheets	----------
	Melamine/fiberglass	Fibrous wads	MIL-M-14
	Silicone/fiberglass	Fibrous putty	MIL-M-14
	Polyester/fiberglass	Fibrous putty, extruded ropes	MIL-M-14

contents above 20 percent.

2-2.1 FABRICATION OF SMC

The manufacture of SMC is a relatively simple process. Capital equipment outlay is low compared to other compounding methods, while material through-put rates per unit are high. The process is depicted schematically in Fig. 2-1. **A** resin blend, consisting of base resin, monomer, chemical thickeners, catalysts, fillers, pigments, and internal lubricants, is pre-mixed and fed through doctor blades to an upper and lower carrier film. Glassfibers continously are cut and distributed over the lower carrier. The two layers are brought together and passed through a series of compaction rollers. At this stage much of the entrapped air is removed and the fibers are wetted by the resin. Temperature control of the rollers permits optimum resin viscosity for fiber wet-out with minimum fiber damage. Alternate schemes use a multiroller de-airing stage followed by a cascade of large diameter drum rollers to increase the contact area and improve compaction of the mat. The last section of the SMC machine consists of a turret rewind stand. Controlled tension as the film-mat sandwich is wound achieves the final glass impregnation without causing excessive resin run-out. The compounded sheet, encased in a barrier film to prevent monomer loss, is wound into rolls and stored for aging. A final thickening or maturation stage is required before the material is ready for molding.

Essential features of the process are that resin content, fiber content, and fiber distribution can be controlled more closely and that the method of compaction allows maximum fiber wetting with a maximum of fiber damage. The fiber length is variable from about 0.5 to 2 in. Fibers usually are maintained at either 0.75 or 1 in. lengths. At 0.5 in., the fibers are more difficult to impregnate, while above 1 in. the compound is more difficult to mold and obtain uniform fiber distribution in ribs, deep bosses, or similar sections. The resin premix is either added from batch mixes prepared in advance or is metered continuously through mixing nozzles. In either case the thickening agent concentration and reaction rates with the resin require close control to insure a mix or paste suitable for processing and subsequent maturation.

Maximum material throughput ranges from 6,000 to 9,000 lb/hr; one manufacturer claims capacities up to 13,000 lb/hr. Sheet widths of 60 in. appear to be the present practical upper limit for production lines. Sheet thickness and weight can be varied to yield mat densities as required. Mat thickness usually does not exceed 0.5 in.; while the maximum weights range from 16 to 32 oz/ft^2.

2-2.2 CHEMICALLY THICKENED RESINS

The exploitation of SMC has been made practical by the development of chemically thickened polyester resin systems. Previous attempts to manufacture molding compounds with unmodified resins or thixotropic agents were unsuccessful due to excessive resin run-out either during processing or during molding. This limitation of the polyester has been overcome by the use of chemical thickeners. A thickened resin, then, performs two basic functions:

(1) It permits the resin mixture, reinforcements, and fillers to be blended into a dry or slightly tacky condition without the addition of solvents; or resorting to a subsequent drying or B-staging (i.e., partial advancement of **a** catalyzed resin to a dry state).

(2) The compound produced can be molded at reasonable pressures without undo separation of resin from the reinforcing fibers.

The chemical thickening agents are alkaline earth oxides or hydroxides. The common

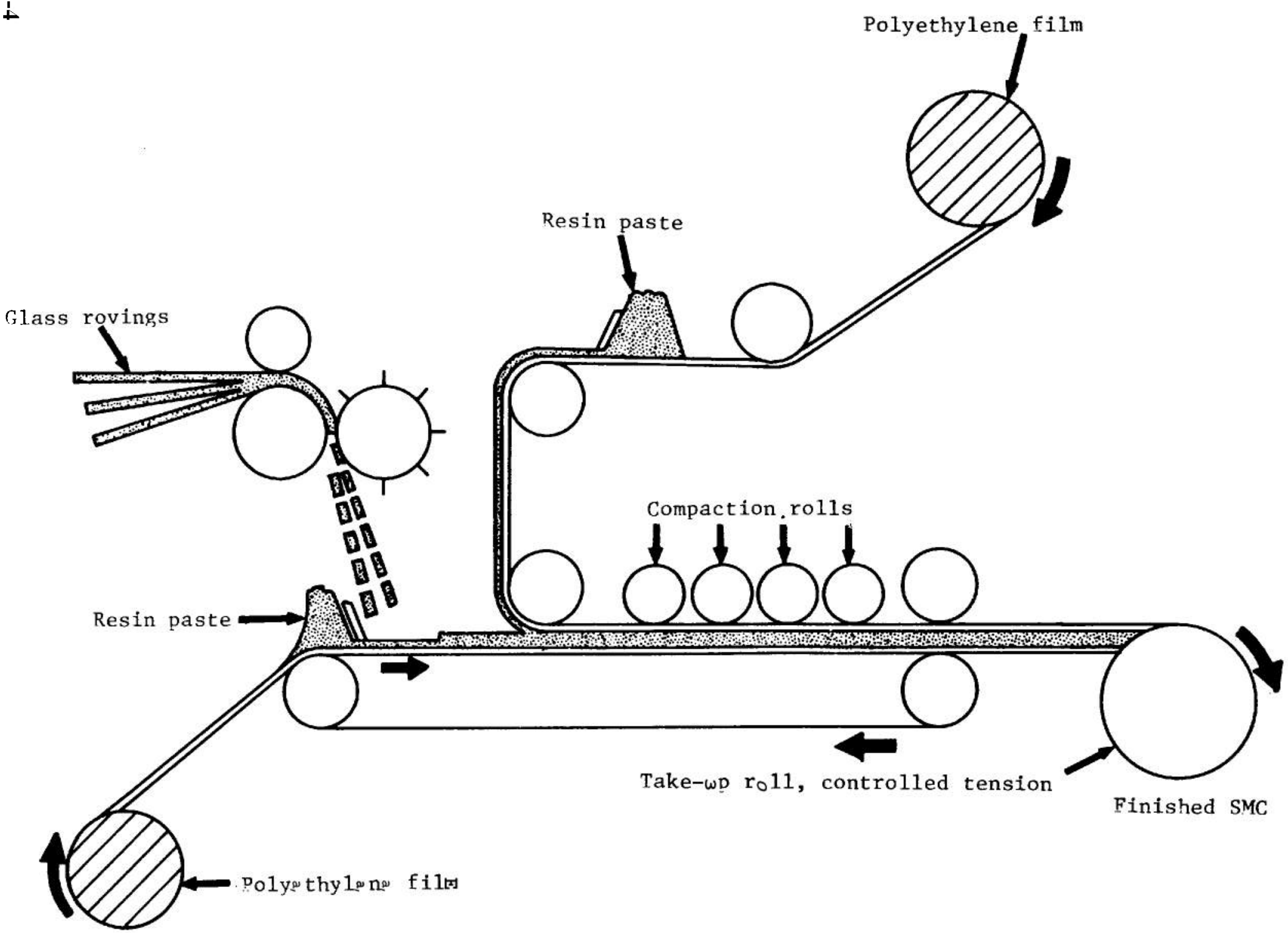


Figure 2-1. Equipment for Preparation of Sheet Molding Compound, Schematic

examples are magnesium oxide, magnesium hydroxide, calcium oxide, and calcium hydroxide. They are added to the resin either singly or as a combination of an oxide with a hydroxide at concentrations ranging from 1 to 3 percent. The thickeners usually are handled in carrier mixes to preserve their stability and avoid extreme reactions with the resins.

The thickening mechanism, as interpreted by current theory, is believed to be an acid-base reaction of the oxide or hydroxide with a carboxyl group on the polyester chain. Water is a by-product. The presence of water is also essential to the initiation of the thickening reaction, a concentration of 0.1 percent being optimum. Commercial resins are shipped with water concentrations usually less than the required 0.1 percent, so that quality control measures are necessary to determine resin moisture content and to make adjustments. The thickening reaction takes place with an uncured resin system, the resin remaining uncured after the reaction. Depending on the resin-catalyst system, the thickeners can effect curing rates during molding. Conversely, the thickening process is accelerated or inhibited by certain catalysts or catalyst concentrations. The various polyester resin types react differently with thickening agents, and in some instances may not react at all. Thickening reaction and rates cannot be predicted with any degree of certainty, and are best established by experimentation. The determination of thickening rates has become an essential quality control measure in production runs.

A typical relationship of resin viscosity with time as the result of thickening reactions is shown in Fig. 2-2. Rates of viscosity changes are given at several thickener concentrations. The differences in viscosity requirements for batch resin feeding processes as contrasted to continuous resin metering are illustrated in Fig. 2-3.

A relatively sharp increase in viscosity at the initial phase of the reaction is desirable, so that the resin mixture reaches a processable range in a short time period. A longer period in which the viscosity shows gradual or little change is indicative of a prolonged shelf-life in which the processed material may be molded. Not all BMC or SMC manufacturers and molders, however, desire the same thickening performance. For example, BMC and SMC suppliers are not concerned whether their material is moldable within a few days. On the other hand, short term maturation is important to molders with automated in-plant processes.

The moldability of a compound is influenced mainly by the resin viscosity at the time of molding and is thus dependent on maturation rate. Typical viscosity effects on moldability are shown in Figs. 2-4 and 2-5. Minimum pressure requirements for mold filling at 300°F are plotted vs viscosity in Fig. 2-4 for a specific SMC compound at approximately 28 percent glass content. Material flow behavior for the same compound is shown in Fig. 2-5 as a function of resin viscosity.

2-2.3 POLYESTER RESINS

2-2.3.1 Composition and Classification

The unsaturated polyester resins used in molding compounds are reaction products of a dibasic acid or an unsaturated anhydride with a glycol. Most polyesters include as a third component a saturated dibasic acid or anhydride. The reaction product is commonly referred to as an alkyd. When dissolved in a vinyl monomer such as styrene, it forms the commercial resin. The monomer and the alkyd, with the addition of catalysts, copolymerize to a cured resin. Numerous variations are possible by changing the composition of the alkyd base or the monomer, yielding resins with a wide range of properties. The effects of reactants on the finished polyester

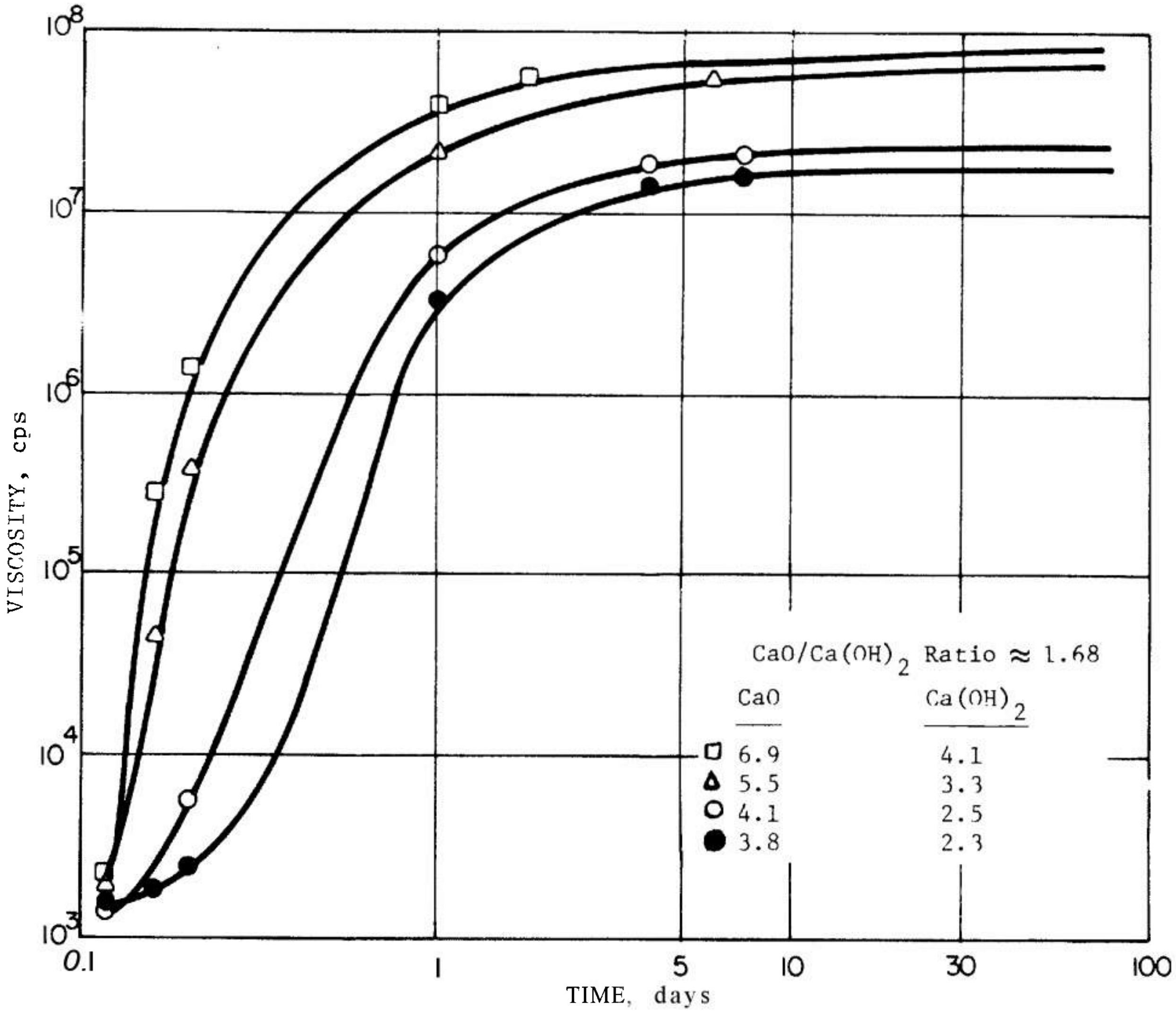


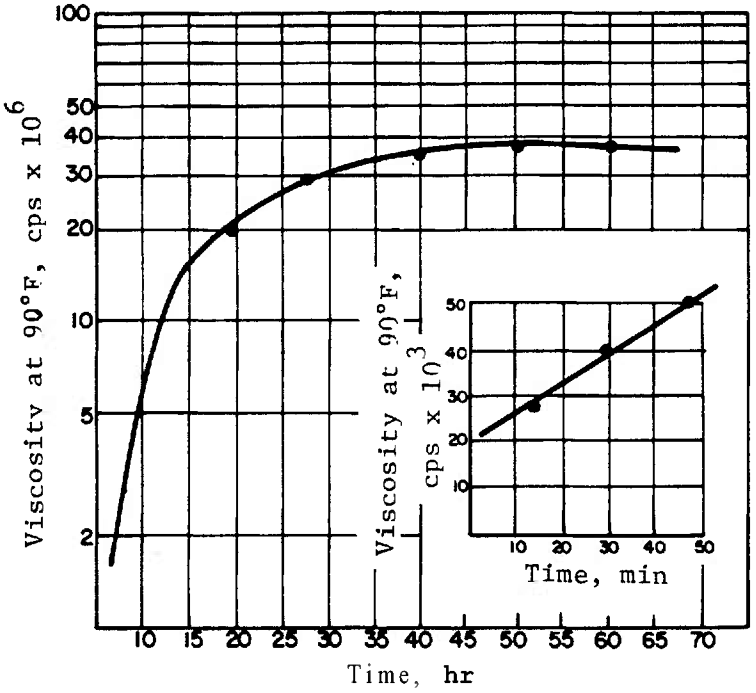
Figure 2-2. Viscosity vs Time at a Constant Ratio of Calcium Oxide to Calcium Hydroxide

are listed in Table 2-2 for components of interest to the reinforced plastics industry. Other factors controlling properties are the molecular weight of the alkyd chain and the degree and spacing of the unsaturation, as determined by the ratio of saturated to unsaturated dibasic acids.

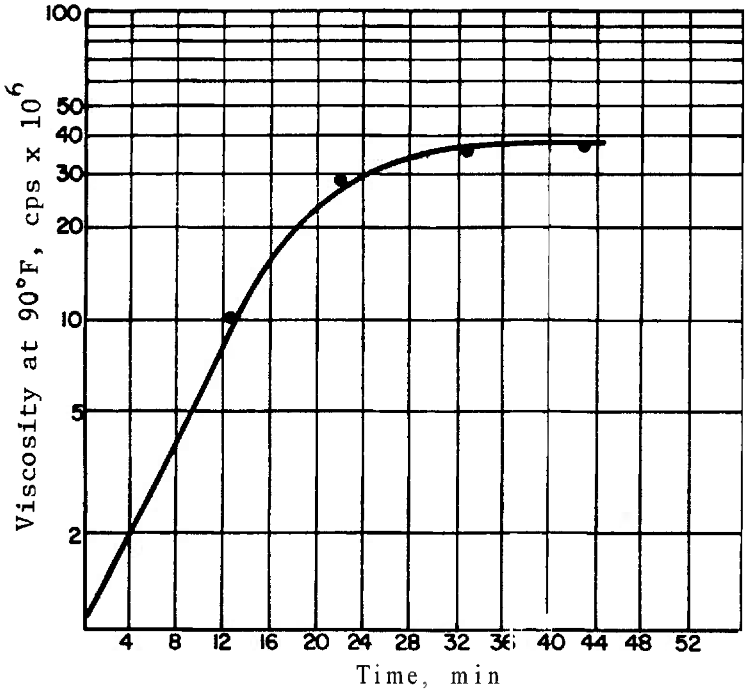
Polyester systems for molding compounds are classified as general-purpose, flame-retardant, electrical, and corrosion-resistant grades. The structural components selected for these resin systems are listed:

(1) *General-purpose.* Maleic anhydride, phthalic anhydride, propylene glycol, and styrene monomer are used for lowest cost; isophthalic acid may be added for higher heat resistance and improved mechanical properties; vinyl toluene is substituted for styrene to reduce volatile loss before molding.

(2) *Flame-retardant.* Chlorendic, tetrabromo-phthalic, tetrachlorophthalic, and hex-



(A) Batch Process



(B) Continuous Process

Figure 2-3. Comparison for Viscosity vs Time for Batch and Continuous Resin Mixes

TABLE 2-2

COMPONENTS IN POLYESTERS AND THEIR EFFECTS ON PROPERTIES[3]

Components	Ingredients	Characteristics
Unsaturated anhydrides and dibasic acids	a. maleic anhydride	a. lowest cost, reactivity moderately high heat deflection temperature (HDT)
	b. fumaric acid	b. highest reactivity (crosslinking), higher HDT, more rigidity
Saturated anhydrides and dibasic acids	a. phthalic (orthophthalic) anhydride	a. lowest cost, moderately high HDT, stiffness, high flexural and tensile strengths
	b. isophthalic acid	b. higher tensile and flexural strength, better chemical and water resistance
	c. adipic acid, azelaic acid, and sebacic acid	c. flexibility (toughness, resilience, impact strength); adipic acid is lowest in cost of flexibilizing acids
	d. chlorendic acid; tetrabromophthalic acid; tetrachlorophthalic acid; hexachloro, octahydromethano naphthalene dicarboxylic acid	d. flame retardance
	e. nadic methyl anhydride	e. very high HDT
Glycols	a. propylene glycol	a. lowest cost, good water resistance and flexibility, compatibility with styrene
	b. dipropylene glycol	b. flexibility and toughness
	c. ethylene glycol	c. high heat resistance, tensile strength, low cost
	d. diethylene glycol	d. greater roughness, impact strength, and flexibility
	e. bisphenol-*A* adduct; hydrogenated bisphenol-A adduct	e. corrosion resistance, high HDT, high flexural and tensile strengths
	f. neopentyl glycol	f. corrosion resistance, light color
	g. trimethyl pentanediol	g. corrosion resistance, possibly lower reactivity
Monomers	a. styrene	a. Lowest cost monomer. High reactivity. High flexural strength. Moderate heat deflection resistance, boiling point 293°F.
	b. methyl methacrylate	b. Light stability, weatherability, fairly high HDT
	c. vinyl toluene	c. Boiling point higher than styrene; 341°F compared to 293°F. Permits higher molding temperatures, faster cycles, reduced cure time. Lower vapor pressure, 2 mm Hg compared to 6.6 mm Hg at 77°F, reduces monomer loss during mixing and later during processing prior to molding. Higher flash point, 140°F compared to styrene at 88°F, reduces chance of fire.

TABLE 2-2 (Continued)

Components	Ingredients	Characteristics
Monomers (cont)	d. alphamethyl styrene	d. Used as a comonomer with other monomers. Does not homopolymerize by the free-radical mechanism. it does copolymerize with styrene and methacrylate, Used at 5-25% replacement for the primary monomer. Raises the heat deflection temperature and increases solvent resistance. Used to low peak exotherm temperature. Shrinks less than styrene, i.e., 12.5% compared to 17.0%.
	e. divinyl benzene	e. Used with styrene to a maximum of 30%. Produces a highly cross linked, three dimensional copolymer. Polymers are harder, brittle, more heat resistant, with excellent resistance to solvents such as ester,, chlorinated hydrocarbons, and ketones.
	f. diallyl phthalate	f. Not commonly used in SMC. Listed here because of its low volatility. Used to make molding compounds with long shelf life,
	g. monochlorostyrene	g. Used with styrene up to 50% Gives short cure cycles, 20-30 sec. Increases cracking and craze resistance Contains 25.6% chlorine by weight Imparts some flame resistance to the molding

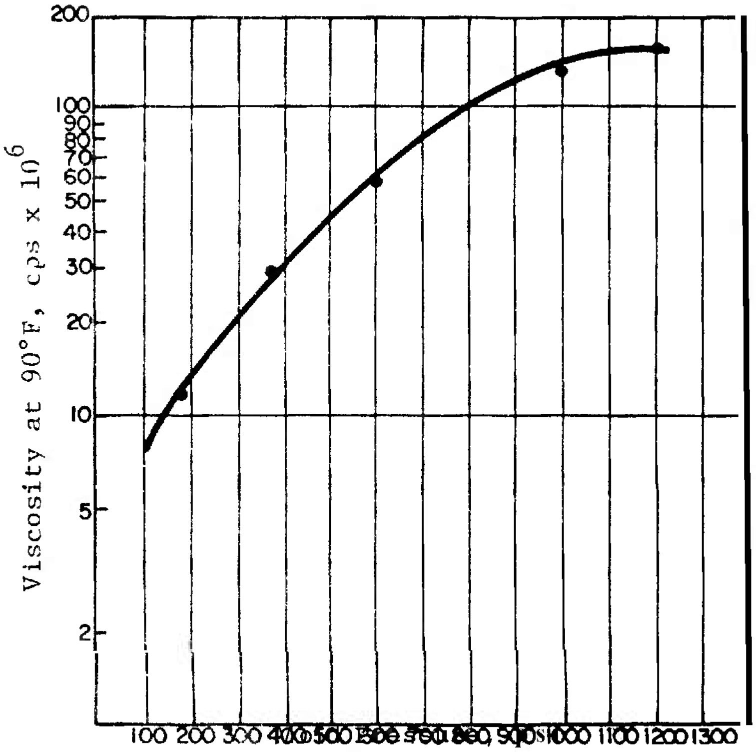


Figure 2-4. Minimum Mold Filling **Pressure vs Resin Viscosity**

achloro-octahydromethano-naphthalene-dicarboxylic acids are used as saturated dibasic acids: flame resistance is also attained by addition of filters.

(3) *Electrical grades.* Maleic anhydride, phthalic anhydride and a mixture of diallyl phthalate with vinyl toluene for the monomer are said to yield superior electrical properties[4].

(4) *Corrosion-resistant.* Bisphenol-A and similar glycols impart improved resistance to various chemicals.

Certain resins sometimes are used which, strictly speaking, cannot be classified as polyesters. The vinyl ester resins are one such group. They are polymerized by a different route than the polyesters, but may be cross-linked and cured by similar monomers and catalysts. Thickening reactions also may be carried out with alkaline earth oxides as with the other polyester systems[5].

Aside from selective polymerization, resins are modified by additives to facilitate processing or to reduce shrinkage in molding. Examples are resins containing thixotropic agents for preform molding and the low shrinkage (also known as low profile) SMC and BMC systems containing finely divided thermoplastics.

2-2.3.2 CURING MECHANISMS

The usual means of initiating the copolymerization of the polyester with the monomer is by the action of organic peroxide catalysts. The specific catalyst system determines the temperature at which curing takes place. Some catalysts are reactive at room

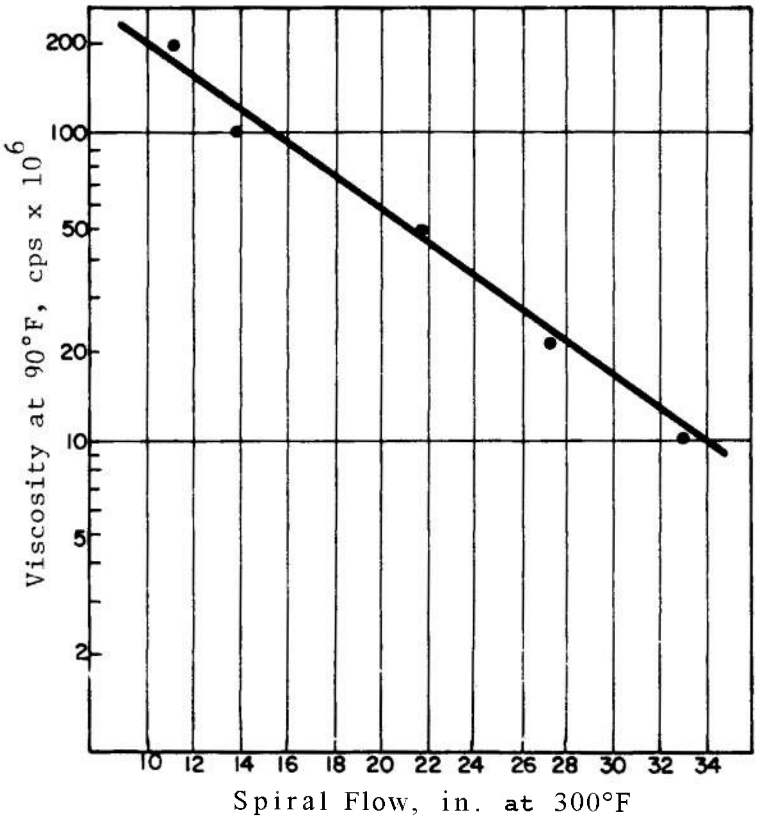


Figure 2-5. Spiral Flow (ASTM D-3173) vs Resin Viscosity

temperatures, while others require the application of varying degrees of heat to initiate reaction. For example, benzoyl peroxide and tertiary butylperbenzoate cure in a temperature range of 235" to 3 10°F while systems based on methylethylketone peroxide and cobalt naphthenate begin to cure at ambient temperatures. A major factor in molding operations, particularly with SMC and BMC, is the shelf-life of the catalyzed compound. Because of its stability and lower price, tertiary butylperbenzoate has been favored in SMC and BMC formulations requiring moderate aging or processing temperatures and a long shelf-life. Other catalysts frequently used are dicumyl peroxide; 2,5-dimethyl-2,5-bis(benzoyl peroxy)hexane (Luperox 118); and 2,5 dimethyl hexane-2,5-diper 2-ethyl hexoate (U.S. Peroxygen 245).

Promoters or accelerators are added to the resin system in specific instances when lower cure temperatures are required. The system also may contain retarders or inhibitors. Retarders serve to reduce peak exotherms from the polymerization reaction, while inhibitors prevent premature polymerization.

The cure rates for the various polyester types depend on the constituent acids and monomers, and to a lesser extent the glycol. For a specific resin system, cure rates and gel times are functions of catalyst and promoter concentration. Inhibitors and retarders have the effect of increasing cure and gel times.

Characteristic of polyester cure is the fact that once the reaction has been initiated it proceeds to completion and cannot be inter-

TABLE 2-3

FILAMENT DIAMETERS FOR FIBERGLASS

FILAMENT	DIAMETER RANGE, in.
G	0.00035 – 0.00040
H	.00040 – .00045
J	.00045 – .00050
K	.00050 – .00055
L	.00055 – .00060
M	.00060 – .00065
N	.00065 – .00070
P	.00070 – .00075
Q	.00075 – .00080
R	.00080 – .00085
S	.00085 – .00090
T	.00090 – .00095

rupted at an intermediate state. Completion occurs when approximately 92-95 percent of the unsaturated ester sites have been depleted. With some systems, post curing may increase the extent of saturation. Post curing, however, normally is not employed with SMC or BMC.

2-2.4 FIBERGLASS REINFORCEMENT

The fiberglass reinforcement for SMC is supplied as a low twist continuous multistrand. The strands are drawn from E-glass, which is a low alkali, lime-alumina borosilicate, or a low alkali calcia-alumina-silica glass. A single strand consists of 204, 408, or 816 individual monofilaments and is coated with a size as it leaves the forming bushing. A number of strands are gathered together into a roving. Roving yield (the number of yards per pound) depends on the number of filaments and the filament diameter. For SMC the normal yield is from 210 to 230 yd. Filament diameters are either K or G (see Table 2-3 for diameter range). The general trend in industry is towards the larger diameter filaments.

Sizing systems are applied to the strands to increase the resin-glass bond strength, to improve the wet strength retention of finished moldings, to preserve strand integrity during processing, and to impart other characteristics which aid in fabrication. Sizing systems for polyesters preferably contain silane-type coupling agents. Within this system the glass is described as having a “hard”, “medium”, or “soft” finish. A hard finish and/or coarse strands lead to good strand integrity, sounder knit lines, less fiber orientation, improved mold flow, but reduced chemical and electrical properties. Soft finish and/or finer strands yield improved chemical and electrical properties, but poorer knit lines, reduced flow, and increased fiber orientation. The effects of the medium finish are intermediate. Table 2 4 gives some indication of the variation in mechanical properties resulting from different sizing systems.

The effect of fiber length on properties appears to be optimum at either 0.75 or 1 in. Longer fibers provide higher tensile strengths, but present fabrication problems. Impact strength is slightly lower or unchanged as fiber length is increased beyond 1 in.; orientation during mold flow is higher. Shorter fibers

TABLE 2-4

MECHANICAL PROPERTY VARIATION WITH GLASS TYPE[6]

Property	Glass Type		
	A	B	C
Tensile Strength, ksi	9.2	10.4	12.6
Flexural Strength, dry, ksi	21.7	24.6	28.0
Flexural Strength, wet[1], ksi	23.5	24.6	26.0
Impact Resistance, ft-lb/in. notch	13.5	14.1	8.7
Glass Content, wt, %	25.4	24.6	27.0

[1] 2-hr boil

lead to lower tensile strength and improved flow. In high flow molding situations impact strength is retained and fiber orientation is minimum.

For commercial applications, maximum fiber loadings are held between *30-35* percent by weight. Suppliers have been able to raise this level to 40-45 percent in order to meet the requirements of Federal Specification L-P-383, *Plastic Material, Polyester Resin, Glass Fiber Base, Low Pressure Laminated.* It has not yet been established whether higher loadings with resultant increases in tensile strength are within the capabilities of the SMC process.

2-2.5 FILLERS AND ADDITIVES

Calcium carbonate is the principal filler in SMC formulations. It is used as an extender and to reduce mold shrinkage. At high filler loadings, the practice is to replace up to 20 percent of the $CaCO_3$ with finely divided clay to improve flow and to prevent cracking of thick sections.

Aluminum hydrate is added to give flame retardancy to the compound, and to improve its stability upon extended heat-aging.

Talc as a filler provides water resistance, improved electrical properties, and facilitates finishing operations such as sanding or drilling.

Various finely divided thermoplastics – including polyethylene, polystyrene, polyvinyl chloride, and methylmethacrylate – are added as shrinkage control agents and to improve the surface of finished moldings. Polyethylene, for example, at concentrations below **4** percent improves the wear resistance and flow properties, while at concentrations of from 12 to 15 percent, it reduces the shrinkage of the resin.

Stearic acid. zinc stearate. dnd calcium stearate are common mold release agents for SMC formulations. Stearic acid, which melts at about **157°F,** is used best at mold temperatures of from 260" to 280°F. Zinc stearate and calcium stearate are effective for mold temperatures above **300°F.** Excessive amounts of release agents (above 1 percent by weight) may result in a reduction of mechanical properties.

Numerous other fillers and additives are used with molding compounds, but are not discussed here. For a detailed account of fillers and their properties, see Ref. 7.

2-2.6 SMC FORMULATIONS

SMC formulations represent optimizations in which low cost, moderate strength and ease of processibility are the main parameters. Within this framework modifications are made to adapt materials to broad application areas. For example, formulations can be identified which yield improved mechanical, electrical, low shrinkage, corrosion resistant, and flame retardant properties or a combination of such properties. Other trade-offs are possible to achieve more specific material characteristics as abrasion resistance, weatheribility, and resistance to heat-aging. With some sacrifice in mechanical strength, formulas can be further adjusted to attain injection molding versions of these material grades.

Variations in composition include the type and amount of base polymer, monomer, fillers, and thermoplastic additives, and the amount and length of fiber reinforcement. Formulation changes are generally based on prior experience and thus will vary with individual molders and material suppliers. More formalized optimization procedures are available in which constraints can be placed on material density and mechanical properties as well as the minimum cost'.

Roughly, the three main constituents in formulations will be present somewhat as follows:

TABLE 2-5

TYPICAL SMC FORMULATIONS

Ingredient	Parts Per Hundred By Weight		
	General-purpose	Electrical	Low Shrinkage
Polyester[1]	30.0 -35.0	33.0- 38.0	22.0- 30.0
Dicumyl Peroxide	0.6- 0.7	0.6- 0.7	–
Luperox 118[2]	0.06-0.07	0.06-0.07	–
Tertiary butylperbenzoate	–	–	0.30-0.45
Zinc Stearate	0.6- 0.7	0.6- 0.7	0.6- 0.7
Calcium Carbonate[3]	25.0- 40.0	–	34.0 -40.0
Calcium Silicate	0.0- 3.5	–	–
Clay	0.0- 5.5	5 - 8	–
Calcium Hydroxide	0.6- 0.7	0.95-1.05	–
Magnesium Hydroxide	–	–	0.7- 0.9
Thermoplastic Powder	–	1.0- 2.0	4.0- 8.0
Hydrated Alumina	–	24.0- 30.0	–
Fiberglass	30.0	20.0- 25.0	30.0

[1] Polyester resin includes all monomer in systems, may be a two or three component system.
[2] 2,5 dimenthyl 2,5 bis (benzoyl peroxy) hexane.
[3] Calcium carbonate may be used alone or with calcium silicate or clay.

Constituent	Weight Percent	Volume Percent
Resin System (Includes monomers, catalysts, and thermoplastics)	30	45
Filler System	40	33
Fiberglass	30	22

As fiberglass is added or subtracted, corresponding changes are normally made in the filler content. Typical formulations for three grades of SMC are shown in Table 2-5. The electrical grade, it is noted, also can be considered flame retardent.

2-3 BULK MOLDING COMPOUNDS (BMC)

Bulk molding compounds are prepared as mechanical mixtures of resin, catalysts, release agent, fillers, and reinforcing fiber. As with SMC, the terminology is specific and refers to compounds with chemically thickened polyester systems. Again, chopped glass strands are the reinforcing fibers. In certain formulations, sisal is substituted for fiberglass and these are also classified as BMC. Some molders with in-plant facilities for compound fabrication tend to use thixotropic agents in place of chemical thickeners. Such materials are designated as "Premix" or preimpregnated molding compounds in the handbook.

The processing of BMC is generally more severe than is the case with SMC, and can result in fiber deterioration with subsequent loss of strength. Shorter fiber lengths and lower fiber loadings are the rule. Tensile strength, impact strength, and other mechanical properties are lower than those attained with SMC.

2-3.1 FABRICATION OF BMC

Traditionally, the manufacture of BMC has been a batch process. More recent improvements have allowed the use of continuous processing. (See Figs. 2-6 and 2-7 for flow diagrams of both methods.) The resin, catalysts, inhibitors, fillers, release agents, and other ingredients are premixed in shear type or high speed blenders. The preblend is conveyed to a sigma or spiral blade mixer, at which point the precut reinforcing fibers are added. The finished mix may be used in bulk form or fed to an extruder that converts it into logs, ropes, or other conveniently handled shapes. The compounded material is stored for maturation of the thickened resin prior to molding.

The mixing of the resin blend and fibers is a critical stage. Excessive working damages the fibers, while insufficient blending results in resin-fiber separation and poor flow during molding. Time cycles vary with equipment and rate of temperature rise from blending. Optimum blending temperatures range from 120° to 150°F.

The extrusion step removes entrapped air and densifies the mixture as well as converting it to a more moldable form. A denser more uniform product is obtained with screw-type extruders, but the possibility of fiber degradation is intensified. Ram-type extrusion results in preformed shapes of variable density and lower compaction. Fiber breakdown, however, is minimized.

2-3.2 BMC FORMULATIONS

As previously noted, BMC and SMC formulations and grades are closely related. The same base resins, monomers, catalyst systems, thickeners, fillers, release agents, and glass reinforcements are used in both materials. The principal differences are in the proportions of fillers and fiberglass, and the length of the fibers. Filler content may be as high as 60 percent compared to 40 percent for SMC. Glass contents generally fall within a 10 to 30 percent range, 15 to 20 percent being optimum. Above 20 percent an increased amount of glass degradation is encountered during fabrication, and compounds are difficult to extrude or injection mold. Up to 20 percent, increases in mechanical properties are proportional to the increments in glass content. Beyond 20 percent the efficiency of fiber utilization is decreased. Fiber length appears to be optimum at 0.25 in. Shorter lengths impart reduced tensile and impact strengths. Shorter lengths have been used in electrical grades where strength can be sacrificed for increased uniformity in electrical properties. Longer lengths are difficult to mix and cause fiber orientation in molding.

Silane type finishes on the glass, as with other polyester compounds, are preferred. Variations in finishes occur within the silane systems, effecting material toughness. Binders that are insoluble in styrene or other monomers, maintain strand integrity, leading to improved mold flow and higher strengths in finished moldings. Fibers with soluble binders degrade more readily in processing which results in uneven molded surfaces as well as reduced mechanical properties. Soluble binders are used in small moldings for electrical applications where dimensional stability is a consideration. Variation in molded properties due to the binder is illustrated in Table 2-6; typical formulations for several grades of BMC are shown in Table 2-7.

2-4 PREFORM MOLDING

Preform molding refers to a two-stage process in which fiber glass reinforcements are first bonded into a shape closely conforming to the finished molded article. A low viscosity preblend consisting of the polyester resin, catalyst, and fillers is added to the preform during the molding. Mold closing pressure forces the resin into the preform and the two are consolidated as curing takes place. The

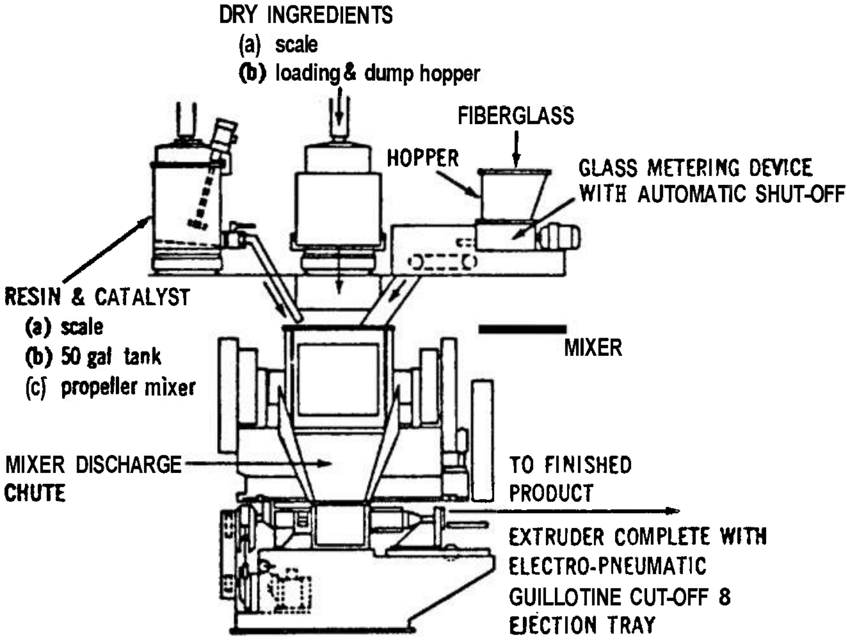


Figure 2-6. Automated Glass, Resin, and Filler Feed System for Compounding Batch-type BMC

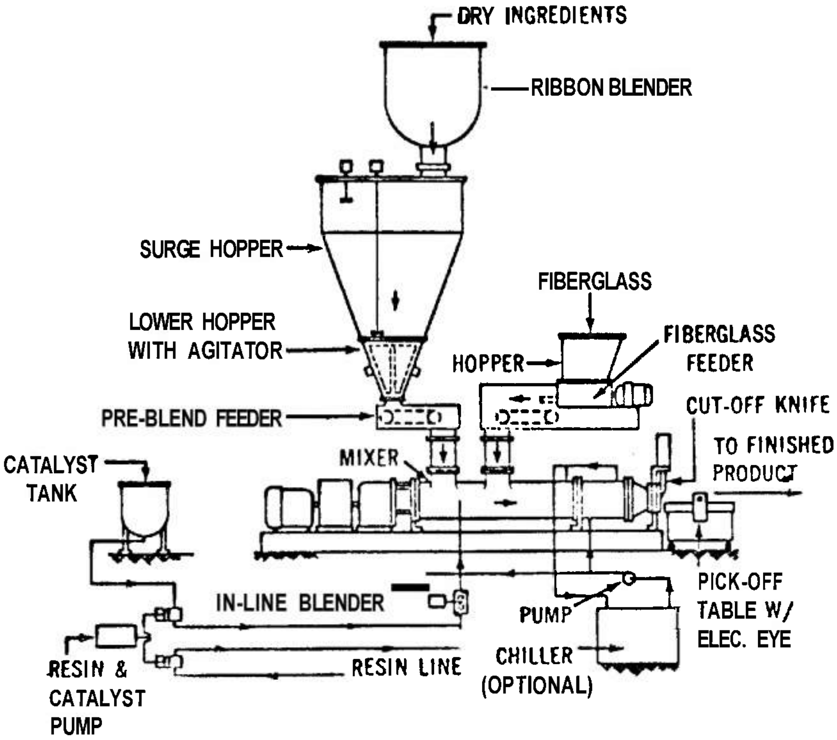


Figure 2-7. Continuous-feed Automated System for Feeding Glass, Resin, and Filler to a Continuous, In-line Mixer for Preparation of BMC

TABLE 2-6

EFFECT OF GLASS BINDER ON BMC PROPERTIES’

Glass Type’	308A	308	200
Glass Content, wt, %	15	15	15
Fiber Length, in.	0.25	0.25	0.25
Fiber Bulk Density, g/cm^3	90-115	90-120	120-150
Styrene Solubility	Insoluble	Insoluble	Soluble
Flexural Strength, ksi			
1-min mix	11.2	11.4	11.7
2-min mix	12.3	11.6	9.5
3-min mix	11.5	10.6	9.1
Impact Strength, ft-lb/in. notch			
1-min mix	5.5	5.0	4.2
2-min mix	5.2	4.2	3.4
3-min mix	3.2	2.9	2.5

[1] Johns-Manville designation for chopped strand

nethod is also classified as one of the ‘wet-processes’’ for the fabrication of reinorced plastics.

Despite the somewhat primitive nature of he process, it can be integrated with automated handling equipment. Overall producion costs for such systems, however, are igher than for other material types. The nain advantage of preform molding is that it :an be adapted to large moldings and that strengths are high due to higher glass loadings and longer fiber lengths. Its disadvantages are a nonuniformity of fiber distribution and an inherent density gradient through molded sections.

The principal methods for the fabrication of preforms are briefly described in the paragraphs that follow. A more complete treatment may be obtained from other sources[6,10]

TABLE 2-7

TYPICAL BMC FORMULATIONS

Ingredient	Parts Per Hundred by Weight General-purpose	Electrical	Corrosion Resistant	Low Shrinkage
Polyester’	28.4	25.0	30.0	24.0
Organic Peroxide	0.2	0.2	0.3	0.2
Zinc Stearate	0.5	0.5	0.7	0.5
Calcium Carbonate[2]	40-60	39-50	—	38-59
Clay’	—	0-4	15-30	—
Calcium Hydroxide	0.9	0.9	0.9	0.9
Hydrated Alumina	—	4.4-9.4	20-26	—
Thermoplastic Powder	—	—	2.4	3.5
Fiberglass’	10-30	10-30	10-30	10-30

[1] Includes all monomer in system
[2] Total glass and filler content usually kept constant

2-4.1 DIRECTED FIBER PREFORMING

Fiberglass roving is chopped continuously and deposited by an open air spray onto a rotating screen. The screen is a replica of the molded shape. A resinous binder solution or emulsion, of which there are several types, simultaneously is sprayed on the chopped glass. Air suction holds the wetted preform to the screen. Following the required thickness build-up, the preform is dried in place by hot air circulation, or is removed for oven drying and curing of the binder emulsion. Distribution of the glass and binder are controlled manually.

This method can accommodate large preforms, and different shaped parts may be handled intermittently. Fibers can be placed in selected areas for increased reinforcement or for variations in section thicknesses. Fiber lengths are variable and normally are from 1 to 2 in.

2-4.2 PLENUM CHAMBER PREFORMING

The glass chopping and spraying is conducted in an enclosed housing. The glass is deposited by a blower system onto the preform screen. A roving chopper is mounted at the top of the chamber while binder spray heads are located around the periphery to cover the screen. Several versions are employed such as a single station plenum chamber, shuttle, self-curing shuttle, and automatic rotary types. Depending on machine type, the preform may be removed for oven drying; or after rotating through a series of turntable stations, it is removed as a finished preform. The rotary automatic type is fully automated and provides uniform, rapid, and low cost preform production. It is limited to symmetrical, or nearly symmetrical, shapes and to sizes which fit the turntable, usually in the order of from 30 to 40 in. in diameter.

2-4.3 MAT PREFORMING

Mat preforming is restricted to relatively simple shapes with shallow draws and uniform section thicknesses. The mat is cut, folded, or stapled to fit the desired mold contour. Binder solutions are added to the mat as procured. Chopped strand mat generally is used. Here fiber lengths are from 1 to 2. A second mat type for preforming is made from continuous strand in a swirled pattern.* Continuous strand mat produces molded products with mechanical properties somewhat superior to chopped strand mat.

2-4.4 PREFORM MOLDING FORMULATIONS

Polyester resins, monomers, catalysts, mold release agents, fillers, and reinforcements for the wet molding preform processes are similar to those described for SMC and BMC. Clay, talc, and calcium carbonate, either singly or in combination, are the more common fillers. Asbestos, calcium silicate, magnesium silicate, silica, and alumina are employed to a lesser extent. The metallic stearates are used for mold release when mold temperatures are above 270°F. For mold temperatures in the 230° to 270°F range alkyl phosphates or lecithin are more satisfactory.

Control of resin viscosity and flow during molding is maintained by monomer addition and by the amount and type of filler in the formulation. Filler contents up to 50 percent by weight of the resin premix have been used in some instances, but are optimum at about 25 to 30 percent. Excessive filler loadings require greater mold closing pressures which can result in fiber washout, poor impregnation, and resin rich areas in finished moldings.

Maximum fiber loadings up to 50 percent by weight can be attained, although usually they are not in excess of 35 percent. Minimum loadings are in the order of 20 percent. It should be noted that these are average

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*Continuous strand mat is an apparent exception to the category of short fiber composites. However, the fibers are random and material properties are related more closely to discontinuous fibers.

TABLE 2-8

FORMULATIONS FOR THE PREFORM METHOD OF MATCHED DIE MOLDING[10]

Ingredient	Resin Mix	Combining Ratio as Mixed at Press	% Final Composition
1. Resin Polyester resin, 35 poise viscosity	68.0	65.0	48.7
2. Monomer Styrene (to lower viscosity to approx. 8 poise)	7.0		
3. Catalyst Benzpyl peroxide (0.8-1% of resin)	0.6		
4. Fillers Clay, calcium carbonate of combined fillers	25.0		16.3
Internal mold release	0.1		
Color Pigments (if required) Paste dispersions in DAP preferred over dry pigment additions	0.5-5.0		
5. Reinforcement Glass fiber as preform or mat	—	35.0	35.0

percentages and large variations will occur within a molded part.

As with SMC and BMC, wet moldings can be modified for specific fields of application. Low shrinkage, electrical, corrosion resistant, and flame retardant combinations are possible. A typical general-purpose formulation is shown in Table 2-8.

2-5 CHOPPED ROVING COMPOUNDS

Chopped roving compounds have been used in aerospace and military applications which require high strengths and are impractical to mold with woven fabrics or unidirectional composites.

The chopped rovings are prepared by a continuous pre-impregnation process. The reinforcement in the form of continuous rovings, strands, tows, or monofilaments are passed through a resin tank where it is coated with a catalyzed resin. Excess resin is removed by doctor blades, squeeze rolls, or other means and the impregnated material is dried and B-staged in heated tunnels to a tack-free condition. The dried strands are then cut into uniform lengths, normally ranging from 0.5 to 1 in. Depending on the type of reinforcement, the resin is handled as a solution or a hot-melt. For example, glassfibers are readily wetted by a solution. Graphite fibers, on the other hand, must be coated from a melted resin to insure fiber impregnation and sufficient resin pick-up.

Numerous combinations of reinforcing fibers and resins can be processed by such impregnating methods. Considerations as to strength, stiffness, and elevated temperature properties have restricted reinforcements to

E-glass, S-glass and graphite, and the resin systems to epoxy. The epoxy types are either the diglycidyl ether of bisphenol-A (DGEBA) or epoxy novolacs. Catalyst systems are variable and usually are adjusted to give 250° or 350°F resin curing systems. Total resin content can be readily maintained to a ±2 percent tolerance; when warranted, it can be held as close as ±1 percent. Residual volatiles are present when the resin is added from a solution. Maximum volatile content should fall in a **2** to **3** percent range. Excessive volatiles result in moldings with high void contents and may cause resin flashing when molded. Material flow properties are controlled by the degree of B-staging. Optimum fiber contents are from 50 to 55 percent by volume for fiberglass and from 55 to 60 percent for graphite fibers. The shelf life for most finished compounds is in the order of six months. In some cases, refrigerated storage is required.

The main advantages of chopped roving compounds are:

(1) High strength to weight and modulus to weight ratios are possible.

(2) Properties are more predictable due to closer controlled resin to reinforcement ratios.

(3) Resin-reinforcement selections can be tailored for specific needs.

The disadvantages are:

(1) The materials are more expensive.

(2) Curing cycles are longer than for other molding compounds.

(3) Higher molding pressures are required for both transfer and compression molding.

(4) Materials are bulkier and hence less suited for automated molding processes.

2-6 MISCELLANEOUS MATERIAL PROCESSES

Two processes for preparing short-fiber moldings are briefly noted. One, ***open-mold spray-up,*** is an older method that is still used extensively, particularly in boat construction. The other, ***cold press molding,*** is a more recent innovation that is gaining acceptance for low cost, short run applications. Both processes use fiberglass roving with polyester resin. In open-mold spray-up the fiberglass is chopped from roving and codeposited with resin into a mold. The mixture is compacted by hand rollers and cured at room temperature.

Cold press molding in many respects is similar to preform molding. The **glass** reinforcement can be made into a preform using similar methods as described in par. 2-4. The resin is catalyzed for room or low temperature curing. Fillers may be added to the resin mix. Curing takes place in matched metal dies where the resin and preform are brought together. The advantage of this process is that low cost tooling and low molding pressures may be used. Properties are superior to those attained by hand lay-up open mold methods and begin to approach hot press moldings.

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9. R. H. Bengston, ***11th Seminar, SPI Premix Committee,*** SPI Reinforced Plastics Division, 19 May 1967.

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CHAPTER 3

MATERIAL PROPERTIES

3-1 INTRODUCTION

The mechanical, electrical, and thermal properties of the short fiber molding compounds are presented in this chapter. The material property data have been extracted from several sources which include the open literature, trade journals, product data sheets published by material suppliers and from reports of Govemment sponsored programs in which material evaluations have been conducted. Data are supplied for specific molding compounds that are representative of SMC, BMC, and other preimpregnated molding materials. Property estimates are also given for preform-wet layup material types and for inplant formulations of SMC and BMC. The properties of laminates fabricated from woven fiberglass fabrics with polyester binders are included for comparative purposes. Chemical resistance of a compound is a function of the resin system. Data regarding the resistance of specific resin to a specific reagent can be obtained from the resin suppliers.

The property values presented are considered to be "typical values"; i.e., they represent an average value for a particular specimen and no statistical significance can be assigned to them. When ten or more specimens are tested as a single sampling, it is customary to give an average value with the calculated standard deviation. The typical values are most useful for comparative purposes and for preliminary design estimates. They are not intended for use as design allowables. In situations where design allowables are required, it is necessary to conduct tests for determining property values and the associated standard deviations. Procedures for obtaining such information are furnished in MIL-HDBK-17A, *Plastics for Aerospace Vehicles, Part 1, Reinforced Plastics.*

Nearly all physical properties will vary depending on the types of proportions of reinforcing fibers, fillers, and resins. Mechanical properties also are influenced by the length of fiber reinforcement. In general, formulation optimizations represent a compromise for moderate strength at lowest cost. Specific material characteristics may require optimization at some other ratios of fiber, filler, and resin. It is, therefore, useful to ascertain the effects of these variables on various properties. Such data are provided wherever available.

Significant influences on property values, reproducibility, and reliability result from variations in material manufacturing processes, maturation rates of chemically thickened resin systems, storage life prior to molding, and in the molding operation. These parameters may produce such adverse material effects as fiber misalignment, segregation of resin from reinforcement:, uneven fiber distribution, nonuniform material bulk densities, and erratic flow properties during molding. It is apparent in compiling existing data that these effects are known only quantitatively and have not been assessed with sufficient accuracy to be of service in anticipating material behavior. In some cases, therefore, it may be necessary to estimate material response based on limited data or by analogy with other composite material types.

Formulation and processing variables which influence material properties are discussed in Chapters 4 and 5.

3-2 TEST METHODS

A list of standard methods for the testing of reinforced plastics and composites is shown in Table 3-1. Where applicable, the table lists an accepted ASTM Standard Procedure' and the equivalent method of Federal Test Method Std. No. 406[2]. In cases, where ASTM methods do not apply, references are given which describe suggested test methods. Unless stated otherwise, it is to be assumed that the test data included in the handbook are based on the test methods as listed.

3-2.1 CONDITIONING PRIOR TO TEST

It is customary to test for the mechanical properties of plastic materials in the "dry" and "wet" condition. The "dry" condition is defined as an equilibrium at a temperature of from 70° to 75°F and a relative humidity of from 45 to 55 percent. A ten-day period is considered the minimum for attaining equilibrium. "Wet" conditioning is specified as an equilibrium either at 95" or 125°F and at a relative humidity of from 95 to 100 percent. Ten days is again the minimum period of exposure. In some instances, plastic materials are tested after a 24-hr immersion in water or after a 2-hr water boil.

Conditioning for electrical testing generally complies with the procedures of ASTM D618-61 (Reapproved 1971), ***Standard Methods of Conditioning Plastics and Electrical Insulating Materials for Testing'.***

3-2.2 TEST TEMPERATURE

Tests are conducted at several temperatures. Normally, the standard temperatures for military applications of −65°, 73°, and 160°F will suffice. It may be desirable in some instances to test at higher temperatures corresponding with the anticipated continuous service. Elevated temperature testing generally denotes a test at the specified temperature after a 0.5-hr exposure to attain equilibrium.

3-2.3 TESTING FOR FLAMMABILITY

Test methods have been developed by the ASTM, the Underwriters' Laboratory, and other organizations for determining the flame spread, ignition temperature, smoke generation, oxygen index, tunnel testing, intermittent flame spread, and other buming characteristics of polymer-based materials. Currently, these tests are being reevaluated as to their efficacy and interpretation. Results of those tests as reported by manufacturers are not included. It is recommended that manufacturers be consulted as to the specific tests best suited for environmental conditions expected during the service life of a material. Published data now existing should be used only for comparative purposes.

3-3 PROPERTIES OF SHORT FIBER COMPOUNDS BASED ON POLYESTER RESINS

3-3.1 PROPERTIES OF SMC

The mechanical properties of Structoform S-6413, a commercial SMC produced by the Fiberite Corporation, are summarized in Table 3-2. The fatigue properties of this material are shown in Fig. 3-1.

The mechanical properties of a similar compound, Structoform S-6300 are shown in Table 3-3. Stress-strain relations in tension, compression, and flexure are given in Figs. 3-2, 3-3, and 3-4. Fig. 3-5 shows the effect of humidity aging at 145°F on flexural stress-strain relations.

Table 3-4 lists the properties of three Structoform compounds as taken from the material supplier's data sheets. Except for tensile strength, the mechanical properties are in relatively close agreement with the two previous evaluations.

The physical properties of sheet molding compounds supplied by Premix, Inc., and by Marco Chemical Division are shown in Tables 3-5 and 3-6, respectively. The Premix data

TABLE 3-1

TEST METHODS FOR DETERMINING THE PHYSICAL PROPERTIES OF PLASTIC MATERIALS

TEST	ASTM METHOD[1]	STD. NO. 406 METHOD[2]
A. MECHANICAL PROPERTIES		
TENSILE	D638-72	1011
Max Stress-		
Strain at Maximum		
Modulus		
COMPRESSIVE	D695-69	1021
Max Stress-		
Strain at Maximum		
Modulus		
IN-PLANE SHEAR	Ref. 3	----------
Max Stress		
Modulus		
POISSON'S RATIO	Ref. 4	----------
Tensile Stress-Strain		
FLEXURAL	D790-71	1031
Max Stress		
INTERLAMINAR SHEAR	D2733-70	1042
Max Stress		
BEARING STRENGTH	D953-54	1051
Max Stress		
Stress at 4% Strain		
IMPACT RESISTANCE	D256-72a	1071
Izod Strength		
Work to Break	†	
B. ELECTRICAL PROPERTIES		
DIELECTRIC STRENGTH	D149-64	4031
DIELECTRIC BREAKDOWN VOLTAGE	D149-64	4031
DIELECTRIC CONSTANT	D150-70	4021
DISSIPATION FACTOR	D150-70	4021
ARC RESISTANCE	D495-71	4011
TRACK RESISTANCE	02303-68	----------
C. THEHMAL PROPERTIES		
THERMAL CONDUCTIVITY	C177-71	----------
COEFFICIENT OF LINEAR THERMAL EXPANSION	D696-70	2031
MOLD SHRINKAGE	D955-73	----------
DEFLECTION TEMPERATURE	D648-72	2011

†Area under tensile stressstrain curve.

TABLE 3-1 (Continued)

TEST	ASTM METHOD'	STD. NO. 406 METHOD[2]
D. CHEMICAL PROPERTIES		
CHEMICAL RESISTANCE RESINS	C581-68	----------
CHEMICAL RESISTANCE PLASTICS	D543-67	7011
PROPELLANT COMPATIBILITY	----------	7081
VACUUM STABILITY-PROPELLANT	Ref. 5	----------
STORAGE WITH PROPELLANT	Ref. 6	----------

TABLE 3-2

MECHANICAL PROPERTIES OF STRUCTOFORM S-6413 MOLDING COMPOUND'

Material Type: SMC
Glass Content, wt, %: 35-38

Supplier: Fiberite Corp.
Fiber Length, in.: 2
Specific Gravity: 2.00-2.05

Conditioning	75"F, 50% RH			95°F, 100% RH		
Test Temperature, °F	–65	75	135	–65	75	135
Tensile						
Max Stress, ksi	18.7	14.1	13.1	15.4	------	13.1
SD[1], ksi	1.5	1.8	1.3	1.3	------	1.4
Modulus, psi x 10^6	2.33	1.97	1.48	2.43	------	1.74
SD, psi x 10^6	0.23	0.29	0.03	0.12	------	0.12
Compressive						
Max Stress, ksi	35.1	28.4	22.4	37.6	------	21.5
SD, ksi	3.2	1.6	1.2	2.8	------	2.6
Modulus, psi x 10^6	2.92	2.21	1.87	2.51	------	1.69
SD, psi x 10^6	0.19	0.13	0.11	0.10	------	0.14
Flexural						
Max Stress, ksi	------	33.8	------	------	30.1	------
SD, ksi	------	2.0	------	------	7.6	------
In-Plane Shear						
Max Stress, ksi	6.1	7.3	4.8	6.4	4.4	4.0
SD, ksi	1.1	1.8	1.0	1.0	0.3	0.4
Modulus, psi x 10^6	0.74	0.77	0.68	0.80	0.84	0.61
SD, psi x 10^6	0.15	0.29	0.10	0.16	0.05	0.07
Interlaminar Shear						
Max Stress, ksi	5.64	4.70	3.75	------	4.19	3.91
SD, ksi	0.58	0.12	0.18	------	0.48	0.23

[1] SD = Standard Deviation

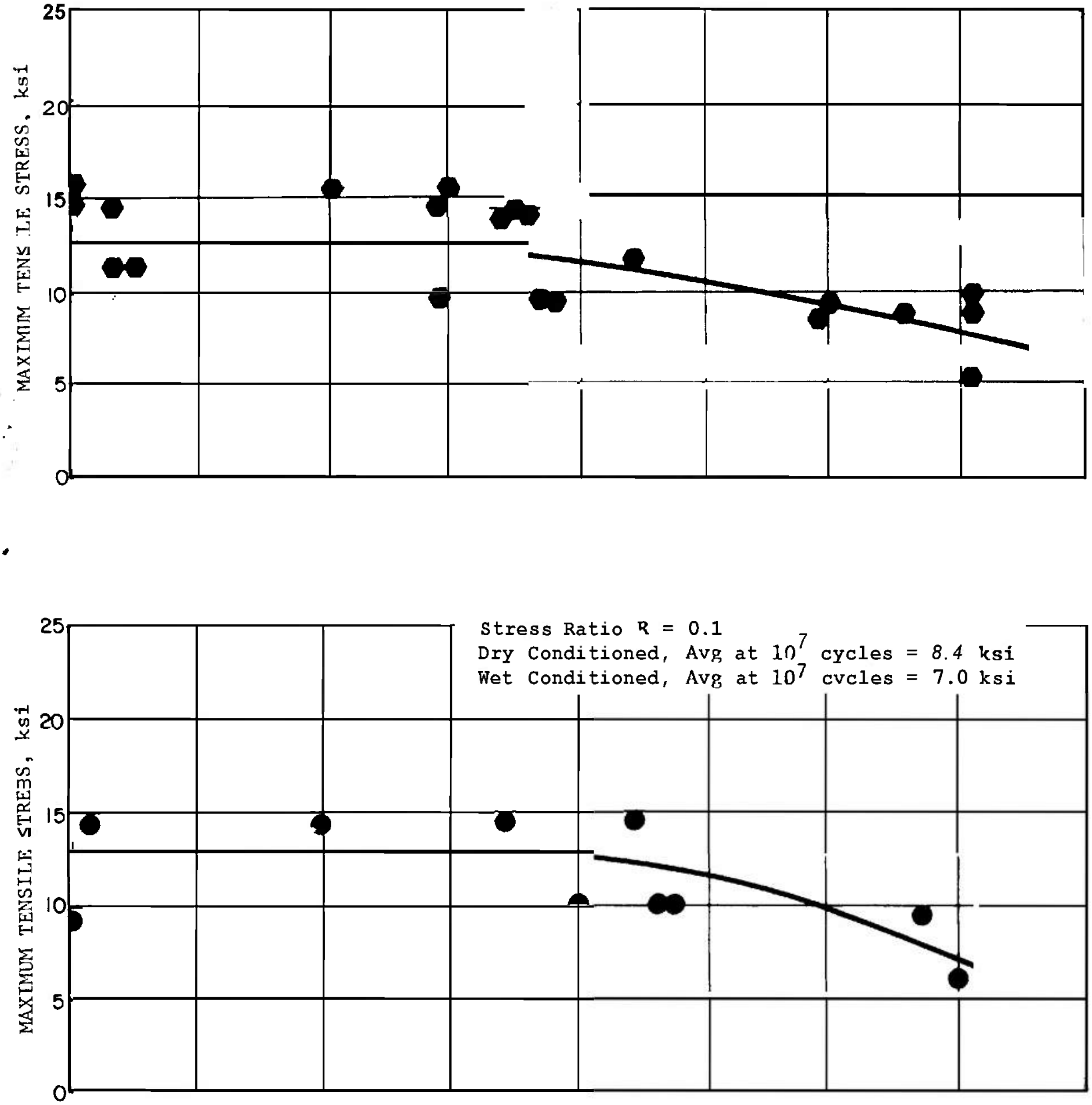


Figure 3-1. Fatigue of Structoform S-6413. Sheet Molding Compound

TABLE 3-3

MECHANICAL PROPERTIES OF STRUCTOFORM S-6300 MOLDING COMPOUND[9]

Material Type: SMC	Supplier: Fiberite Corp.
Glass Content, wt, %: 35	Fiber Length, in.: 1
	Specific Gravity: 2.02

	AVG. VALUE 15 SPECIMENS		ASSIGNED VALUES[1]	
Test Temperature, ° F	74	200	74	200
Tensile				
Max Stress, ksi	11.4	9.5	8.7	7.8
Max Strain, %	1.3	1.3	------	------
Modulus, psi x 10^6	1.91	1.01	1.4	0.9
Compressive				
Max Stress, ksi	28.2	13.3	24.5	15.2
Max Strain, %	2.0	1.7	------	------
Modulus, psi x 10^6	1.49	0.83	1.2	0.75
Flexural				
Max Stress, ksi	30.0	17.9	25.8	11.3
Max Strain, %	2.3	2.0	------	------
Modulus, psi x 10^6	1.54	0.89	1.3	0.8
Bearing Strength				
Max Stress, ksi	24.7	19.4	22.8	17.2
Stress at 4% Strain, ksi	19.9	13.1	------	------
Impact Resistance ft-lb/in. notch	19.0	15.9	17.0	14.8

[1] Design allowables assigned by referenced company.

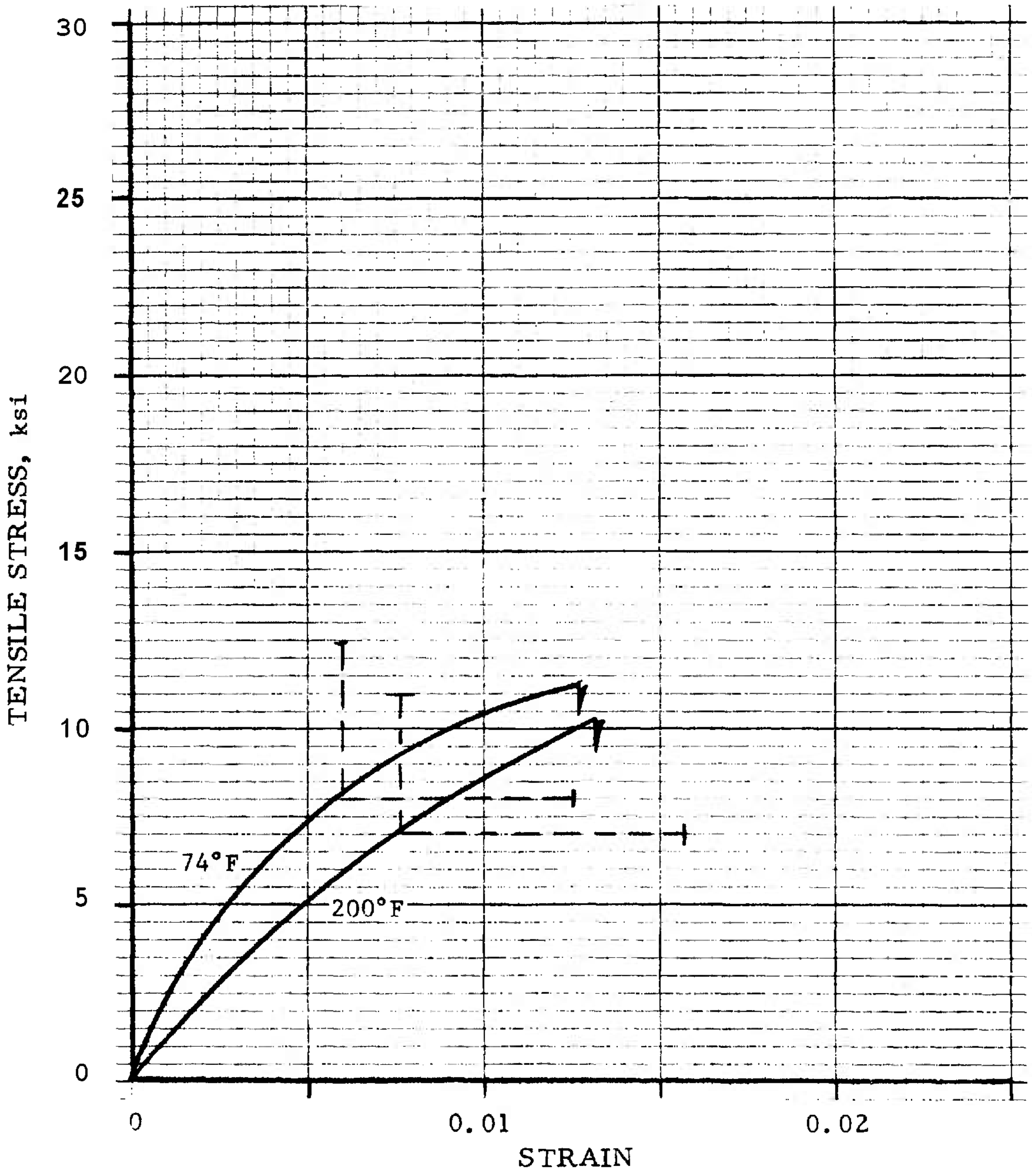


Figure 3-2. Tensile Stress-Strain for Structoform S-6300Molding Compound

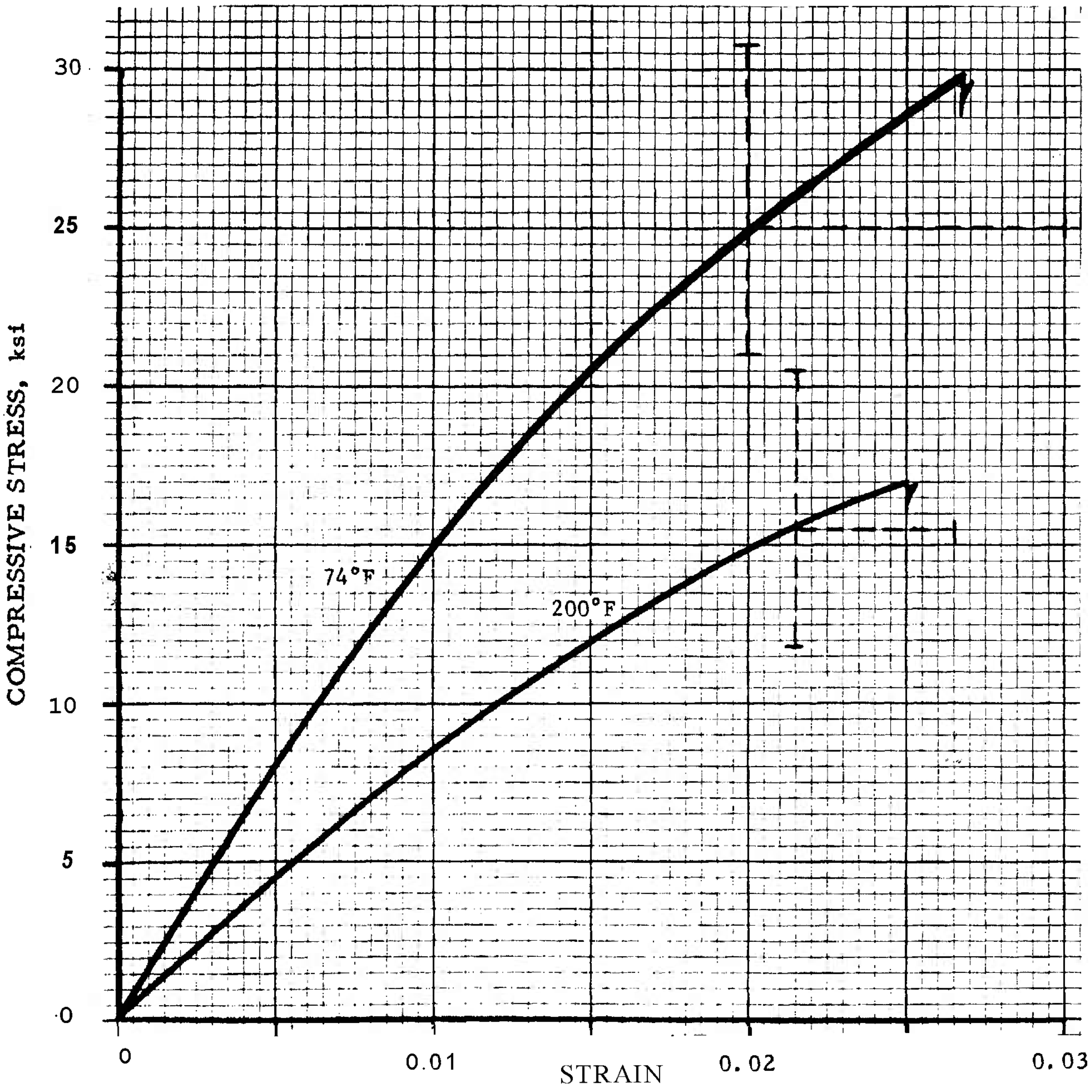


Figure 3-3. Compressive Stress-Strain for Structoform S-6300 Molding Compound

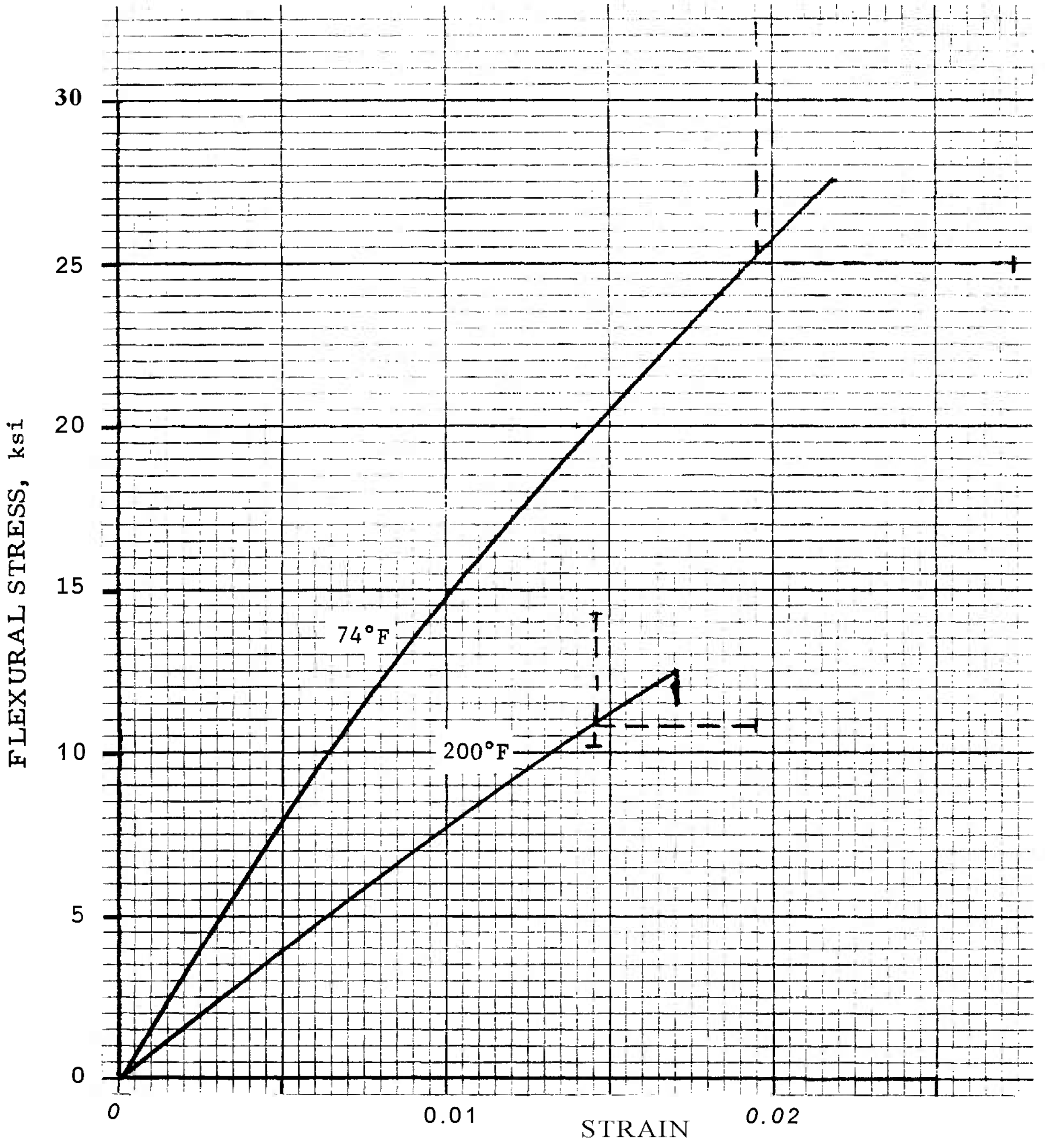


Figure 3-4. Flexural Stress-Strain for Structoform S-6300 Molding Compound

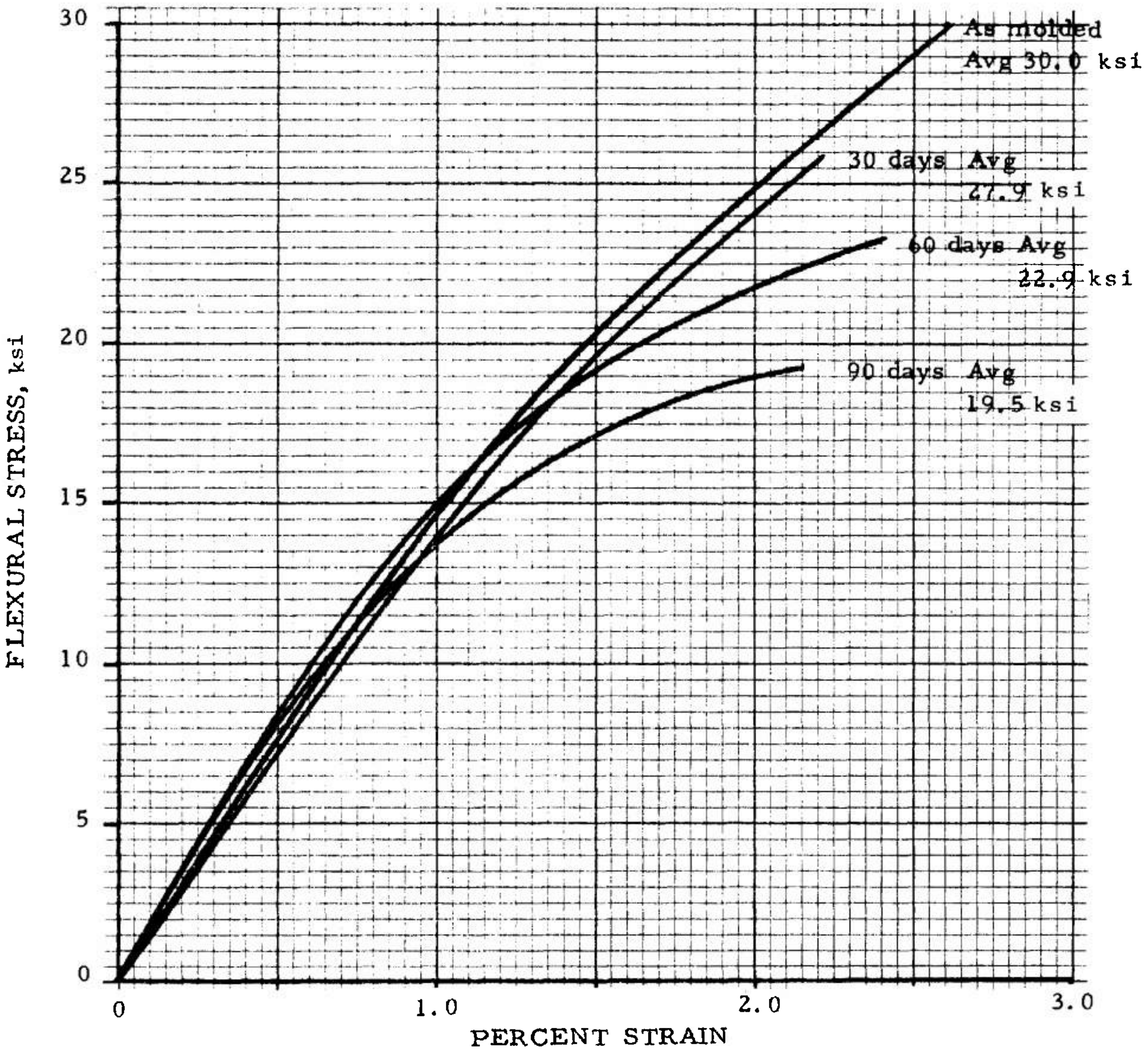


Figure 3-5. Effect of Aging at 145°F and 100 Percent Relative Humidity on the Flexural stress strain of Structoform S-6300 Molding Compound

TABLE 3-4

PROPERTIES OF STRUCTOFORM MOLDING COMPOUNDS

Material Type: SMC
Reference: Fiberite Products
Data Sheets

Supplier: Fibetite Corp.

Material	S-6413[1]	S-6300[2]	S-6400[3]
Glass Content, wt, %	35-38	33-36	33-36
Specific Gravity	2.02	2.00	1.94
Tensile, Max Stress, ksi	21.5	18.0	15.0
Max Strain, %	1.85	1.5	1.5
Compressive, Max Stress, ksi	32.0	20.0	25.5
Flexural, Max Stress, ksi	37.0	36.0	31.5
Modulus, psi x 10^6	1.8	2.2	2.0
Impact Resistance, ft-lb/in. notch	------	15.0	13.6
Dielectric Strength, V/mil	------	------	------
Short Term, dry	------	335	380
Step-by-step, dry	------	307	351
Dielectric Constant, MHz, dry	------	6.1	4.95
Arc Resistance, sec	------	184	191
Thermal Conductivity, Btu/hr-ft^2-(°F/in.)	------	4.4	4.4
Coef. Thermal Expansion, Micro in./in./°F		------	11.2
Mold Shrinkage, mil/in.	1.0	1.0	1.4
Deflection Temperature, 264 psi, "F	------	480	510

[1] Formulated for higher **mechanical** properties
[2] Gkneral **purpose** grade
[3] Flame retardant equivalent of S-6300

TABLE 3-5

PROPERTIES OF PREMI-GLAS MOLDING COMPOUNDS

Material Type: SMC
Reference: Premix Products
Data Sheets

Supplier: Premix, Inc.

Material Designation	1200 SMC-LS[1]			2200 SMC-LS[2]			3200 SMC-LS[3]			4200 SMC-LS'		
Glass Content, wt, %	15	22	30	15	22	30	15	22	30	15	22	30
Specific Gravity	1.85	1.85	1.85	1.75	1.77	1.80	1.75	1.77	1.80	1.80	1.78	1.75
Tensile, max stress, ksi	6.0	9.0	14.0	6.0	8.0	10.0	6.0	8.0	10.0	8.0	11.0	14.0
Compressive, max stress, ksi	24.0	26.0	30.0	20.0	24.0	28.0	20.0	24.0	28.0	24.0	30.0	36.0
Flexural, max stress, ksi	18.0	23.0	29.0	16.0	18.0	20.0	16.0	18.0	20.0	18.0	25.0	31.0
Impact, ft-lb/in. notch	8.0	10.0	12.0	7.0	12.0	16.0	7.0	12.0	16.0	9.0	11.0	14.0
Dielectric Strength, short term dry, V/mil,	320	320	320	400	375	350	400	400	400	380	360	350
Arc Resistance, sec	120+	120+	120+	180	180	180	180	180	180	120	120	120
Track Resistance, min		Tracks		200+	200+	200+	500	400	400		Tracks	
Mold Shrinkage, mil/in.	1.0	1.0	1.0	**1.0**	**1.0**	**1.0**	1.0	1.0	1.0	2.5	3.0	3.0
Deflection Temperature 264 psi, °F	350	340	300	395	395	395	400	400	400	400	400	400

[1] General Purpose, Low Shrinkage Grade
[2] Electrical, Self-extinguishing, Low Shrinkage Grade
[3] Electrical, Nontrack, Self-extinguishing. Low Shrinkage Grade
'Corrosion Resistant Grade

TABLE 3-6

PROPERTIES OF VIBRIN-MAT MOLDING COMPOUNDS

Material Type: SMC
Reference: Marco Products Data Sheets

Supplier: Marco Chemical Div.
W.R. Grace & Co.

Material Designation and Type	G 2702 L-P-383		G 1600 General Purpose	L 1703 Low Shrinkage	F 2700 Flame Retardant	E 3000 Electrical	E 4000 Electrical
Glass Content, wt,%	38-40	38-40	28-30	28-30	28-30	28-30	28-30
Fiber Length, in.	1	2	1	1	1	1	1
Specific Gravity	–	–	1.72	1.72	1.74	1.74	1.74
Tensile, max stress, ksi	20.5	23.0	14.0	14.3	14.8	13.8	14.2
Compressive, max stress ksi	32.0	33.0	28.0	28.0	26.0	30.5	30.0
Flexural, max stress, ksi	35.4	35.7	26.0	26.0	25.5	28.0	26.8
modulus, psi x 10^6	1.8	1.8	7.5	1.5	1.45	1.5	1.5
Impact, ft-lb/in. notch	21.0	24.0	11.4	13.5	9.2	14.3	13.2
Dielectric Strength, V/mil, short term, dry,	–	–	441	441	470	684	656
Dielectric Constant, 1MHz, dry	–	–	4.55	4.5[1]	4.08	4.50	4.04
60 Hz, dry	–	–	4.62	4.6	4.90	4.65[1]	4.40[1]
Arc Resistance, sec	–	–	134	140	183	190	183
Mold Shrinkage, mil/in.	–	–	1.5	0.5	1.4	0.8	0.8
Deflection Temperature, 264 psi, °F	–	–	400	400	400	400	400
Continuous Service Temperature, max, °F	–	–	300	300	250	300	300

[1] at kHz (1000 cycles/sec)

TABLE 3-7

PROPERTY RANGE FOR IN-PLANT SMC FORMULATIONS[10]

PROPERTY	RANGE
Glass Content, wt, %	15-35
Specific Gravity	1.7-2.1
Tensile	
max stress, ksi	8.0-20.0
max strain, %	0.3-1.5
modulus, psi x 10^6	1.6-2.5
Compressive	
max stress, ksi	15.0-30.0
Flexural	
max stress, ksi	18.0-30.0
modulus, psi x 10^6	1.4-2.0
Impact Resistance	
ft-lb/in. notch	8-22
Thermal Conductivity	
Btu/hr-ft^2-(°F/in.)	1.3-1.7
Deflection Temperature	
264 psi, °F	400-500

cover properties at three glass contents. Marco data are for a nominal **30** percent glass content, except for one product, supplied at 40 percent glass content to meet the requirements of Fed. Spec. L-P-383 for polyester low pressure laminates. Table 3-7 estimates the range of properties to be expected with in-plant formulations of SMC within a range of glass contents of from 15 to 30 percent.

3-3.2 MILITARY SPECIFICATION FOR SMC

MIL-P-46169**(MR)**, *Plastic, Sheet Molding Compound, Polyester, Glassfiber Reinforced (For General Purpose Applications)*, has recently been prepared by the US Army Materials and Mechanics Research Center. **As** proposed, the general purpose grade material will be subdivided into four classes, encompassing a range of glassfiber contents of from 10 to 45 percent. **A** general-purpose flame retardant grade is similarly divided into four classes. Property requirements are listed in Table 3-8.

3-3.3 PROPERTIES OF BMC

Test results for several types of bulk molding compounds are shown in Table 3-9. The data cover three levels of glass content for each type. The total glass and filler content is maintained at a constant level.

Table 3-10 lists the properties of Premix, Inc., bulk molding compound formulations. Glass content is also at three concentrations, but no data are supplied as to filler and resin types and contents.

Table 3-11 covers a range of property values which may be expected from the various formulations of BMC.

3-3.4 PROPERTIES OF PREFORM-WET LAY-UP MATERIALS

Table 3-12 **is** an estimation of property ranges to be achieved using the preform-wet lay-up process. Comparisons are made for preforms deposited by directed fiber or plenum chamber techniques as opposed to mat preform. In Table 3-13 a comparison is made for two types of wet lay-up mat preforms; i.e., mat from chopped strand or mat from continuous strand. **This** table also provides some indication of the electrical properties with these materials. Fig. 3-6 summarizes the results of fatigue tests for polyester-mat laminates.

3-3.5 PROPERTIES OF WOVEN FABRICS WITH POLYESTER RESIN

Table 3-4 and Figs. 3-7 through 3-13 summarize the mechanical properties of laminates made from **a** style 7781 woven glass fabric preimpregnated with a polyester resin, and cured by the vacuum bag-autoclave

TABLE 38

PROPOSED REQUIREMENTS FOR A GENERAL PURPOSE SHEET MOLDING COMPOUND

Grade	General Purpose A				Flame Retardant B			
Class	1	2	3	4	1	2	3	4
Glass Content, wt, %	10-15	16-24	25-35	36-45	10-15	16-24	25-35	36-45
Tensile Strength ksi, min	6.0	8.0	12.0	14.0	5.0	7.5	9.5	11.5
Flexural Strength ksi, min	18.0	20.0	24.0	26.0	15.0	17.0	20.0	22.0
Impact Strength, Izod ft-lb/in. notch, min	7.5	9.5	11.5	13	6.5	9.5	11.5	13
Water Absorption[1] 24 hr, %, max	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Deflection Temperature, 264 psi, °F, min	400	400	400	400	400	400	400	400
Mold Shrinkage mil/in. max	3	3	3	3	3	3	3	3
Flammability[2] in.	<4	<4	<4	<4	—	—	—	—
Flammability[3]	—	—	—	—	94V-1	94V-1	94V-1	94V-1
Ignition Temperature[3] °F, min	—	—	—	—	968	950	932	914
Dielectric Constant[4] 1 kHz, max	5.5	5.5	5.5	—	6.0	6.0	6.0	—
Dielectric Strength[4] step-by-step, V/mil, min	310	310	310	—	310	310	310	—

[1] Tested per ASTM D570
[2] Tested per ASTM D635
[3] Tested per Underwriters' Laboratory UL94, Dec. 73
[4] Applicable only when specified by procuring agency

TABLE 3-9

MECHANICAL PROPERTIES OF BULK MOLDING COMPOUNDS' [1]

Material Type: BMC
Glass Length, in.: 0.25

Material Grade	General Purpose'			Self-extinguishing'			Electrical'			Corrosion Resistant[3]		
Glass Content, wt, %	10	20	30	10	20	30	10	20	30	10	20	30
Resin Content, wt, %	28.4	28.4	28.4	25.0	25.0	25.0	25.0	25.0	25.0	30.0	30.0	30.0
Filler Content, wt, %	60.0	50.0	40.0	63.4	51.4	41.4	63.4	53.4	43.4	55.7	45.7	35.7
Specific Gravity	2.0	2.0	2.0	1.88	1.88	1.84	1.88	1.88	1.84	1.82	1.82	1.82
Tensile,												
max stress, ksi	4.0	5.0	6.0	5.0	6.0	7.0	5.0	6.0	8.0	5.0	6.0	7.0
Flexural,												
max stress, ksi	10.0	17.0	21.0	14.0	16.0	20.0	14.0	16.0	20.0	14.0	16.0	20.0
modulus, psi x 10^6	1.6	1.5	1.4	1.6	1.5	1.4	1.6	1.5	1.4	1.6	1.5	1.4
Impact, ft-lb/in.												
notch	4.0	5.0	7.0	3.0	4.0	7.0	3.0	4.0	7.0	3.0	4.0	7.0

[1] Resin—general purpose polyester; filler—calcium carbonate
[2] Resin—isophtherllic polyester; filler—alumina trihydrate, clay
[3] Resin—bisphenol polyester; filler—alumina trihydrate, clay

TABLE 3-10

PROPERTIES OF PREMI-GLAS BULK MOLDING COMPOUNDS

Material Type: BMC
Reference: Premix Products Data Sheets

Supplier: Premix, Inc.

Grade	A			B			C			D		
Material Designation	1100 BMC			2100 BMC			3100 BMC			4000 BMC		
Glass Content, wt, %	15	22	30	15	22	30	15	22	30	15	22	30
Specific Gravity	1.85	1.85	1.85	1.80	1.82	1.85	1.80	1.83	1.85	1.80	1.79	1.78
Tensile, max stress, ksi	4.0	5.0	6.0	5.0	6.0	7.0	4.0	5.0	7.0	4.0	5.0	6.0
Compressive, max stress, ksi	18.0	21.0	24.0	18.0	20.0	22.0	18.0	21.0	22.0	22.0	24.0	26.0
Flexural, max stress, ksi	14.0	16.0	18.0	13.0	15.0	17.0	13.0	16.0	17.0	15.0	17.0	22.0
Impact, ft-lb/in. notch	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	7.0	5.0	6.0	8.0
Dielectric Strength, V/mil, short term dry	340	340	340	400	375	350	400	400	400	350	340	325
Arc Resistance, sec	120	120	120	190	190	185	190	185	185	120	120	120
Track Resistance, min		Tracks		300	200	200	600	600	400		Tracks	
Mold Shrinkage, mil/in	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.0	3.0	3.0
Deflection Temperature 264 psi, °F	340	320	300	395	395	395	395	395	395	350	350	350

A. General Purpose Grade, Low Shrinkage
B. Self-extinguishing Electrical Grade, Low Shrinkage
C. Nontracking Electrical Grade, Low Shrinkage
D. Corrosion Resistant Grade

TABLE 3-11

GENERAL RANGE OF PROPERTIES OF IN-PLANT BULK MOLDING COMPOUNDS[1 2]

Material Type: BMC

Property	Value	
	Low	High
Specific Gravity	1.4	2.0
Tensile		
max stress, ksi	3.0	10.0
modulus, psi x 10^6	1.5	2.0
Compressive		
max stress, ksi	15.0	30.0
Flexural		
max stress, ksi	6.0	26.0
modulus, psi x 10^6	1.5	2.5
Impact Resistance		
ft-lb/in. notch	2.0	8.0
Dielectric Strength		
V/mil, *short* term, dry	320	400
V/mil, step-by-step, dry	300	330
Dielectric Constant		
1 MHz, dry	2.1	4.6
60 Hz, dry	5.1	5.7
Arc Resistance, sec	100	400
Track Resistance, min	—	>800
Thermal Conductivity		
Btu/hr-ft^2-(°F/in.)	1.32	1.68
Coefficient Thermal Expansion		
μin./in.-°F	—	—
Deflection Temperature		
264 psi, °F	300	>570
Continuous Service Temperature max, °F	250	400

TABLE 3-12

PROPERTIES OF PREFORM-WET LAY-UP LAMINATES[10,13,15]

Material Type	SPRAY-UP PREFORM[1]			GLASS MAT[2] Continuous Strand	GLASS MAT[2] Chopped Strand
Glass Content, wt, %	35	25	25-45	25-45	25-45
Fiber Length, in.	1	–	1-2	–	1-2
Specific Gravity	–	1.61	1.5-1.7	1.5-1.7	1.5-1.7
Tensile					
max stress, ksi	16.8	15.0	12.0-18.0	15.0-20.0	12.0-18.0
max strain, %	–	–	1.0-2.0	1.0-2.0	1.0-2.0
modulus, psi x 10^6	–	1.1	1.0-1.8	1.0-1.8	1.0-1.8
Compressive					
max stress, ksi	–	20.0	20.0-25.0	20.0-25.0	20.0-25.0
Flexural					
max stress, ksi	30.0	25.0	15.0-30.0	20.0-38.0	20.0-35
modulus, psi x 10^6	1.8	1.1			
Impact Resistance ft-lb/in. notch	17	10	10-18	12-18	12-8
Thermal Conductivity Btu/hr-ft^2-(°F/in.)	–	–	1.3-1.8	1.3-1.8	1.3-1.8
Deflection Temperature 264 psi, °F	–	400	350-400	350-400	350-400

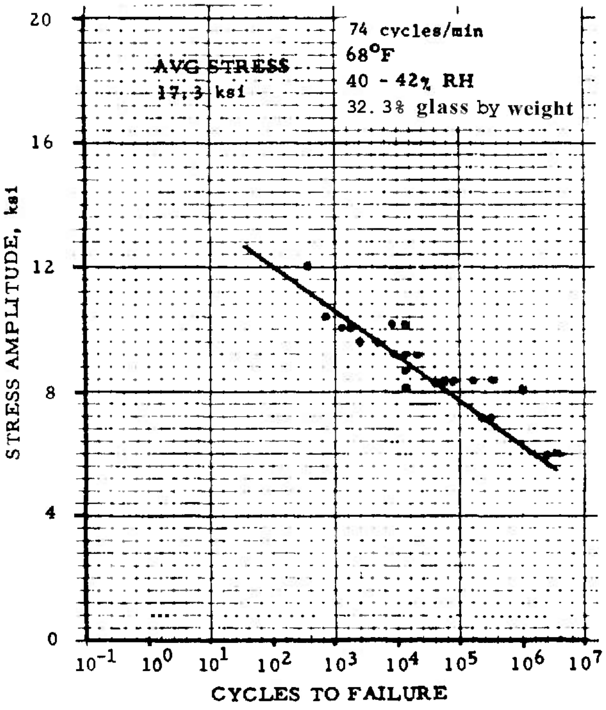
[1] Directed fiber or plenum chamber
[2] Preform from mat

TABLE 3-13

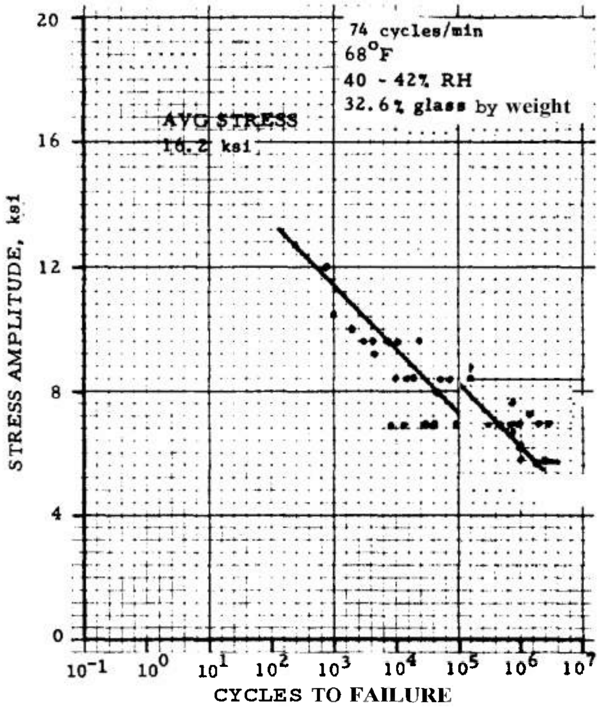
COMPARATIVE PROPERTIES OF CONTINUOUS STRAND MAT AND CHOPPED STRAND MAT LAMINATES[14]

Glass Content, wt, % — Approx. 30 Material Type:	Continuous Strand	Chopped Strand
Tensile		
max stress, dry, ksi	16.3	12.4
max stress, wet, ksi	15.8	14.4
Flexural		
max stress, dry, ksi	35.8	29.6
max stress, wet, ksi	32.4	30.4
modulus, dry, psi x 10^6	1.72	1.70
modulus, wet, psi x 10^6	1.42	1.38
Impact		
ft-lb/in. notch	14.5	12.4
Dielectric Strength		
V/mil, step-by-step cond 40/23/50	518	508
V/mil, step-by-step cond 48/50	523	541
Dielectric Breakdown		
kV, cond 40/23/50	79	79
kV, cond 48/50	49	40
Dielectric Constant		
1 MHz, cond 40/23/50	3.84	3.76
1 MHz, cond 48/50	4.10	4.09
60 Hz, cond 40/23/50	4.10	4.01
60 Hz, cond 48/50	5.07	5.47
Dissipation Factor		
%, 1 MHz, cond 40/23/50	1.35	1.41
%, 1 MHz, cond 48/50	2.27	2.79
%, 60 Hz, cond 40/23/50	1.55	1.53
%, 60 Hz, cond 48/50	9.46	14.4
Arc Resistance		
sec, cond 40/23/50	140	141

Notes:
1. Wet condition, 2-hr boil.
2. 4 ply, 1.25 oz mat, 0.125 in. thick.
3. Cure at 225" F, postcure at 200° F.
4. Resin uses styrene monomer.
5. Filler 30 percent of resin mix.



(A) Low Reactivity Resin



(B) High Reactivity Resin

Figure 3-6. S-N Diagram for Polyester-mat Laminate at Zero Mean Stress' [6]

TABLE 3-14

SUMMARY OF MECHANICAL PROPERTIES OF FERRO CP1304/7781-550 POLYESTER GLASS FABRIC[18]

Fabrication: Vacuum 14 psi	Pressure: 36 psi	Cure: 1 hr at 275° F
Physical Properties: Resin, wt, %, 34.8	Specific Gravity: 1.884	Voids: %, 1.8

Temperature		−65° F				75° F				160°F			
Condition		Dry		Wet		Dry		Wet		Dry		Wet	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	Sd	Avg	SD
Tensile													
max stress, ksi	0"	86.9	4.9	83.5	5.6	69.1	3.6	64.8	3.5	61.2	3.0	55.6	3.2
	90"	69.5	5.1	67.5	4.3	60.8	3.3	53.3	2.7	49.7	2.5	44.7	1.7
max strain, %	0"	3.41	0.09	3.20	0.15	2.65	0.15	2.41	0.11	2.32	0.13	2.08	0.08
	90°	2.94	0.15	2.70	0.13	2.42	0.13	2.24	0.08	2.13	0.15	1.84	0.10
modulus, psi x 10^6	0"	3.79	0.20	3.82	0.19	3.34	0.26	3.40	0.20	3.02	0.13	3.05	0.20
	90°	3.72	0.26	3.86	0.20	3.49	0.30	3.15	0.19	2.72	0.23	2.82	0.11
Compressive													
max stress, ksi	0"	80.5	6.1	75.8	5.1	72.6	3.34	65.9	4.3	50.5	3.5	41.8	3.3
	90"	68.0	2.0	64.6	4.4	60.7	2.00	55.6	3.4	44.7	3.0	36.8	1.9
max strain, %	0'	2.40	0.28	2.29	0.15	2.35	0.91	1.94	0.09	1.64	0.07	1.47	0.08
	90"	2.01	0.20	1.97	0.14	2.03	0.13	1.75	0.07	1.56	0.06	1.33	0.07
modulus, psi x 10^6	0"	3.61	0.28	3.62	0.21	3.29	0.14	3.68	0.26	3.36	0.32	3.00	0.23
	90"	3.66	0.28	3.58	0.22	3.26	0.13	3.57	0.29	3.05	0.26	2.96	0.24
Shear													
max stress, ksi	0°-90"	18.2	—	—	—	14.4	—	—	—	10.1	—	—	—
	±45°	—	—		—	35.2	—	—	—	—	—	—	—
Flexural													
max stress, ksi	0"	111.1	—	—	—	95.4	—	—	—	77.1	—	—	—
modulus, psi x 10^6	0°	3.47	—	—	—	3.25	—	—	—	3.05	--	—	—

TABLE 3-14 (Continued)

Fabrication: Vacuum 14 psi
Physical Properties: Resin, wt, %, 34.8

Pressure: 36 psi
Specific Gravity: 1.884

Cure: 1 hr at 275°F
Voids: %, 1.8

Temperature		−65"F				75°F				160°F			
Condition		Dry		Wet		Dry		Wet		Dry		Wet	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
Bearing													
max stress, ksi	0°	71.2	—	—	—	62.8	—	—	—	47.9	—	—	—
max stress at 4%, ksi	0"	39.7	—	—	—	36.4	—	—	—	28.1	—	—	—
Interlaminar Shear													
max stress, ksi	0°	7.28	—	—	—	7.10	—	—	—	5.76	—	—	—

SD = Standard Deviation
0° = Parallel to warp
90° = Perpendicular to warp
CP1304 = Ferro designation, 7781 is fabric style, 550 is fabric finish

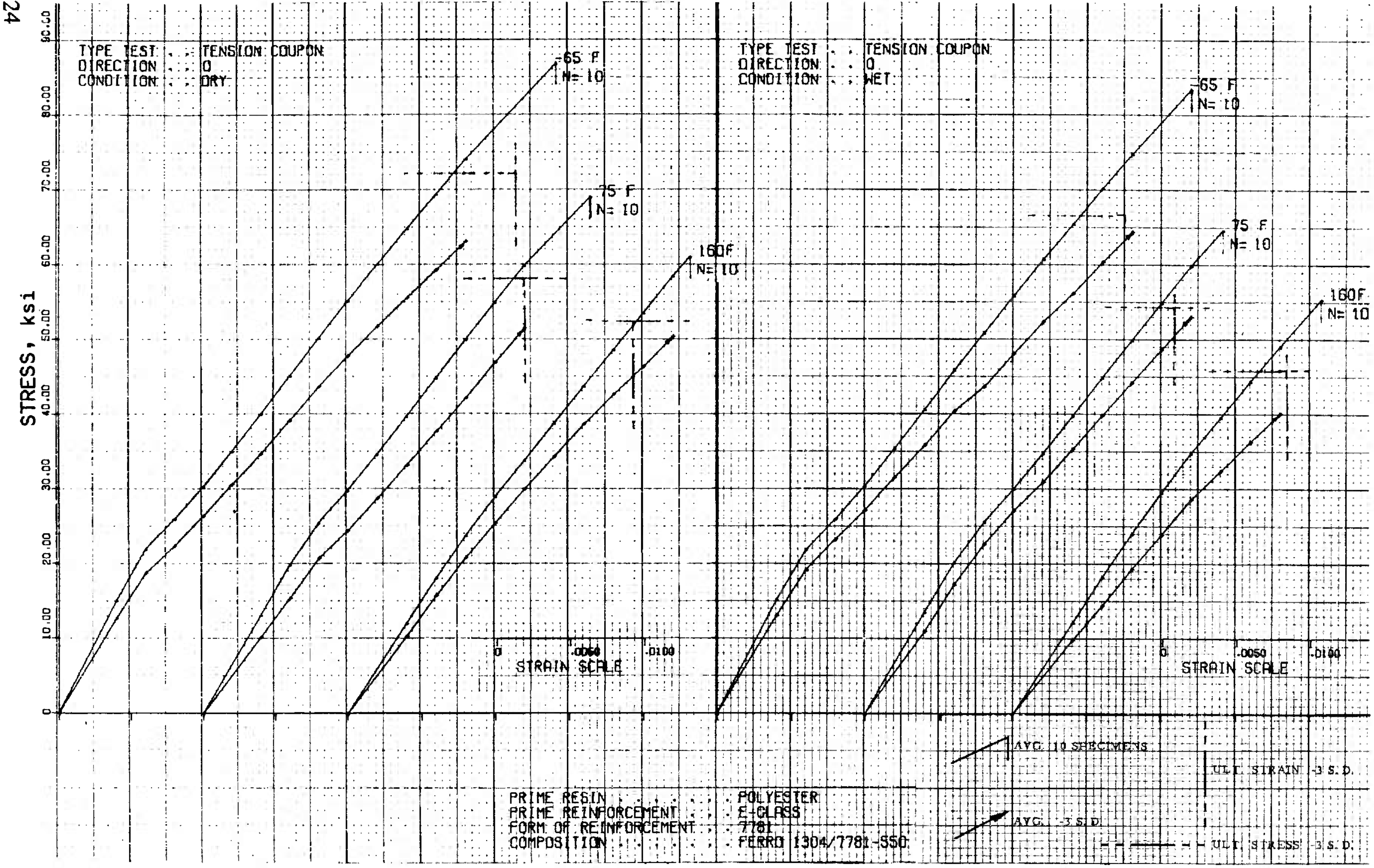


Figure 3-7. Tensile Stress-Strain for CP1304/7781 Fiberglass Polyester Loaded in the 0-deg Direction

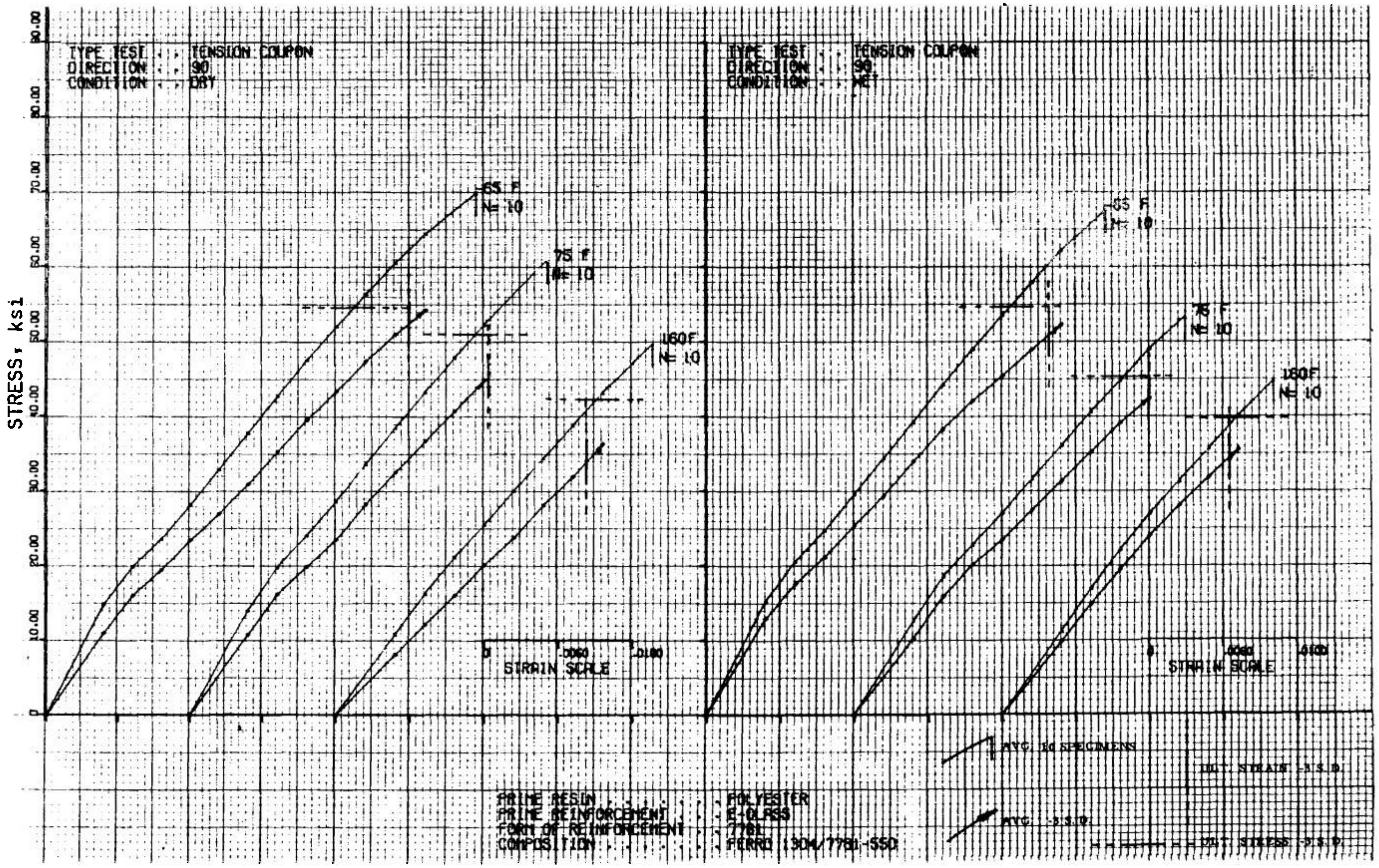


Figure 3-8. Tensile Stress-Strain for CP1304/7781 Fiberglass Polyester Loaded in the 90-deg Direction

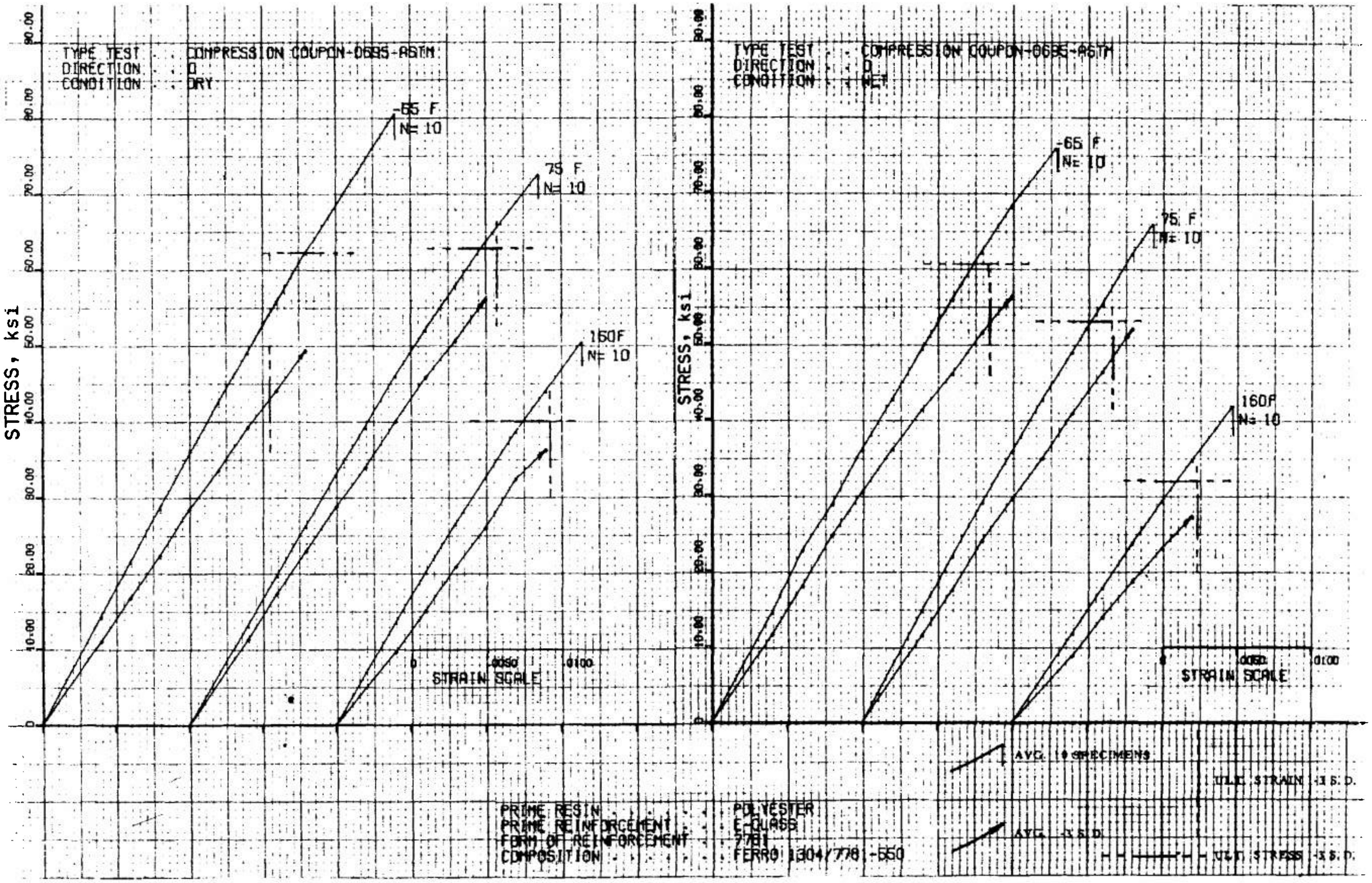


Figure 3-9. Compressive Stress-Strain for CP1304/7781 Fiberglass Polyester Loaded in the 0-deg Direction

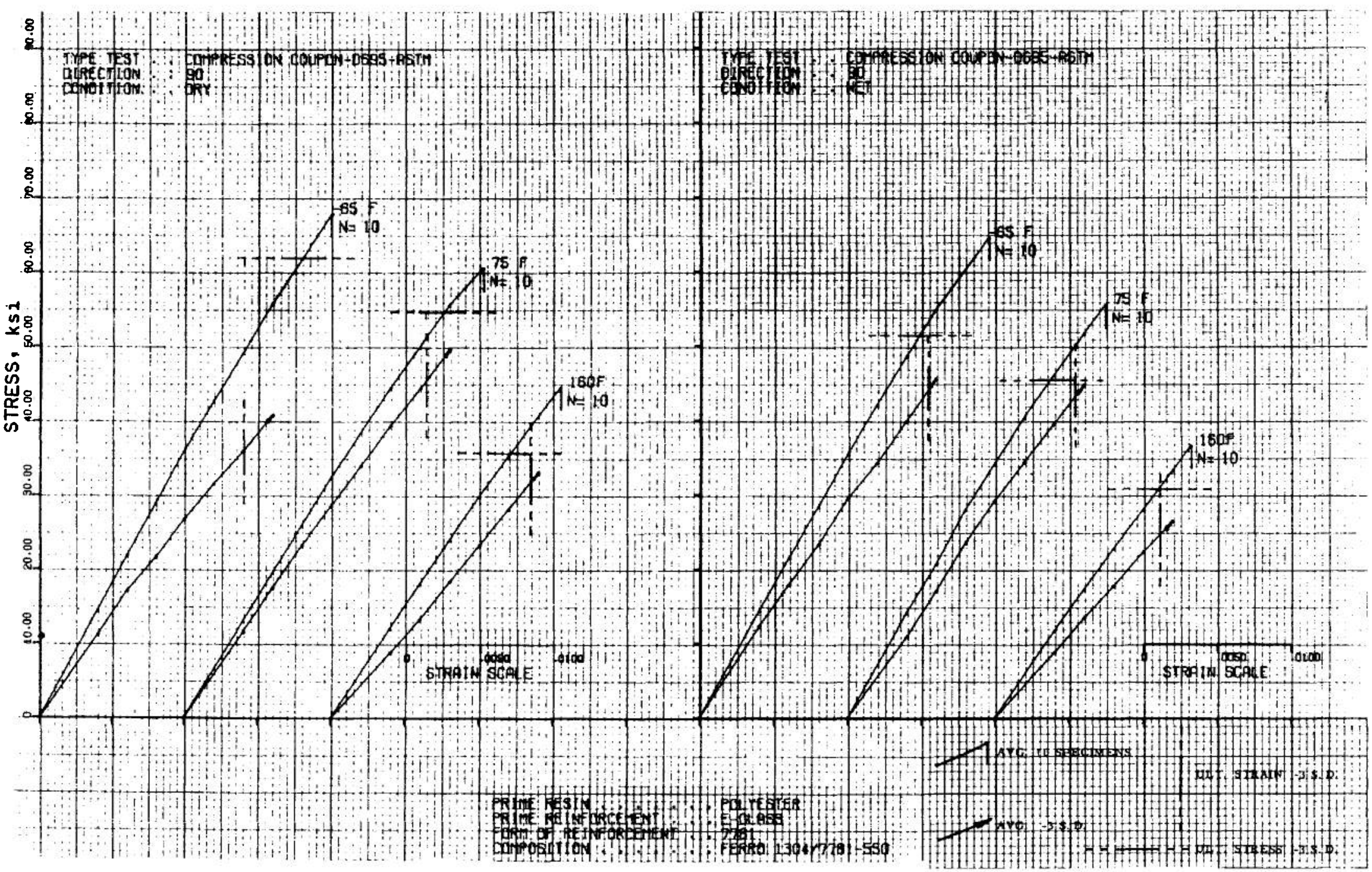


Figure 3-10. Compressive Stress-Strain for CP1304/7781 Fiberglass Polyester Loaded in the 90-deg Direction

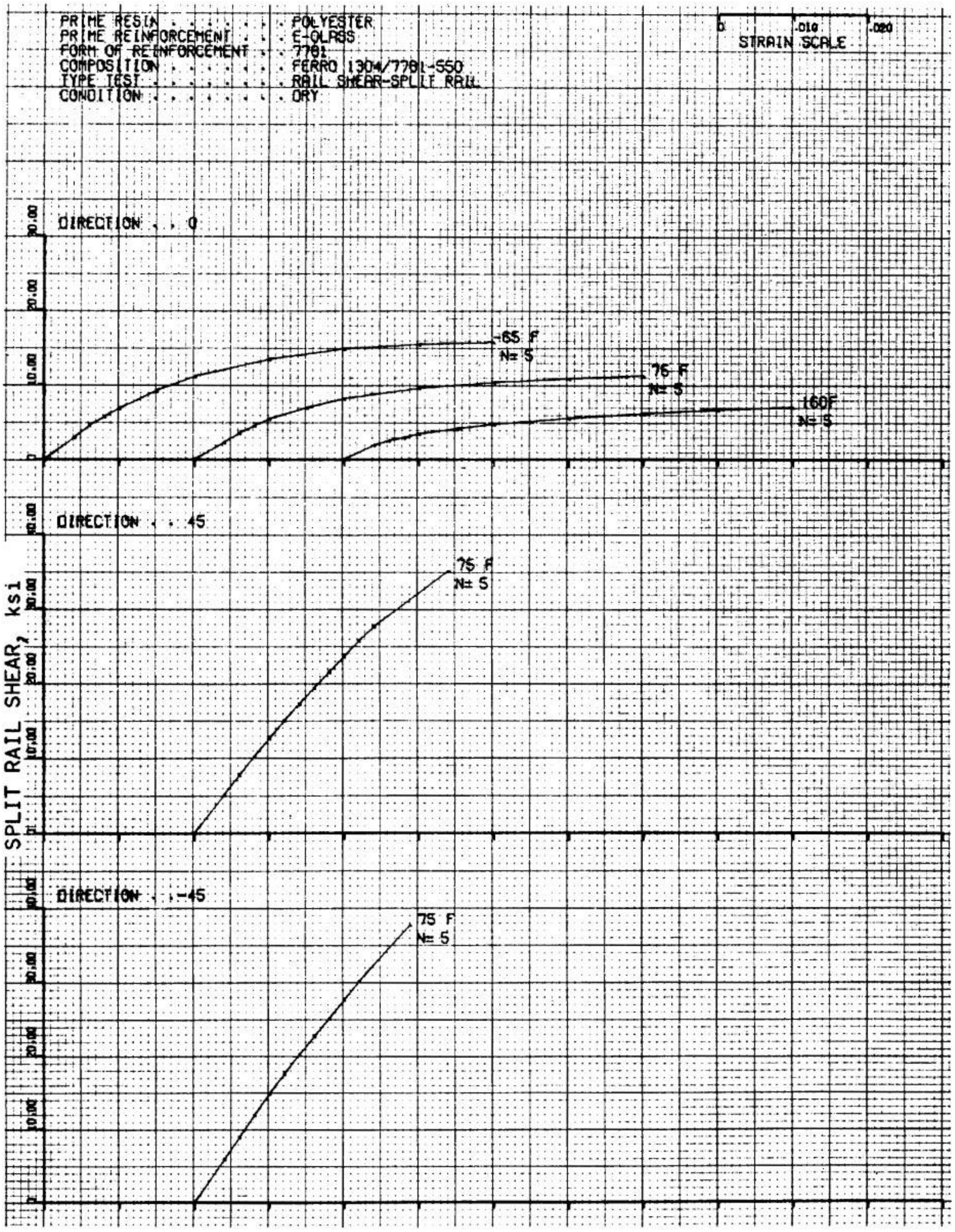


Figure 3-11. Rail Shear for CP1304/7781 Fiberglass Polyester

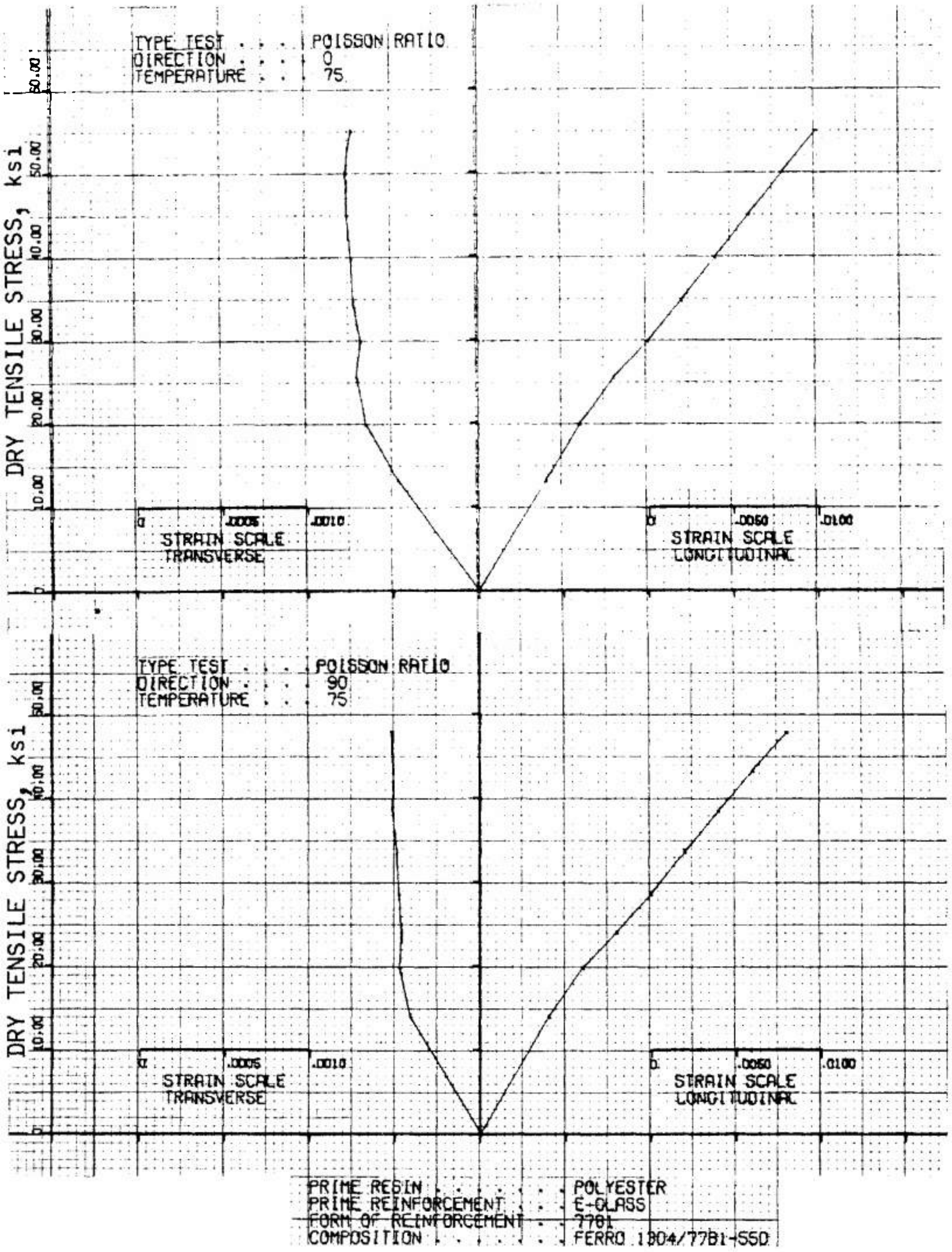


Figure 3-12 Poisson Effects for CP1304/7781 Fiberglass Polyester

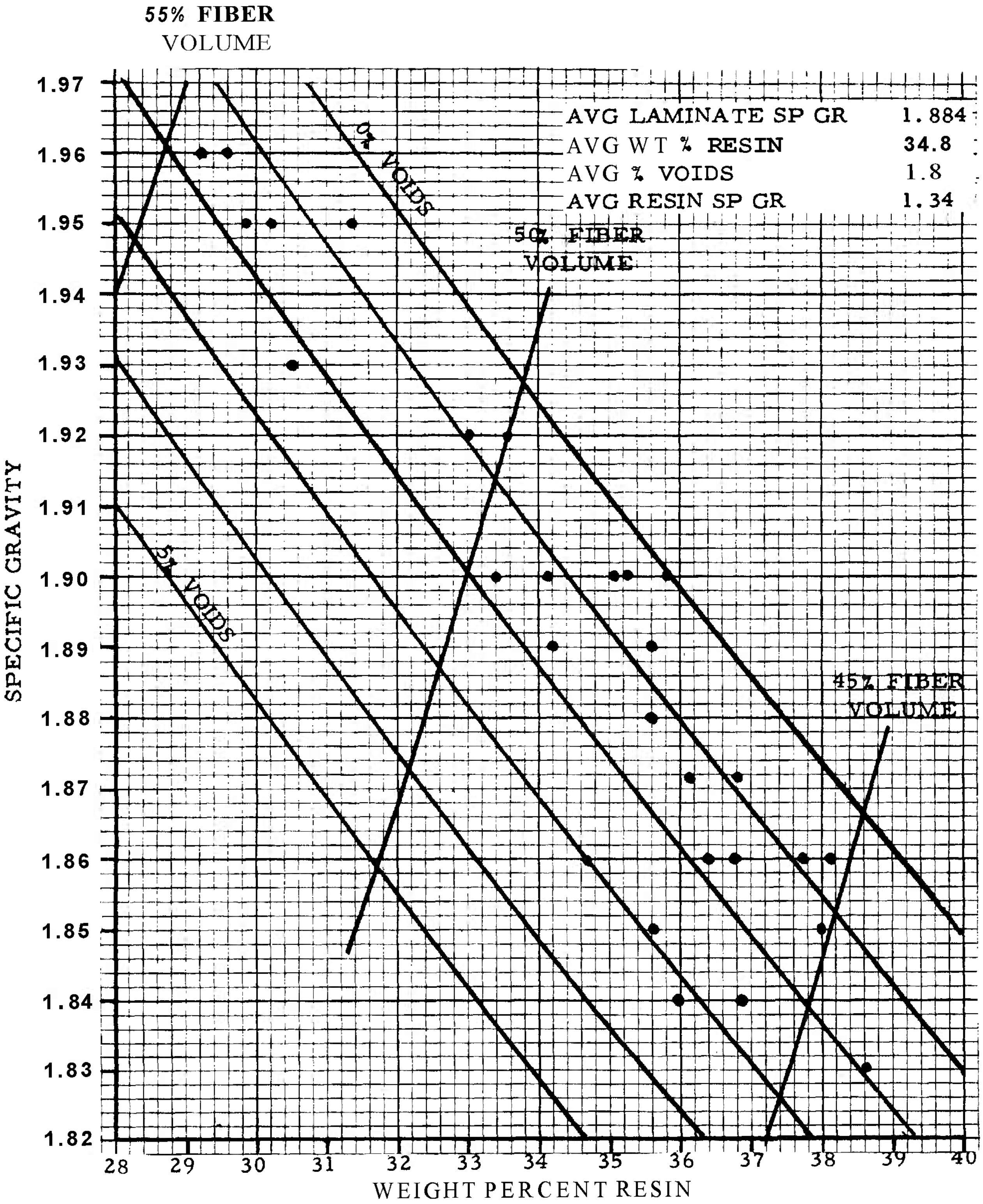


Figure 3-13. Voids vs Resin Content and Specific Gravity for CP1304/7781 Fiberglass Polyester

TABLE 3-15

IDENTIFICATION OF SHORT FIBER MOLDING COMPOUNDS'[9]

Material Type	Formulation			Typical Properties		
				Tensile	Flexural	
	%Resin	%Filler	%Glass	Max, ksi	Max, ksi	Modulus psi x 10^6
SMC						
General Purpose	28	42	30	15.0	30.0	1.8
Low Shrinkage	28	42	30	13.5	27.0	1.8
BMC						
General Purpose	30	55	15	6.0	13.5	1.2
Injection Grade	25	60	15	4.0	10.0	1.2
PREFORM-WET LAY-UP						
Fiber Spray-up	42	28	30	13.5	25.0	1.2
Chopped Mat	42	28	30	13.5	25.0	1.2
Continuous Mat	42	28	30	15.0	30.0	1.2
HAND LAY-UP						
Spray-up'	65	5	30	12.0	25.0	1.2
COLD PRESS						
General Purpose[2]	30	40	30	15.0	30.0	1.7

[1] Co-deposition of resin and glass, cure at ambient temperature, open-mold, no pressure.
[2] Formulated for ambient temperature cure, no heat input during cure cycle.

technique. These results are taken from MIL-HDBK-17, *Plastics for Aerospace Vehicles*, [7] and illustrate the tests used in that document for characterizing a specific material. Many of the characteristics found in mat preform, BMC, and SMC materials are analogous to the behavior of the fabric laminates.

3-3.6 CLASSIFICATION SYSTEM FOR SHORT FIBER POLYESTER BASE

A plan has been suggested for identifying and coding the more commonly used reinforced polyester plastics, based upon key mechanical properties and formulation. Table 3-15 lists the various material types, properties, and formulation range. Such a system serves as a starting point in comparing materials and lists properties that can be readily achieved within the plastics industry. Obviously, the proposed format requires modifications and additions to include other key properties and to cover a broader range of fillers, reinforcements, and resin types.

3 4 PROPERTIES OF SHORT FIBER COMPOUNDS BASED ON EPOXY RESIN SYSTEMS

Test results are given for three fiber glass/epoxy chopped roving compounds. Included are two commercial products and one material fabricated by an "in-plant" operation. The "in-plant" material, designated as 470/438-1/2, uses an S-type glass roving, which has superior properties than the more common E-glass fiber.

Properties of the 470/438-1/2 compound are shown in Table 3-16 and Figs. 3-14 through 3-17. Table 3-17 lists the design

TABLE 3-16

MECHANICAL PROPERTIES OF 470/438-1/2 CHOPPED GLASS/EPOXY MOLDING COMPOUND[20]

Mold Temp: 300°F Mold Pressure: 1000 psi Cure: 20 min
Resin: Den 438 Epoxy Novolac, 31.8% by Wght.
Glass: OCF 470AA S-2 0.5 in. length Specific Gravity: 1.890

PROPERTY	TEMPERATURE °F			STANDARD[1] DEVIATION
	-80	75	160	
Tensile				
max stress, ksi	24.2	20.1	17.4	2.2
modulus, psi x 10^6	3.74	3.41	2.57	0.25
Compressive				
max stress, ksi	49.1	36.5	24.0	3.9
modulus, psi x 10^6	3.06	2.85	2.34	0.20
In-plane Shear				
max stress, ksi	23.7	17.4	15.4	1.1
modulus, psi x 10^6	1.25	1.13	1.14	0.06
Flexural				
max stress, ksi	54.2	50.3	34.5	7.2
modulus, psi x 10^6	3.04	3.35	2.47	0.22
Interlaminar Shear				
max stress, ksi	7.45	7.83	5.10	0.68
Bearing				
yield, ksi	43.8	44.0	29.5	4.9

[1] Includes data at all three temperatures.

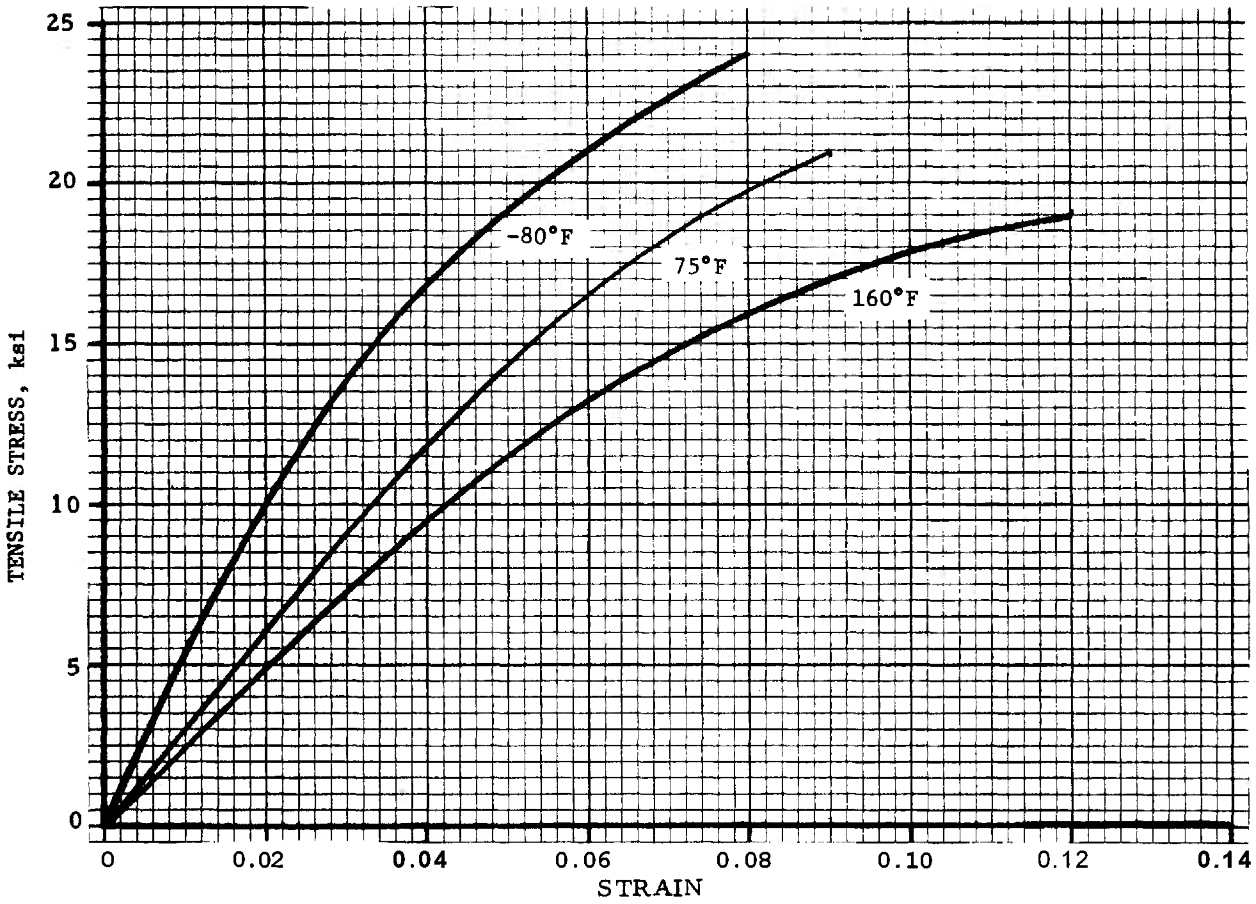


Figure 3-14. Tensile Stress-Strain for 470/438-1/2 Molding Compound

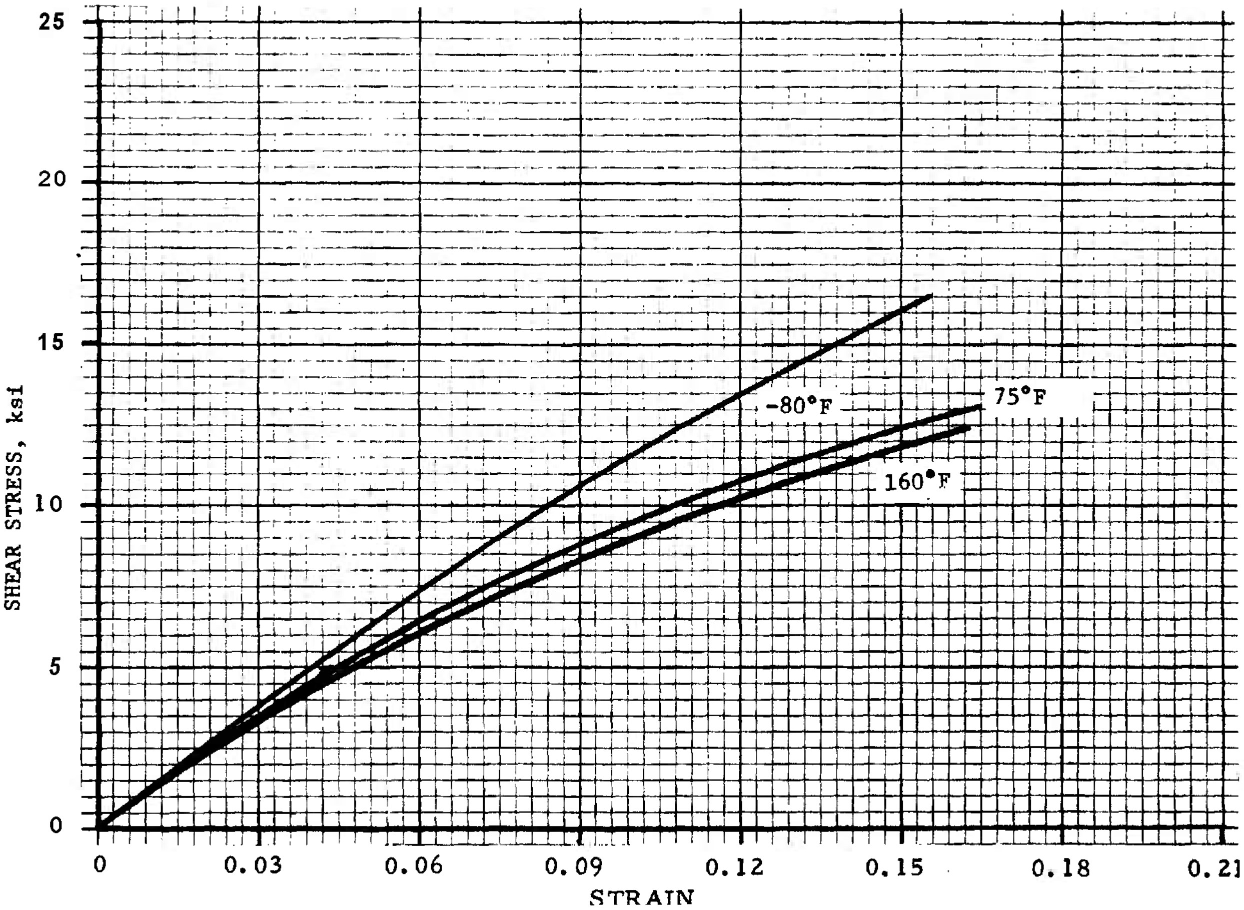


Figure 3-15. Shear Stress-Strain for 470/438-1/2 Molding Compound

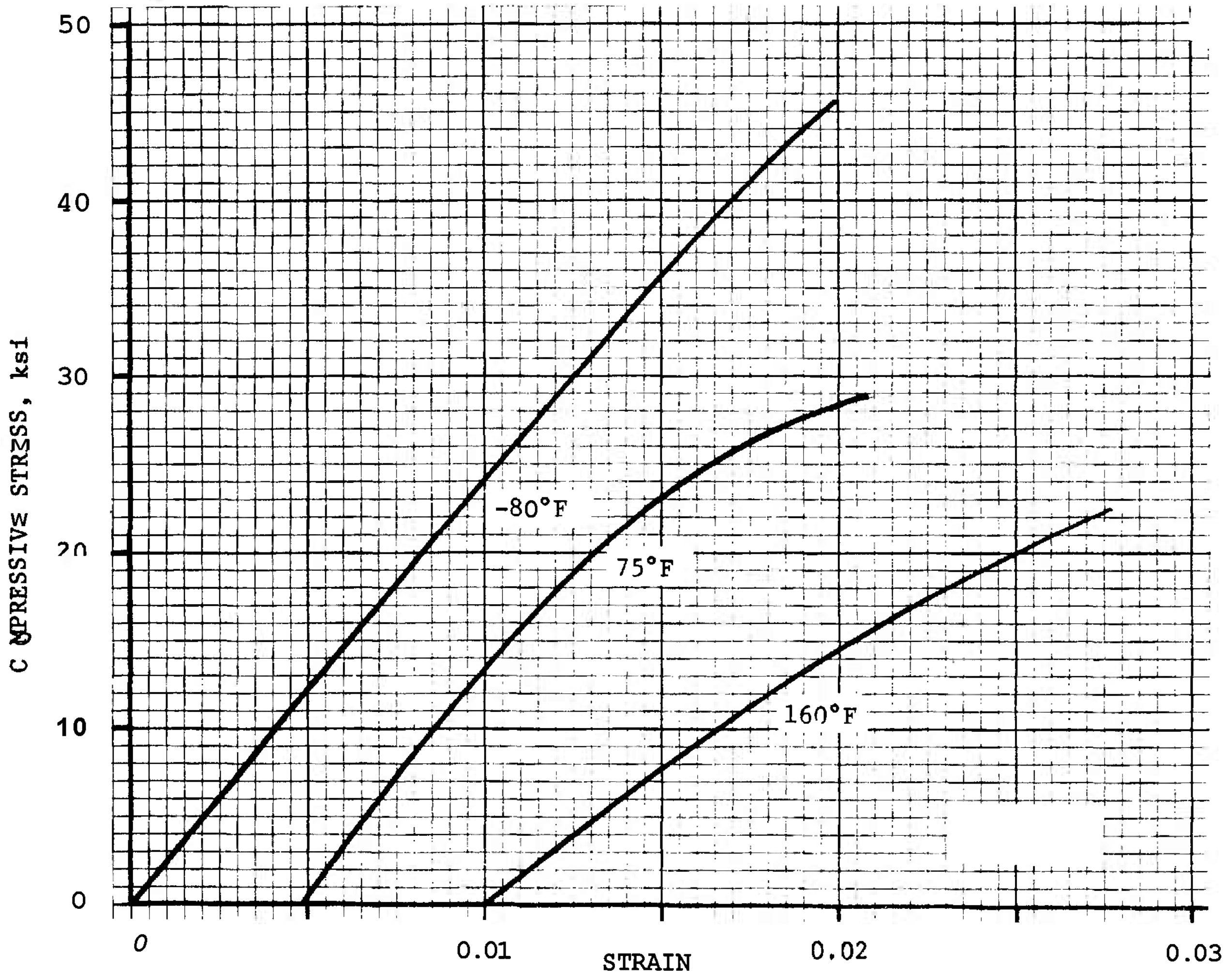


Figure 3-16. Compressive Stress-Strain for 470/438-1/2 Molding Compound

TABLE 3-17

COMPARISON OF AVERAGE AND MINIMUM VALUES WITH CALCULATED DESIGN ALLOWABLES FOR 470/438-1/2 CHOPPED GLASS/EPOXY MOLDING COMPOUND**

PROPERTY	Test Temp, °F	Avg Test Value, ksi	Min Test Value, ksi	Design Allowable	
				A-Basis[1]	B-Basis[2]
Tensile Strength	−80	24.2	19.3	16.3	19.3
	75	20.1	18.2	12.1	15.1
	160	17.4	14.6	5.4	12.4
Compressive Strength	−80	49.1	42.1	35.2	40.5
	75	36.5	31.3	[illegible]	27.9
	160	24.0	21.0	10.1	15.4
In-plane Shear	−80	23.7	22.7	19.5	21.1
	75	17.4	15.2	13.3	14.8
	160	15.4	14.8	11.3	12.9
Flexural Strength	−80	54.2	48.3	28.3	38.1
	75	50.3	42.4	24.4	34.3
	160	34.5	27.5	8.6	18.4
Interlaminar Shear	−80	7.5	6.4	5.0	5.9
	75	7.8	6.9	5.4	6.3
	160	5.1	4.4	2.7	3.6
Bearing Strength	−80	81.5	78.1	58.6	67.3
	75	66.0	56.0	43.3	52.0
	160	43.6	38.2	20.8	29.4

[1] A-Basis. Value above which 99% of population is expected to fall, with 95% confidence.

[2] B-Basis. Value above which 90% of population is expected to fall, with 95% confidence.

allowables assigned to this material, and compares them with average and minimum test values.

Table 3-18 and Fig. 3-18 summarize the data for Fiberite E-360, glass/epoxy chopped fiber.

Similar data for **U.S.** Polymeric EM7302 are shown in Table 3-19 and Figs. 3-19, 3-20 and 3-21.

Table 3-20 is based on supplier's data for the two materials and compares these values with the requirements of MIL-P-46069, *Molding Plastic, Glass/Epoxy Pre-Mix.*

Table 3-21 compares the effect of resin type on material mechanical properties and heat deflection temperatures. Resin type B, an epoxy novolac, generally has superior high temperature properties than the bisphenol-A type, although its properties at ambient temperature are lower.

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TABLE 3-18

MECHANICAL PROPERTIES OF E-360 CHOPPED GLASS/EPOXY MOLDING COMPOUND[22]

Molder: Hughes Aircraft	**Supplier: Fiberite Corp.**
Resin Content, wt, %: 33.7 − 36.3	**Specific Gravity: 1.81 − 1.86**

TEMPERATURE	**−65"F**		**74° F**		**270° F**	
	Avg[1]	**SD[2]**	**Avg[1]**	**SD[2]**	**Avg[1]**	**DS[2]**
Tensile						
max stress, ksi	29.5	4.5	23.0	3.5	19.6	3.6
modulus, psi x 10^6	3.48	0.58	3.93	0.70	3.28	0.71
max strain, %	0.97	0.15	0.76	0.18	0.84	0.23
Compressive						
max stress, ksi	42.4	3.7	42.4	4.8	18.4	3.6
modulus, psi x 10^6	–	–	2.72	0.22	–	–
max strain, %	–	–	1.68	0.10	–	–
In-plane Shear						
max stress, ksi	19.4	1.89	17.7	2.3	16.2	0.9
modulus, psi x 10^6	1.38	0.45	0.79	0.06	1.53	0.68
max strain, rad x 10^{-2}	2.4	0.82	3.4	0.48	1.9	0.42
Flexural						
max stress, ksi	62.4	9.2	60.2	11.6	28.6	5.6
modulus, psi x 10^6	3.13	0.29	3.30	0.30	1.88	0.37
max strain, %	2.34	0.36	2.31	0.25	2.08	0.19
Bearing						
max stress, ksi	78.8	5.2	57.6	5.0	32.2	3.1
stress at 4%, ksi	22.5	2.0	21.3	2.6	15.4	1.3
Interlaminar Shear						
max stress, ksi	–	–	5.92	–	–	–
Impact Resistance						
Izod, ft-lb/in.	64.3	9.2	57.2	8.6	36.9	9.7

[1] Average 15 specimens, except for 10 specimens for in-plane shear
[2] SD = Standard Deviation

TABLE 3-19

MECHANICAL PROPERTIES OF EM7302 CHOPPED GLASS/EPOXY MOLDING COMPOUND[23]

Molder: Hughes Aircraft Co.	Supplier: U.S. Polymeric
Mold Temperature: 310"F	Mold Pressure: 2800 psi
Weight Percent Resin: 29.1	Cure: 30 min
Specific Gravity: 1.93	Glass Length: 0.5 in.

TEMPERATURE	–65° F		73"F		270"F	
	Avg[1]	SD[2]	Avg[1]	SD[2]	Avg[1]	SD[2]
Tensile						
max stress, ksi	24.6	5.3	21.3	3.2	17.6	3.3
modulus, psi x 10^6	4.45	0.55	3.86	0.33	3.15	0.45
Compression						
max stress, ksi	44.3	–	45.2	9.8	19.0	5.1
modulus, psi x 10^6	2.70	0.30	2.80	0.50	1.70	0.40
In-plane Shear						
max stress, ksi	–	–	19.5	1.8	–	–
modulus, psi x 10^6	–	–	0.71	0.04	–	–
Flexural						
max stress, ksi	63.7	11.5	55.5	8.7	34.3	9.3
modulus, psi x 10^6	4.42	0.57	3.30	0.29	2.57	0.64
Bearing						
max stress[3], ksi	37.5	8.4	27.6	6.1	19.3	3.4
max stress[4], ksi	49.0	13.0	41.5	6.7	29.3	3.7
Impact Resistance						
ft-lb/in. notch	>33	–	>31	–	27	3.6

[1] Average - 15 specimens
[2] SD = Standard Deviation
[3] Hole to *edge* ratio = 1.5
[4] Hole to edge ratio = 2.0

TABLE 3-20

PHYSICAL PROPERTIES OF CHOPPED GLASS/3-20 EPOXY MOLDING COMPOUNDS

Reference: Product Data Sheets

Supplier	U.S. Polymeric	Fiberite	MIL-P-46069
Material Designation	EM-7302	E-360	–
Resin Type	Modified Epoxy Novolac	Epoxy	Epoxy
Resin weight, %	36	–	37 ± 3
Glass Fiber Length, in.	0.5	"Long"	–
Specific Gravity	2.0 (max)	1.85	–
Tensile, max stress, ksi	25.0	25.0	22.0
modulus, psi x 10^6	3.0	–	–
Compressive, max stress, ksi	40.5	–	–
Flexural, max stress, ksi	65.0	64.0	50.0, min
modulus, psi x 10^6	4.1	3.5	2.6, min
Impact Resistance, ft-lb/in. notch	30	30	18 min
Dielectric Strength, V/mil			
short time, dry	439	400	–
step-by-step, dry	405	380	–
short time, wet	440	–	–
step-by-step, wet	344	–	–
Dielectric Constant,			
1 MHz, dry, RT	5.4	4.5	–
1 MHz, 383°F	–	4.8	–
Dissipation Factor, 1 MHz RT	0.014	0.0015	–
Thermal Conductivity, Btu/hr-ft^2-(°F/in.)	1.5	–	–
Coef. Thermal Expansion, μin./in.-°F			
parallel laminate	19.4	12.0	–
perpendicular laminate	6.2	–	–

TABLE 3-21

EFFECT OF RESIN TYPE ON CHOPPED GLASS/EPOXY MOLDING COMPOUNDS PROPERTIES[3-24]

Material Type:	Chopped Prepeg Roving/Epoxy
Resin System:	A. Bisphenol-A, 0.2 epoxy equivalent per 100 g B. Epoxy cresol novolac, 0.4 epoxy equivalent per 100 g C. 50/50 blend of A and B, 0.3 epoxy equivalent per 100 g

Reinforcement: 30 End E-glass roving, chopped to 0.5 in. length
Fiber Content, Wt, %: Apptox. 60

Resin	A	B	C
Specific Gravity	1.9	1.8	1.8
Tensile			
max stress, ksi	25.6	15.4	22.5
modulus, psi x 10^6	4.1	3.5	3.2
max strain, %	0.69	0.61	0.67
Compressive			
max stress, ksi	34.5	29.6	35.9
modulus, psi x 10^6	2.6	2.1	2.2
Flexural			
max stress, ksi	44.8	44.0	41.0
modulus, psi x 10^6	3.3	3.4	3.0
Impact Resistance			
ft-lb/in. notch	30.5	29.5	30.5
Deflection Temperature			
264 psi, °F	489	>572	>572

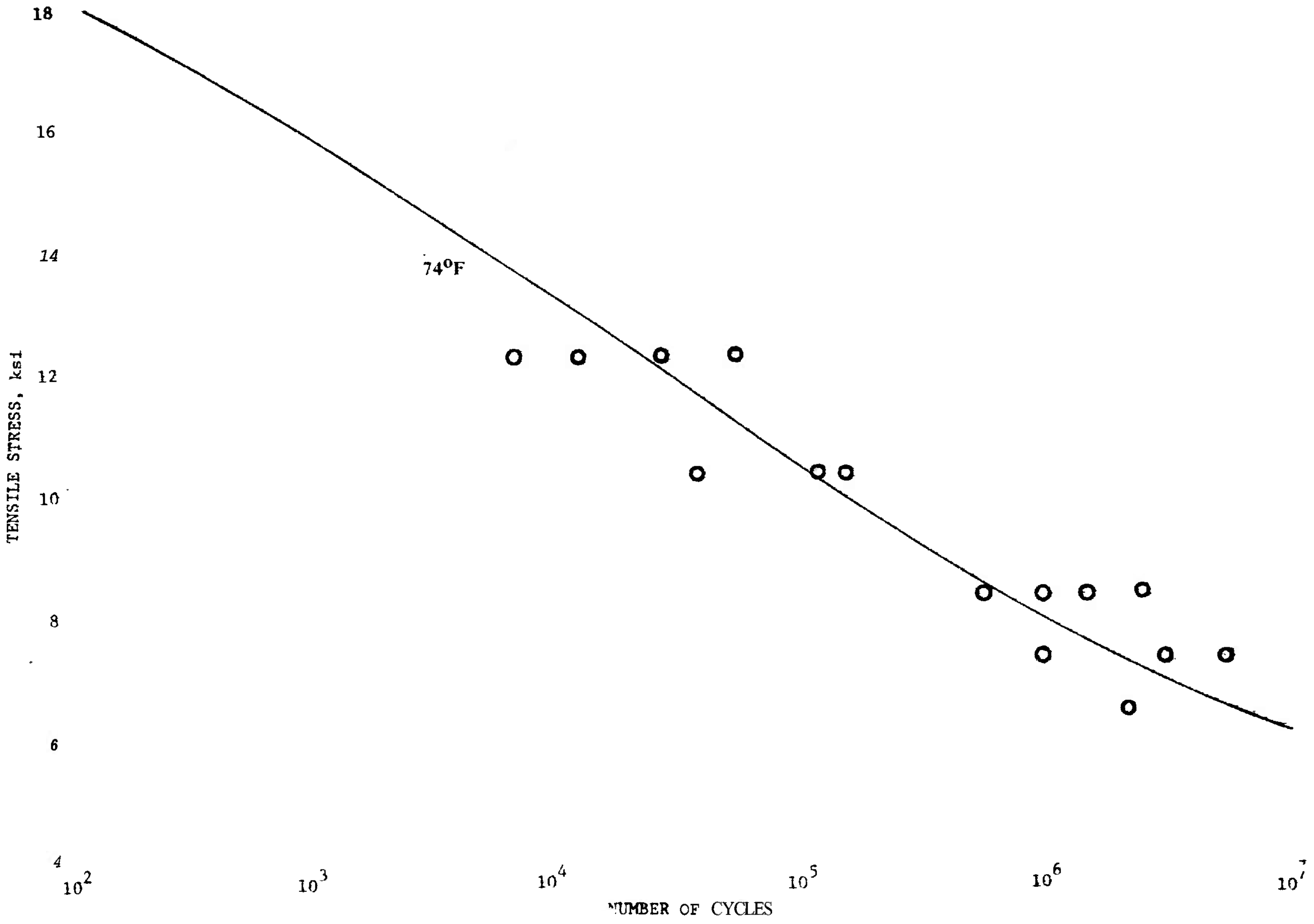

Figure 3-17. Tensile Fatigue Curve for 470/438 Composite[21]

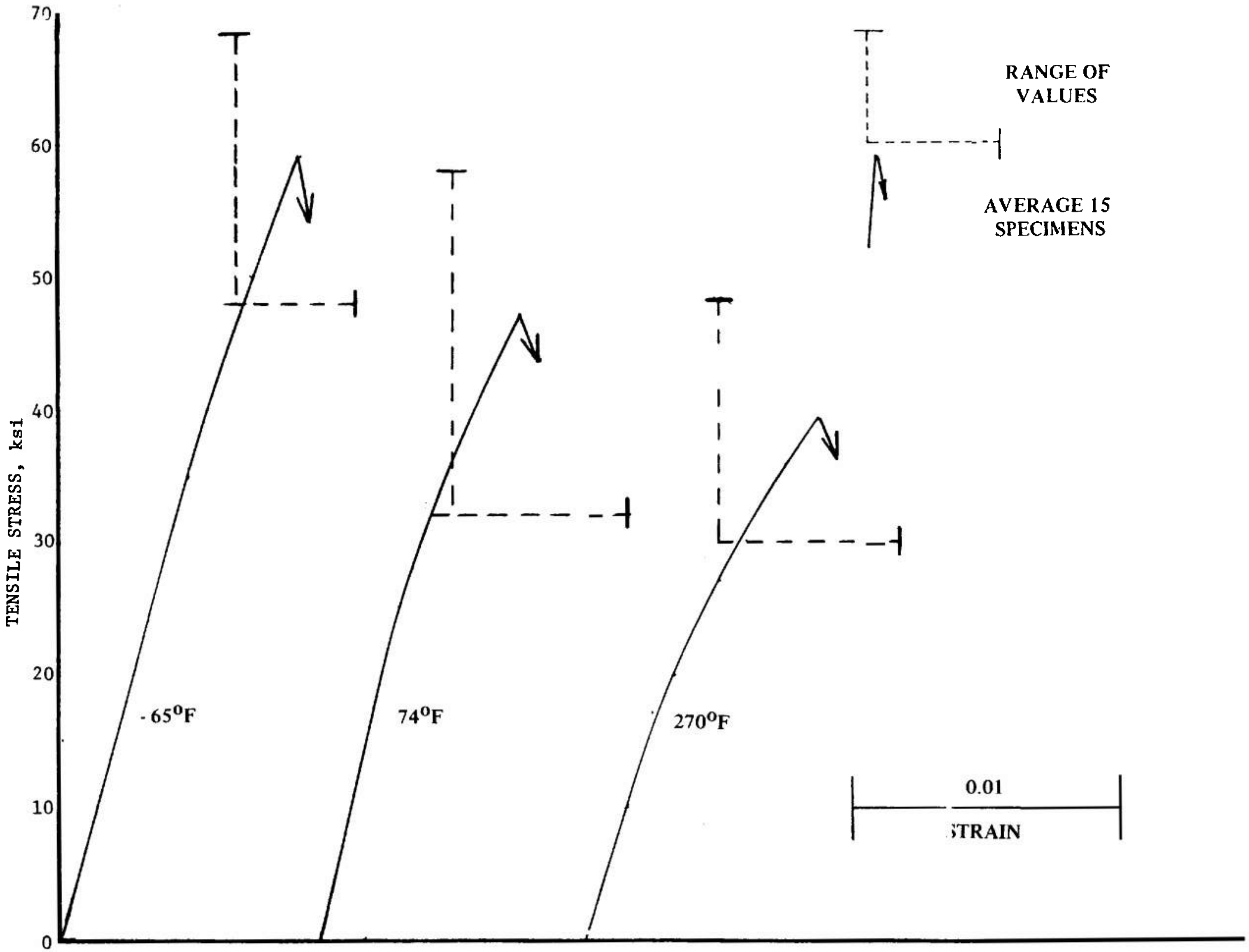

Figure 3-18. Typical Tensile Stress-Strain for E-360 Molding Compound[22]

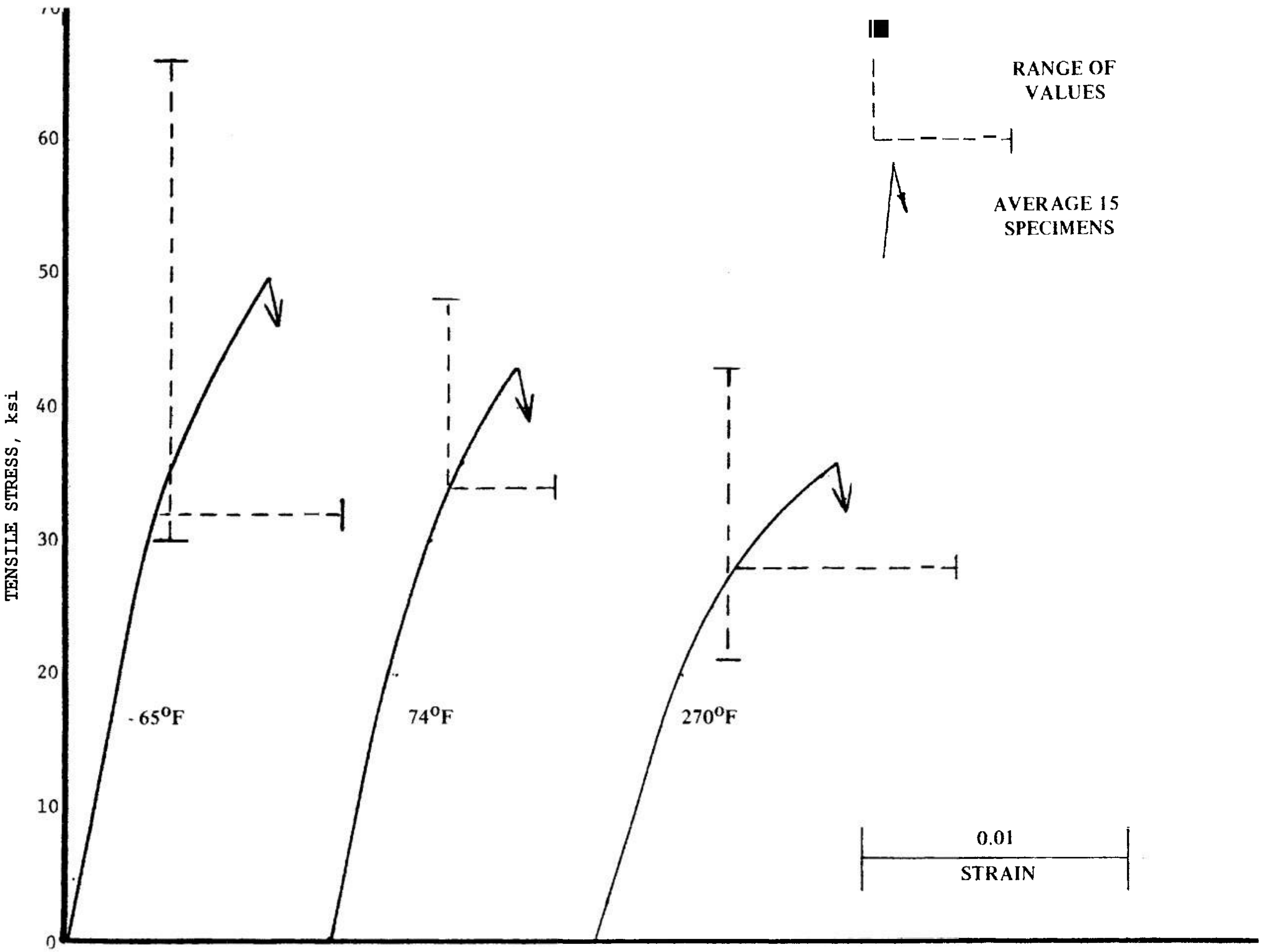

Figure 3-19. Typical Tensile Stress-Strain for EM 7302 Molding Compound[23]

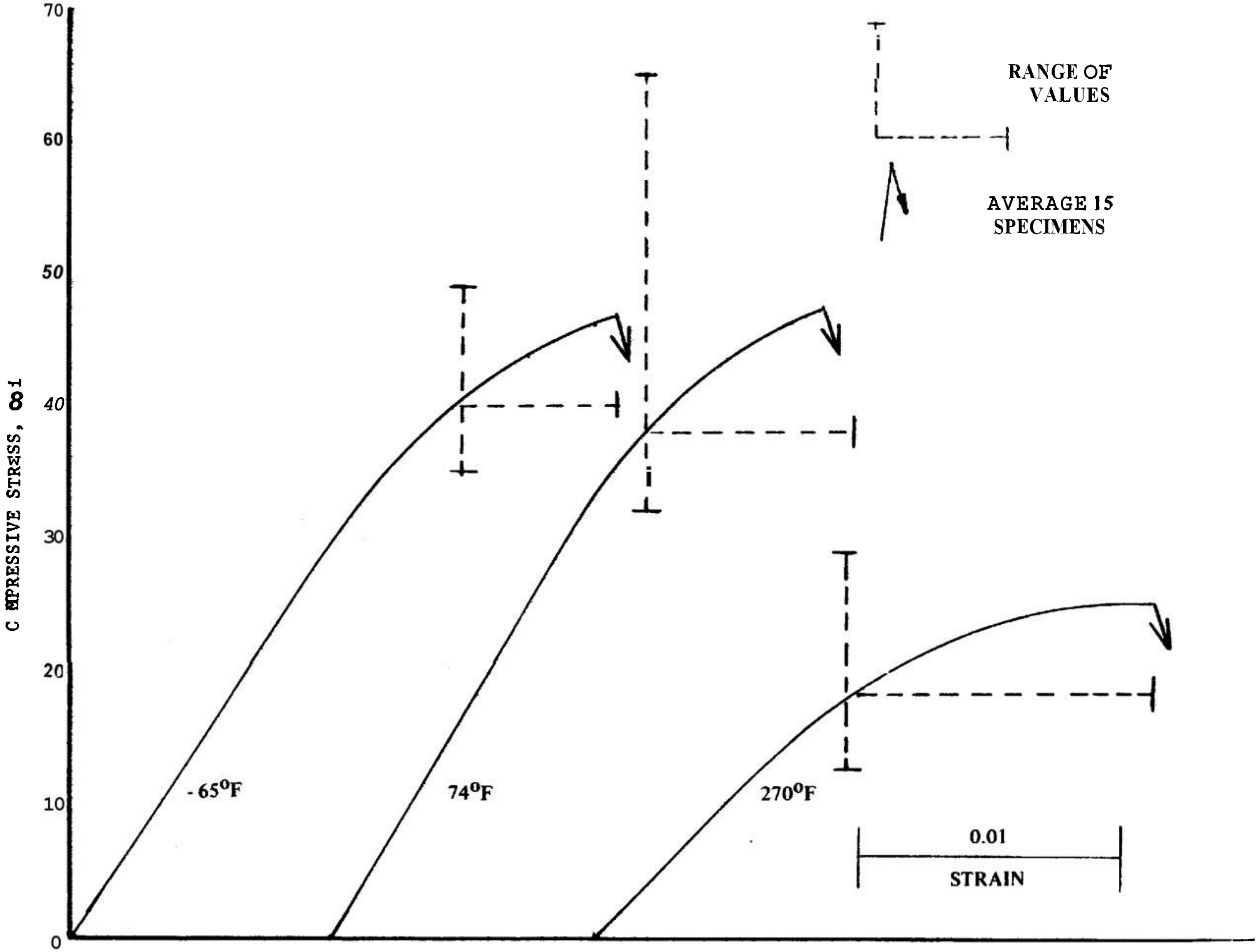

Figure 3-20. Typical Compressive Stress-Strain for EM 7302 Molding Compound[23]

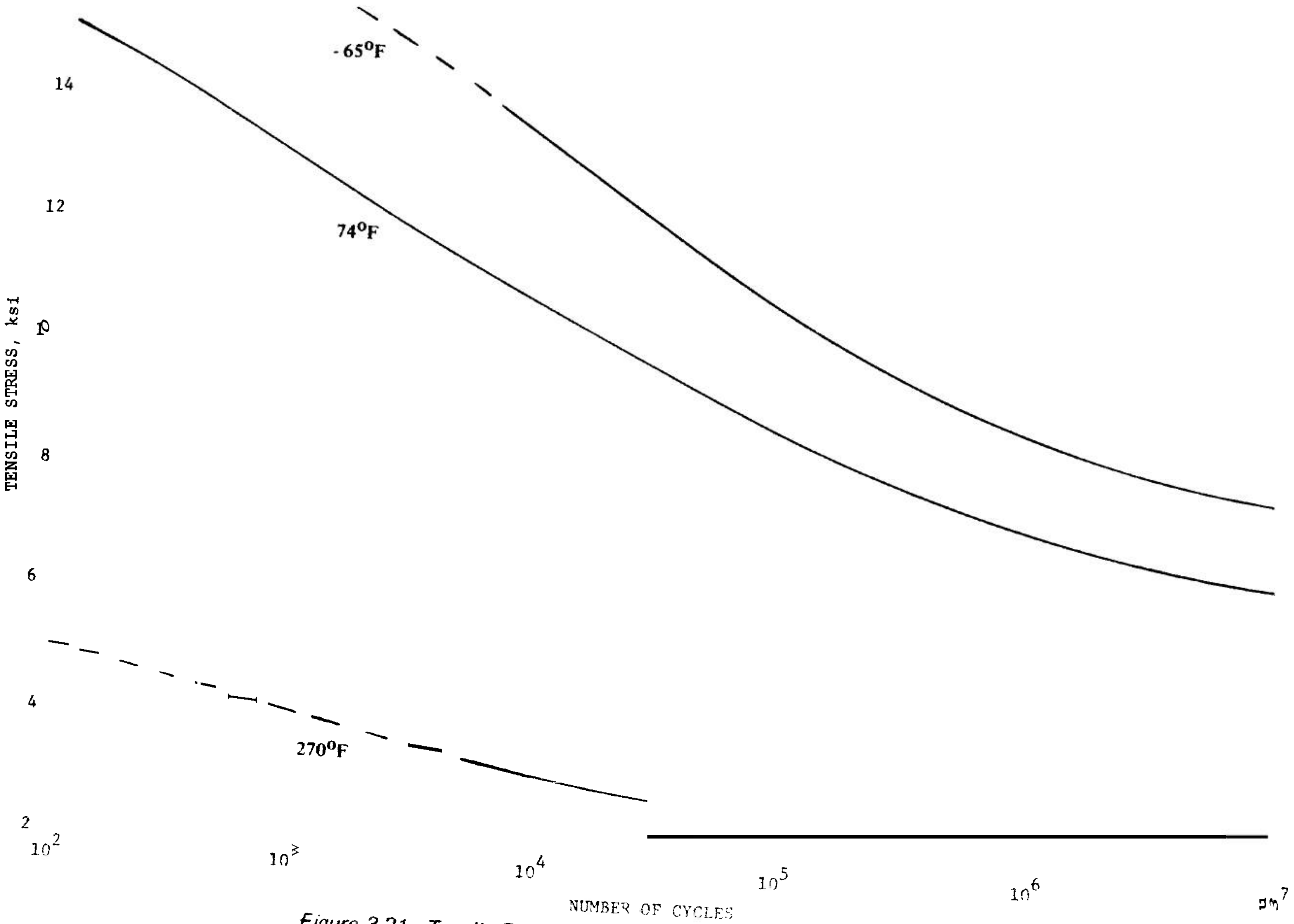

Figure 3-21. Tensile Fatigue Curves for EM 7302 Molding Compound

CHAPTER 4

STRENGTH AND STIFFNESS OF SHORT FIBER COMPOSITES

4-1 INTRODUCTION

Analytical procedures for determining stress-deformation, instability, laminate optimization, and other characteristics of continuous aligned (filamentary) composites have reached a high degree of sophistication and have become indispensable tools in solving problems in design and stress analysis[1,2]. For the short (discontinuous) fiber composites, the applications of such theoretical methods as yet have not been completely established. The finite fiber length, distribution of the fiber in space, and stress concentrations at fiber ends complicate the analysis. Procedures generally are limited to determination of the strength and elastic moduli of the composite. The composite models for analysis may be two-dimensional (planar) or threedimensional. The planar model appears well suited to compression molded structures that tend to be oriented in two-dimensional arrays. A three-dimensional model applies to injection molding. The composite also may be oriented randomly or exhibit varying degrees of anisotrophy.

Procedures for determining the elastic constants of random short fiber composites have been carried out in several ways: (1) experimentation, (2) statistical averaging of fiber distribution or inter-fiber bond, (3) integration of unidirectional properties, and (4) by analogy with the quasi-isotropic laminate. While all of these methods have deficiencies, the fourth is the most versatile since it may be applied to thermal properties and mechanical properties other than stress-strain relationships[3]. It has been used to estimate composite strengths for various fiber and matrix combinations. Such estimates have significance in understanding material behavior and potentialities, but require further experimental verification before acceptance as design tools.

Composite material systems used for models are usually fiberglass or graphite fibers with epoxy matrices or fiberglass with various thermoplastics. One drawback of the analysis is that provisions are not made for a three-component material system or for the effects of fillers on the matrix properties.

4-2 QUASI-ISOTROPIC LAMINATE ANALOGY

The procedure outlined in this paragraph is based on the method proposed by Halpin and Jerina[4] for determining the strengths of discontinuous fiber composites. It has been demonstrated that short fiber systems behave as a two-dimensional random array and can be modeled as a quasi-isotropic laminate. The assumption is made that a linear strain field exists through the thickness and that it is compatible with classical laminated plate theory.

The stress-strain response of a unidirectional ply or laminate is characterized by a high modulus, elongation, and strain in the longitudinal direction (parallel to the fibers). In the transverse direction (perpendicular to the fibers) the modulus, elongation, and strength are relatively low. When the plies are laminated at various orientations, the stress-strain relation assumes a position intermediate to the longitudinal and transverse response. Fig. 4-1 illustrates the effect as the number of ply orientations is increased for a continuously reinforced laminate. As shown, the laminate strength approaches the isotropic

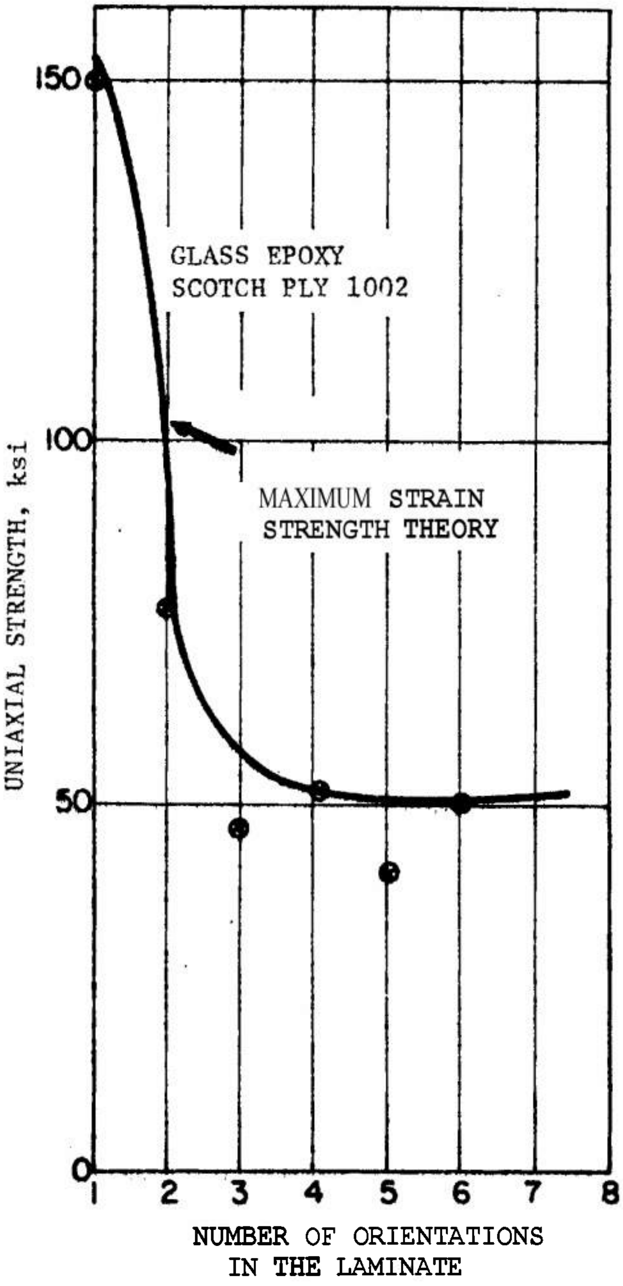

Figure 4-1, Strength as a Function of the Number of Orientations in a Continuous Reinforced Laminate

condition asymtotically and four ply directions (0 deg, 90 deg, +45 deg, −45 deg) are adequate for isotropic simulation. The laminate is balanced and symmetrical; in conventional notation it is designated as a $(0°|90°|\pm45°)_S$ laminate.

Maximum strain theory[5] is modified to predict strengths for the case of randomly oriented short fiber composites. As a first step, the longitudinal stiffness of an aligned short fiber ply is calculated from the properties of the fiber and matrix. The Halpin-Tsai

TABLE 4-1

HALPIN-TSAI EQUATIONS[2]

Elastic Constant	Notation	Equation
Young's modulus parallel to fiber direction, lb/in.^{2}	E_{11}	$E_{11} \approx E_f V_f + E_m V_m$
Young's modulus transverse to fiber direction, lb/in.^{2}	E_{22}	$E_{22} = \dfrac{E_m [1 + \zeta V_f (E_f/E_m - 1)(E_f/E_m + \zeta)]}{1 - V_f (E_f/E_m - 1)(E_f/E_m + \zeta)}$
Shear modulus for shear stress-strain in the 1-2 phase	G_{12}	$G_{12} = \dfrac{G_m [1 + \zeta V_f (G_f/G_m - 1)(G_f/G_m + \zeta)]}{1 - V_f (G_f/G_m - 1)(G_f/G_m + \zeta)}$
Poisson's ratio relating contraction in the transverse direction due to extension in the fiber direction	ν_{12}	$\nu_{12} \approx \nu_f V_f + \nu_m V_m$

V = Volume Fraction

Subscripts: f = fiber

m = matrix

ζ = a measure of reinfacement, dependent on boundary conditions

equations (Table 4-1) are used for this purpose. It is noted that the longitudinal modulus and the associated Poisson's ratio are approximated by the "rule of mixtures". This is not the case for the transverse and shear moduli. The fiber modulus, which controls the composite longitudinal modulus, is a function of the aspect ratio (fiber length/fiber diameter). Short fiber stiffness approaches the continuous filament asymtotically as the aspect ratio increases. For the composites under consideration, the fibers are sufficiently long and the short fiber modulus is assumed equivalent to the continuous fiber. Fiber strength is also a function of the aspect ratio, reaching a limit as length is increased. Finite element analyses have been conducted which indicate the effects of stress concentrations at fiber discontinuities and their relations to the aspect ratio[6]. Based on these and similar results, the short glassfiber strength is taken as 60 percent of the continuous reinforcement'. In applying the maximum strain theory, the allowable longitudinal strain is reduced to 60 percent of the continuous thus accounting for the lower fiber strength of the short fibers. The results of an experimentally measured stress-strain curve are compared to the prediction from maximum strain theory and laminate analogy in Fig. 4-2. In Fig. 4-3 theoretical predictions are shown with experimental results over a range of fiber volume fractions.

Similar predictions for a quasi-isotropic laminate with continuous glass reinforcements are shown in Fig. 4-4 for comparative purposes. Ultimate strength of the short-fiber composite is approximately two-thirds the

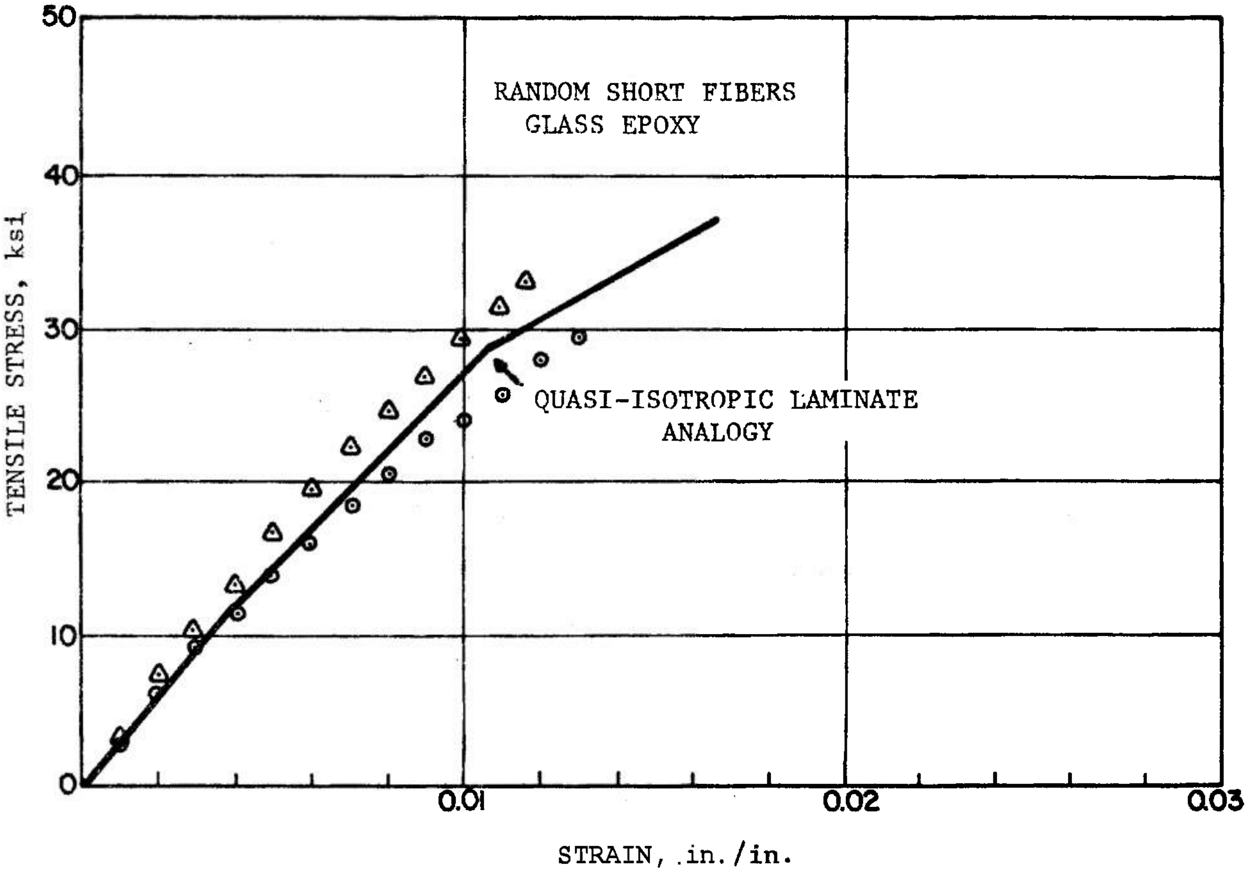

Figure 4-2. Randomly Oriented Short Fiber Stress-Strain Curve With the Maximum Strain Theory Prediction

strength of the continuous or about 35,000 psi. The short fiber composites do not attain such strength due to fiber breakage in processing or molding, to nonuniform fiber distribution which induces large strains in the resin, and to partial fiber orientation.

In some cases, it may be desirable to orient the fibers in order to optimize properties. An analysis corresponding to the quasi-isotropic analogy can be used to predict strengths of composites with a known fiber orientation distribution function. The theory requires that the fiber orientation be handled as a complex laminate of weighted groups of angle plies and assumes a symmetrical angular distribution to match the actual fiber orientation. Different orientations contribute to the overall laminate response in proportion to their fractional thickness. The laminate stiffness moduli are determined as with the quasi-isotropic example. The strength is predicted by incrementally loading the laminate and examining each of the angle plies with respect to the maximum strain failure criterion with the reduced longitudinal ultimate strain for short fibers. Any ply that has exceeded the criterion has failed and is deleted from the calculation. This procedure is continued until final ply failure.

As a general rule, fiber distributions are not known with a high degree of certainty and only a few such determinations have been

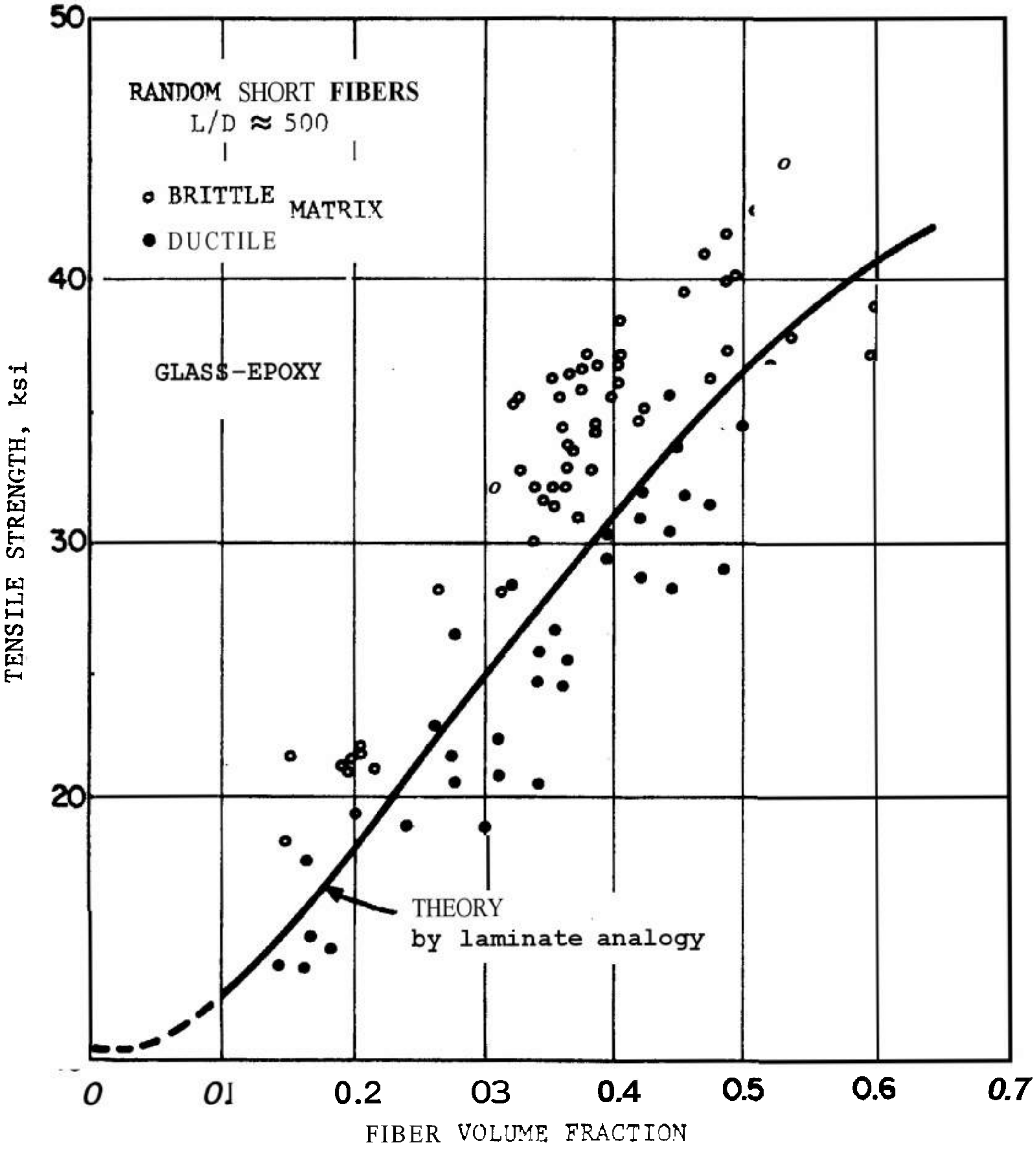

Figure 4-3. The Effect of Volume Fraction on the Strength of a Randomly Oriented Short Fiber Composite as Predicted by Maximum Strain

made. The distribution used by Halpin and others in calculating E_{11} and E_{22} for biased fiber orientation is listed in Table **4-2.** Results are shown in Fig. **4-5** at various fiber volume fractions and compared to a random orientation. In the nonrandom case, samples were molded from an extruded material. The major portion of the fibers were within ± **20** deg to the flow direction, resulting in a substantial difference between the longitudinal and transverse modulus. Irregularities in the curves are due to the fact that the angular distributions were not identical at all fiber volume fractions.

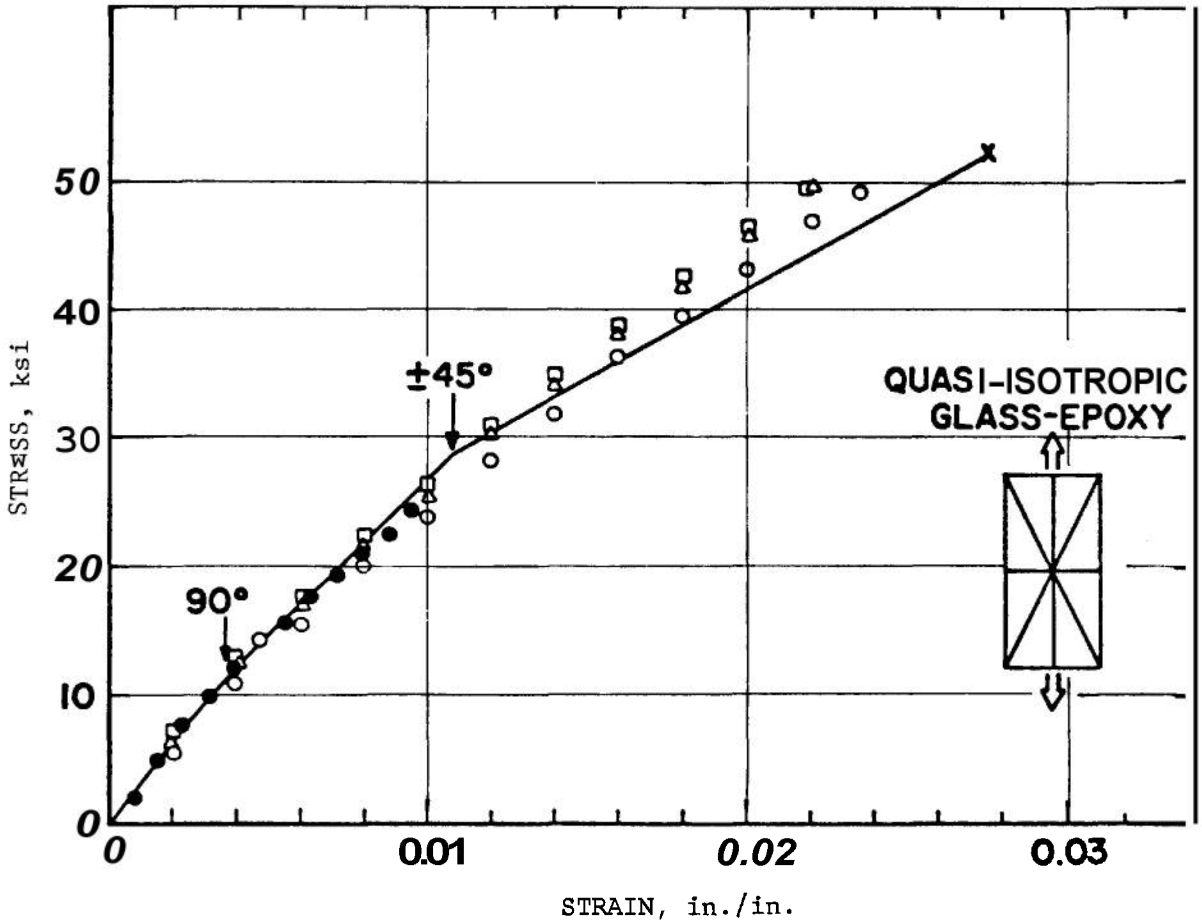

Figure 4-4. Stress-Strain Relationship for a Quasi-Isotropic Laminate With the Maximum Strain Theory Prediction

As noted previously, the quasi-isotropic laminate analogy has a potential use in determining thermal properties and other mechanical properties. Such results have been computed for the continuously reinforced random composite[3]. Estimates which have been made for boron/epoxy, graphite (Thornel 50)/epoxy, and S-glass epoxy include heat capacity, in plane heat conductivity, through thickness heat conductivity, in plane thermal coefficients of expansion, normal moduli, shear moduli, Poisson's ratio, failure stresses, ply residual stresses, and tensile impact energy density to initial damage. These properties are determined over a range of fiber volume fractions. It is believed that similar calculations are possible for the short fiber random composite if appropriate modifications are made to account for differences due to the discrete fiber lengths.

4-3 REINFORCEMENT EFFICIENCY

The tensile stress-strain curves in Fig. 4-6 for fiberglass/epoxy laminates made from random may indicate that maximum strength is attained at approximately a 50 percent fiber volume loading. The same results are

TABLE 4-2

FIBER ORIENTATION DISTRIBUTION IN A COMPRESSION MOLDED COMPOSITE[7]

Orientation, deg	Percent Fibers at Each Orientation			
2.5	23.4	25.4	25.0	36.5
7.5	17.9	18.1	23.8	23.9
12.5	12.0	12.3	16.4	14.2
17.5	16.0	7.7	10.0	5.7
22.5	6.2	6.4	6.8	3.0
27.5	5.9	5.6	4.8	2.7
32.5	4.4	4.6	3.1	1.8
37.5	4.6	3.1	2.4	2.0
42.5	2.6	3.4	1.6	1.0
47.5	1.7	1.9	1.3	0.4
52.5	0.4	1.3	0.8	0.7
57.5	0.7	0.7	1.1	0.8
62.5	1.0	1.4	0.9	0.5
67.5	0.7	1.1	0.7	0.7
72.5	0.1	2.1	0.4	0.5
77.5	0.9	0.9	0.6	0.8
82.5	0.5	2.3	0.3	0.9
87.5	1.0	1.4	0.1	0.8
Volume Percent Fibers	20	30	40	50

Glass Fibers, Aspect Ratio ≈ 360

Original Data Source, R. Tock & others
Monsanto Res. Corp. HPC-69-97. Nov 1969
AD 865 291

brought out in Fig. **4-3** where strength is plotted against fiber content of the composite. Here it appears that strength increases are linear with increments in fiber volume up to about 40 percent. Thereafter the rate of increase falls off, indicating a decrease in the efficiency of fiber utilization. Also to be noted is the decrease-in ultimate elongation as glass content is increased.

Rough estimates of the reinforcement efficiency can be made by assuming that only the fibers parallel to the stress direction carry the load or by use of the ultimate composite strain to calculate maximum fiber stress:

$$\sigma_g = E_g \epsilon_c \text{, psi} \tag{4-2}$$

where

σ_g = average fiber stress at ultimate
E_g = fiber modulus (10.5×10^6 psi for E-glass, 12.4×10^6 psi for S-glass)
ϵ_c = ultimate composite strain, in./in.

Table 4-3 lists the estimated fiber efficiency for several composite types at various fiber volumes. The decrease in efficiency is apparent as the reinforcement is changed from continuous, to woven, to random chopped fiber. It should be noted that these values are over-simplifications and do not in reality reflect the true state of stress within a laminate. For example, the known stress concentrations at fiber ends for the chopped fibers and at cross-over points for woven fabrics would have substantial effects on calculations.

TABLE 4-3

ESTIMATED FIBER EFFICIENCY FOR SEVERAL COMPOSITE TYPES

Material Type	Fiber Volume, %	Glass Type and Strength, ksi	Composite Stress, ksi	Fiber Stress, Calculated ksi	Fiber Efficiency, %
Nonwoven Unidirectional	62.5	S - 500	270	420	84.0
Nonwoven Crossply	60	S - 500	140	430	86.0
Nonwoven Quasi-isotropic	59	S - 500	75	425	85.0
Nonwoven Unidirectional	48	E - 400	160	327	82.0
Woven Fabric, Style 7781	50	E - 400	70	256	64.0
Chopped Roving, Random	50	E - 400	35	180	45.0
SMC, Random	30	E - 360	20	150	42.0

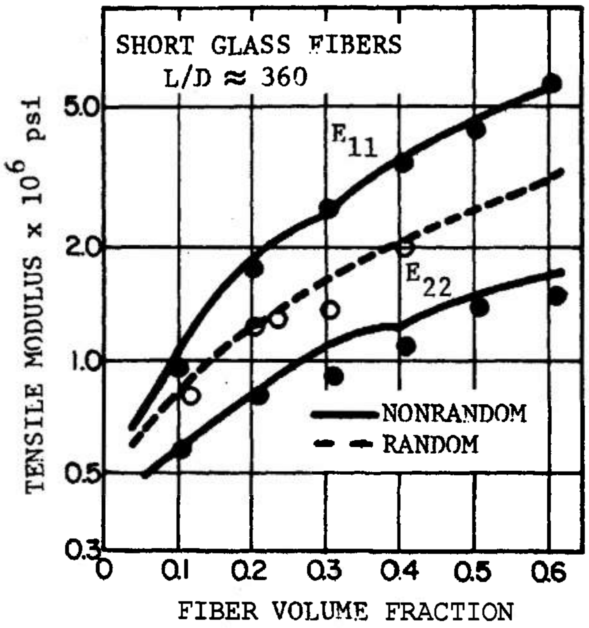

Figure 4-5. Random and Biased Fiber Orientation, in a Polymeric Matrix, Compared With Theory

For random short fiber composites, Nielsen and Chen[10] have defined a fiber efficiency factor F from

$$E_c = E_m V_m + F E_f V_f, \text{ psi} \tag{4-2}$$

where

E = modulus, psi
V = volume fraction
subscripts c, m, f = composite, matrix, and fiber, respectively

The fiber efficiency factor F is a slowly varying function of V_f as well as a function of E_f/E_m. For most composites of practical interest F varies from about 0.15 to 0.60 and E_c/E_{11} varies from 0.15 to 0.70.

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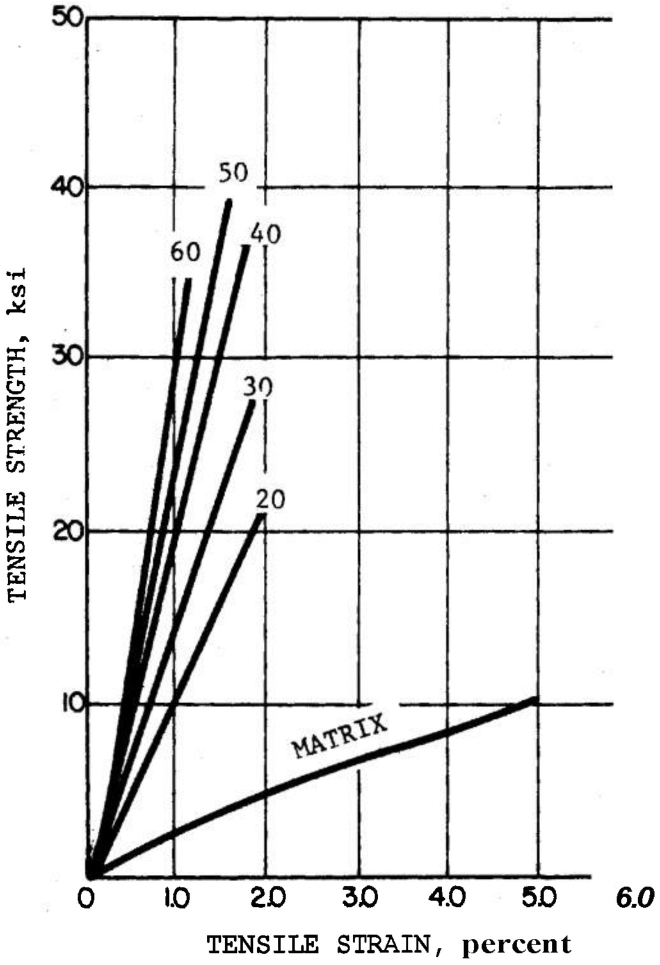

Figure 4-6. Stress-Strain for Random Fiber Glass/Epoxy at Several Fiber Volume Fractions

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CHAPTER 5

MOLDING SHORT FIBER THERMOSETS

5-1 INTRODUCTION

Compression molding has been the traditional method used to convert reinforced thermoset molding compounds into finished parts. In recent years there has been a growing trend towards the use of transfer and injection molding processes. Each of these methods imposes its own requirements on the materials to be processed and on the properties to be attained in the finished moldings. The processibility of each compound depends to a great extent on its rheological properties, which in turn are related to fiber or filler contents, fiber length, and resin viscosity. Fiber flow patterns and orientations within the confines of a mold are thus seen as variables associated with material rheology and shear rates developed during the molding process. The interrelationship of material, molding process, and mold or part design are discussed in this chapter. Processing equipment is discussed insofar as it affects other parameters.

5-2 PRESSES FOR COMPRESSION MOLDING

Most compression molding presses in service today develop the required mold closing and clamping pressures by hydraulic or combined hydraulic-mechanical means. The newer plastic materials such as SMC or fiber reinforced thermoplastic sheet, with their potential for reliable high rate, low cost processing may warrant the use of mechanically driven metal working presses for increased economy of operation. Conversion of metal stamping or forging presses to accommodate plastic materials can be accomplished with relatively minor revisions.

In both the hydraulic and mechanical cases, many types of machines are manufactured which are suitable for matched die molding. Press capacities vary over a wide range. The largest presses in current use' are believed to be those in the 4,000-ton class and designs exist for increasing pressures up to 20,000 tons or higher. Probably the greatest percentage of molding presses fall in a range of from 200 to 1500 tons, which is adequate for most moldings.

Press types and characteristics are briefly noted here. It is the intent to acquaint the designer-engineer with the features that will materially affect the part arid mold design, maximum part dimensions, flow control, dimensional control of molded parts, and potential production rates. For more detailed discussion of press construction and operation, reference is made to other sources[1-4]

5-2.1 HYDRAULIC PRESSES'

5-2.1.1 TYPES

Press types are classified by the frame design and type of tension members for positioning the platens. *Open rod or column presses* use rods or columns to position and retain the top and bottom platens. They also serve as guides for platen movement. Most presses have four rod members, but for unusual service conditions two-column or multiple-columns may be employed. The ends of the columns are shouldered to pass through the platens, and the ends are threaded to receive retaining nuts. In high-tonnage presses, the construction is altered. Columns are not shouldered; threaded full nuts or threaded split collars are placed above the bottom platen and below the top platen; additionally, threaded nuts are applied at the rod ends. Through-holes at each corner of the moving platen are lined with replaceable bronze bushings. This type of press allows accessibility from four sides, but will accept only limited off-center loading unless specifically designed for this purpose.

Welded frame presses provide a rigid machine with few components since the entire frame is welded and machined as a unit. They are limited in available platen sizes and are not recommended for capacities over 500 tons. The design assures close parallelism and because of inherently low stresses is better suited for off-center loading. Accessibility to the platens is lower than for the open rod press. Bottom platens, as with other rigid frame presses, are cored for cooling to prevent heat deformation or "A-framing".

Housing type presses may have open housing or closed side housing construction. In the open housing, four box-like uprights at the corners separate the top and bottom platens. A prestressed tie rod through each upright locks the assembly together. The closed side housing has two sets of uprights, one at each side of the press and similar tie rods. The hydraulic cylinder and pressure ram which activate the moving platen are located on the top platen for both types. The moving platen is guided by full-length, removable, and tapered gibs. For normal plastic molding, four gibs are sufficient and specially designed eight-point gibs can be installed for severe off-center loading. Open housing presses are capable of handling a wide variety of work and incorporate many features found in the closed housing. They are designed to handle pressures from 250 tons and up. Closed side housing presses are available in a number of bed sizes, tonnages, daylight openings, strokes, and speeds. They are desirable in the molding of reinforced parts with large areas.

***Side** plate presses* which are available up to 3000 tons are designed so that the tension members also form the frame. They are fabricated from heavy steel plates or weldments, and are keyed and rigidly bolted to the top and cylinder platens. Ram diameters equal or approach platen dimensions so that platen deflection is minimized. Side plate presses are more economical to build, but are limited to applications where relatively short strokes are required. Down acting side plate presses may be rib-reinforced for structural economy and high production rates at somewhat greater daylight openings.

Loop frame presses represent a more recent principle in press design. The usual construction consists of two J-formed plates welded together. The inside loop is machined to receive the resistance and cylinder platens. Tolerances can be held to a few thousandths of an inch and the press can handle severe eccentric loadings. A limitation is a short ram stroke (normally a 15-in. stroke is maximum). With modifications the press can attain strokes up to 60 in. These presses are extremely versatile and can be made in upstroke or downstroke models, or with self-contained or accumulator operated hydraulic equipment. Pressures, speeds, and time cycling can be varied so that fully automatic operation is possible.

5-2.1.2 PERFORMANCE CRITERIA, HYDRAULIC PRESSES

While performance will vary depending on press type, it has been suggested that the following design criteria should be considered as essential to all hydraulic presses:

(1) *Combined bending and **shear** deflection* of a moving platen or press bed should not exceed 0.002 in./ft measured at the center of any line across the platen or bed including the maximum diagonal length; deflection to be measured at maximum press tonnage, uniformly distributed over two-thirds of the platen. area.

(2) *Parallelism* between heated platens of 0.001 in./ft based on the moving platen resting on four parallels without load is to be achieved.

(3) *Pressure build-up time* from zero to maximum tonnage at a specified working stroke should be less than 5 sec.

5-2.2 MECHANICAL PRESSES

The use of mechanical presses for plastic molding is relatively new and has been motivated by developments in the automotive industry, in which metal working presses were modified to process SMC. Similar presses have been adapted to the "cold-forming" of thermoplastic sheet. Generally straight-side mechanical presses are used. These are similar in frame design to closed side housing type hydraulic machines. Drive mechanisms vary and are intended to supply sufficient energy as required for specific operations. For example, *nongeared* (flywheel drive) types are used mainly in piercing and blanking operations where low energy and comparatively high press speeds are needed. *Single geared* crankshaft types are applicable to shallow draws, forming, or similar work requiring more energy. *Double geared* types are used in deep draw work requiring high energy at relatively low press speeds. Eccentric gear drive is an alternate method of providing power and an improvement over crankshaft drive. It normally is used on presses rated over 300 tons and for drawing or similar operations requiring long strokes. Alterations for plastic compression molding are required to automatically control the press through a complete cure cycle, to control pressure release at the end of the curing cycle, and to control closing speed and application of pressure.

5-2.3 TRANSFER MOLDING PRESSES

Transfer molding is similar to compression molding and requires only modifications to receive the transfer pot of the mold. Most four post hydraulic presses can be converted to transfer molding, provided the press opening is sufficient. The hydraulic transfer cylinder, which forces material into the closed mold, may operate at an angle from the side or through a hole in the top platen directly over the mold. In other cases, the transfer cylinder may be activated directly by press closing action. The press tonnage represents the clamping pressure of the mold and must exceed any forces that tend to open the mold during the press cycle.

Transfer molding may be automated for high speed operation, particularly with comparatively small molded parts. This usually is accomplished in conjunction with preheating of the molding compounds to reduce the overall cure cycle time. Press controls are installed for automatic or semiautomatic operation of all phases of the molding cycle.

5-2.4 INJECTION MOLDING MACHINES

The injection molding of thermosets closely resembles the thermoplastic injection molding process. The material is preplasticized, and forced through a runner and gating system into the mold. Clamping pressure is maintained during the curing cycle. The significant equipment differences are in the screw and barrel designs required to maintain temperature control of the material and to prevent a premature curing in the injection machne. Most thermoplastic injection machines which operate with in-line reciprocating screws can be converted to thermoset molding. Screws are built with a lower compression ratio and may be cored for cooling. The barrels also are jacketed and zoned so that temperature at the feed end and at the injection end can be adjusted as required. Screw rotational speed is another variable for controlling stock temperature.

In other respects – such as clamping, drive mechanisms, hydraulic systems, and framing – the thermoset and thermoplastic machines can be considered identical.

For a full discussion of machine operating characteristics and other information related to the injection molding of thermosets, see Refs. 2, 5, and 6.

5-3 MATCHED DIE MOLDING

The matched die or compression molding process is applicable to the forming and curing of all thermoset compounds – including SMC, BMC, preforms, chopped rovings, and other premixed materials. Although the process is an old one, numerous improvements have kept it competitive in the production of reinforced plastic parts. Improvements, in general, have been related to press construction and operation, mold construction details, the use of faster curing, and controlled flow molding materials. Matched die molding results in maximum reliability and reproducibility in regard to finished part dimensions and physical properties, but requires large volume production, in the order of 6,000 to 10,000 units at a minimum, to justify capital expenditures. At low volumes, mold amortization costs may become prohibitive.

The various process requirements which are discussed in this paragraph are associated with the press, the die-set, the molding compound, and their interrelations.

5-3.1 PRESS REQUIREMENTS

Press capacity must be adjustable to accommodate different molding materials. Adjustments in press tonnage should begin at about 10 percent of press maximum rating and continue to maximum. The accuracy in control of pressure should be within 5 percent. As a precautionary practice, it is customary to allow an excess capacity, in the order of from 15 to 25 percent above the minimum mold closing pressure. Such excess in press capacity will account for miscalculations in pressure requirements or variability in material flow properties.

TABLE 5-1

MOLDING PRESSURES AND TEMPERATURES FOR VARIOUS MATERIAL TYPES

Material Type	Molding Pressure Range, psi	Molding Temperature Range, °F
SMC	500-1500	265-350
BMC	300-1500	265-350
Preform	250-1500	170-320
Premix	500-1500	280-350
Chopped Roving	1000-3000	300-330
Phenolic Molding Compound	2000-4000	300-360

Mold closing pressures are estimated by assigning a value for the material in pounds per square inch and multiplying this by the projected mold surface area in square inches. These estimates are only approximations and do not account for pressure drops in the system due to deep draws, channels, thin-sections, or the like. Normally, they are close enough for determining the required press size. Typical mold pressure requirements for various types of molding materials are listed in Table 5-1.

The press closing rate must be adjustable within the limitations set by the molding compound. Fast closing is required so that the material does not precure prior to full closure. The speed is reduced just before contact is made with the material, otherwise the charge placement will be altered or some material may be flashed from the mold. A slower speed is maintained until final closing. Typically, rapid press advance will be specified at a minimum of 600 in./min, with final closing advance adjustable from 0 to 20 in./min. Intermediate speeds would be from 40 to 50 in./min. Pressure build-ups from no load to full load should be attained within a maximum time of 5 sec. Pressure build time determines the rate at which material will be distributed within the mold. The break away or mold opening capacity is normally at 20 to 25 percent of rated press capacity. The return speed is equal to rapid closing speed.

Dimensional control on the molded part requires that the parallelism of the press platens be maintained and that press and mold deflections be minimized. Several factors contribute to misalignment and deflection. The part design may result in eccentric loading since the centroids of the part and the platen do not coincide. Thermal expansions occur in the platen from mold heating. Clearances in press guide bushings may be excessive. Measures to alleviate these conditions include cooling and insulation of press platens, and the use of beveled temperature compensated bushing guides with phenolic wear plates. In addition, loads should be kept within specified press limits. In off-center loading, the vertical component is resisted by the press platen, while the horizontal component is resisted by the mold structure.

5-3.2 FEATURES IN MOLD DESIGN

Mold design and fabrication for reinforced plastics as well as other plastic materials are specialized arts, and require close cooperation between the mold designer, the molder, the pattern maker, and the tool maker in order to attain a functional design. In many instances several solutions can be reached for specific problems. Various tool steels or other materials are available for producing satisfactory molds. Similarly, there are a number of processes in addition to machining which can be used to form the mold. Standard texts and trade articles have been published which elaborate on the various aspects of compression, transfer, and injection mold design. Included are such items as mold heating systems, guides, runner systems, gating, ejection, sprue design, low cost tooling, standardized mold bases, mold construction materials, and others. Selected references are given which can serve as a guide to the available literature dealing with mold design and evaluation*[,3,5,7,8,9]. Attention is given to design features peculiar to the several types of short-fiber thermosets.

Semipositive molds are used widely in compression molding the short fiber reinforced materials. Die stops are provided which tend to force the platens into a parallel position. The stops or land area absorb most of the energy after the part is filled out.

Right angle shear edges are provided for closing off the mold and reducing the flash thickness. The shear edge is machined as an integral part of the mold. The shear edge contains a by-pass or "pinch-off" where the male and female halves of the mold come together. The shear edge conditions vary for different material types and part thickness. Suggested dimensions for the shear edge are given in Table 5-2; also included in the table are elements related to use of stops and requirements for guide and ejection systems. Table 5-3 lists suggested materials for mold fabrication.

5-3.3 MATERIAL FACTORS IN DESIGN

It has been pointed out already that the various materials behave differently when placed into a mold and subjected to molding pressures and temperatures. The basic limiting factor is the ability of a material to flow in restricted mold spaces without undue separation of fiber and resin or damage to the fibers. The various material types have evolved in response to this effect; the objective being to incorporate a maximum fiber volume into the compound for strengthening purposes and to retain maximum moldability. Certain design elements will thus vary with the material type. Table 5-4 lists a number of such elements for SMC, BMC, and preform molding. Cold molding, thermoplastic molding sheet compound, and spray-up molding also are shown for comparisons.

These "design rules", as indicated in the

TABLE 5-2

COMPARISON OF MAJOR STRUCTURAL AND OPERATIONAL ELEMENTS FOR MOLDING OF SMC AND PREFORM[2]

Type or Method of Molding	Matched Metal Dies for Preform or Mat Molding	Matched Metal Dies for Molding SMC
Mold Surface	High polish satisfactory; can be chrome-plated if desired	Chrome plating preferred over 325-1200 grit finish, buffed and polished
Shear-edge	Flame hardened to resist pinching and dulling due to glass	Flame-hardened or chrome-plated to reduce abrasive wear
Guide pins	Required 0.001 in. clearance on diameter	Extra-strong and accurate guide pins required to resist sideways thrust due to off-center charge or asymmetrical mold; must protect shear edge
Ejector pins	Not necessary for most matched-die molding	Generally required for SMC; air-blast ejection preferred; cellophane preferred to cover ejector head during molding
Telescoping at shear edge	Travel should be 0.040–0.050 in.	SMC requires 0.025–0.8 in. telescope for developing proper back pressure and best mold fill-out
Clearance at pinch-off	0.002–0.005 in.	0.004–0.008 in.
Landing or molding to stops	Needed to define part thickness properly	Not necessary; part thickness determined by weight of charge
Optimum part thickness	0.090-0.125 in. optimum = 0.100 in.	0.125 in.
Molding temperature	235° – 275°F	1 sec, per 0.001 in. at 275° – 280°F Range = 265" – 290"; 340°F for thin parts
Mold temperature variatibn	±5 deg F	±5 deg F
Molding pressure	200 – 500 psi	500 psi for flat to 1500 psi for deep draw; slow close required for last 0.25 in. travel.

table, are intended to serve as a guide and afford rough estimates as to thickness and tolerance limitations. They would be affected materially by increases or decreases in fiber content and by variations in material flow properties.

5-4 MOLDING PARAMETERS

The primary variables in a short fiber composite determining its structure and mechanical properties are the fiber loading, fiber length, fiber orientation, fiber dispersion, fiber wet-out, and the void content. During the time interval when the fiber-matrix suspension is flowing and filling the mold, hydrodynamic forces are generated which change.the structure of the composite. These forces in turn are dependent on other factors such as mold pressure, mold closing

TABLE 5-3

MATERIALS FOR FABRICATION OF MOLDS FOR REINFORCED PLASTICS[2]

Material	Suitability of Use and Comments
Cast plastic and plastic-faced	Suitable for short runs and prototypes
Meehanite-cast (semi-steel)	Extensively used in early RP/C molding, but rarely used today. The material is not durable and develops too much porosity due to casting. Requires continual patching in service.
Kirksite-cast	Has greater expansion than steel when used in combination, and also "grows" in continual service at molding temperatures. Not 100% suitable.
1040 and 1045 steels (50 carbon type)	Good machinable mold material. Suitable for parts where post-molded surface finish is not critical.
4140 steel	Suitable for parts where appearance is a prime requirement. Has some porosity.
P-20 steel or equivalent	Best mold material available. Almost no troublesome porosity, and has good polishability. Better grade of steel and is preferred for extremely long runs. Cost is approximately 2.5 times that of 1045.

rate, mold temperature, geometry of the mold cavity, charge location, viscosity of the resin mix, and variables related to the preparation of the molding compound prior to entry into the mold. For transfer and injection molding, additional considerations are the material temperature and the dimensions and location of the gate and runner systems'[2].

Investigations of these variables have been fragmentary and mostly empirical in nature. Currently, there is a trend toward the establishment of theoretical models that are applicable to injection and transfer molding. In the compression molding of SMC and BMC, the objectives have been to achieve a random fiber distribution and to maintain the fiber strand integrity. Placement of the charge in the, mold, molding pressure, and the viscosity of the thickened resin system are the significant variables. It has been shown with SMC that parts which have been molded with a large portion of the mold surface area covered by the charge remain uniform in strengths, and there is little orientation. Some flow, however, is required to remove entrapped air or other volatiles. Studies have been made of the extreme cases when flow is extensive, i.e., only about 25 percent of the mold is covered'[3]. Results indicate that the glass content remains uniform within 1 to 2 percent throughout the molded surface. Reductions in tensile, flexural, and impact strength in the order of 10 percent occur in samples taken at the mold extremities and compared to center sections. Samples taken parallel and perpendicular to the flow direction show that the strength differences are due to partial flow orientation effects and variations in resin content are magnified. At higher viscosity, fiber damage is increased. The effect of increased molding pressure is to decrease the void content, accompanied by slight improvements in mechanical properties. For a detailed analysis of the effects of voids on material properties see Ref. 14.

TABLE 5-4

DESIGN RULES FOR MATCHED DIE **MOLDING**[10,11]

Design Factor	**SMC**	**BMC**	Preform	**Cold** Molding	Spray-up Open-mold	Reinforced Thermoplastic Sheet
Minimum Inside Radius, in.	1/16	1/16	1/8	1/4	1/4	1/8
Molded in Holes	Yes[1]	Yes[1]	Yes[2]	No	Large	Yes[2]
Trimmed in Mold	Yes	Yes	Yes	No	No	Yes
Core Pulls and Slides	Yes	Yes	No	No	No	No
Undercuts	Yes	Yes	No	No	Yes	No
Minimum Draft:						
0.25-6 in. depth, deg	1-3	1-3	1-3	2	0	1-3
over 6 in. depth, deg	3	3	3	3	0	3
Minimum Practical Thickness, in.	0.050	0.060	0.030	0.080	0.060	0.050
Maximum Practical Thickness, in.	1.0	1.0	0.250	0.500	0.500	0.500
Normal Thickness Variation, ±in.	0.005	0.005	0.008	0.010	0.020	—
Maximum Thickness Buildup	As needed	As needed	2 to 1	2 to 1	As needed	3 to 1
Corrugated Sections	Yes	Yes	Yes	Yes	Yes	Yes
Metal Inserts	Yes	Yes	NR[3]	NR[3]	Yes	No
Bosses	Yes	Yes	NR[3]	NR[3]	Yes	Yes
Ribs	Yes	Yes	NR[3]	NR[3]	Yes	Yes
Molded in Labels	Yes	Yes	Yes	Yes	Yes	Yes
Raised Lettering	Yes	Yes	Yes	Yes	Yes	Yes
Gel Coat Surface	No	No	Yes	Yes	Yes	—
Max Part Size to date, ft^2	50	25	200	50	3000	—
Typical Glass Loading, wt%	15-35	10-30	25-40	20-35	20-30	20-45

[1] parallel and perpendicular to ram action
[2] parallel to ram action
[3] not recommended

increased molding pressure is to decrease the void content, accompanied by slight improvements in mechanical properties. For a detailed analysis of the effects of voids on material properties see Ref. 14.

In transfer (closed mold) molding, flow distance and restrictions are greater so that more marked effects can be expected. The results of experiments by Goettler on glass/epoxy short fiber composites are summarized[12].

(1) *Fiber loading.* Increases in tensile strength and modulus generally are observed at higher fiber loading. Increases are approximately linear with fiber concentration for composites with imperfect longitudinal orientation. Moldings that exhibit highly transverse orientations are exceptions. For example;

data on moldings with 1/8 in. long fibers show that a 20 percent fiber volume transverse tensile strength is 25 percent higher than for a 40 percent loading.

The degree of variation in fiber concentration that occurs in a typical molding through a gate is:

(a) axial:	molding compound	41.6% fiber
	gate	44.7% fiber
	molding	49.7% fiber
(b) transverse:	outside	41.6% fiber
	core	**43.9% fiber**

These data indicate that the fiber on the average moves faster than the resin.

(2) *Fiber wet-out.* While fiber wet-out takes place during the preparation of a compound, additional wetting will occur during molding. Increased resin viscosity results in decreased wet-out. Molding speed, gate size, and mold temperature had no apparent effect on wet-out.

(3) *Fiber orientation.* When the degree of dispersion in aligned systems is low, fibers do not fracture and failures are characterized by interfacial debonding. The degree of variation in test results with longer fibers supports the contention that strength is orientation controlled. Some improvements are made by improved wet-out and dispersion of fiber bundles by lowered viscosity.

(4) *Fiber damage.* Most fiber damage occurs due to restricted flow at entrances to gates and channels, and not in flow through uniform channels. The average fiber length is reduced substantially by reducing one dimension of a gate. Flow rate or pressure do not appear to affect the fiber length distribution.

(5) *Fiber dispersion.* Preparation of the compounds requires that the glass be maintained as a strand or bundle, rather than dispersing into individual filaments. However, attainment of high strengths requires dispersion. It is necessary to avoid fracture through pure resin along a bundle or grain interface that is transverse or at an acute angle to the stress direction. These cleavage type fractures severely limit the strength of flow molded composites. Resorting to high flow rates and readily soluble binders appears to be an optimum solution.

Flow problems. Flow problems in injection molding are intensified by the additional effects imposed by the plasticizing screw as well as by the required runner systems. The following conclusions can be drawn:

(1) *Injection.* Most fiber damage occurs at this stage and may be minimized by improved screw designs; a compression ratio of 1.8 to 1 appears to be the maximum allowable.

(2) *Gates and Runners.* Increasing the thickness of these elements and reducing entrance restrictions lead to significant increases in strength.

(3) *Material Properties.* Superior flow properties are required; glass binders should prevent separation of fiber bundles; a 0.25-in. fiber length appears to be the present maximum.

(4) *Processing Effects.* Excessive cavity pressures result in degraded tensile and impact properties; longer fill times improve tensile strengths; increased temperatures cause higher part shrinkage and lower impact strengths.

(5) Process Controls. Control points or monitoring should include stock temperature at the nozzle area; material pressure at the nozzle; shot size; hydraulic injection pressure; pressure at sprue, runners, gates and at multicavities for a pressure balance; mold temperatures especially at ejector pins; flow rates, mold clamping pressure; ram travel speed; screw turning speed; and screw forward time[2]

5-5 SUMMARY OF MOLDING METHODS

Matched-die (compression) molding remains as the most effective means for attaining optimum material properties. Controlled fiber alignment does not appear feasible with compression molding, and processing should be geared to attain a random fiber orientation. Improvements in properties are most likely through improved material formulation, and control of fiber wet-out and fiber dispersion during the preparation of the compound.

The injection molding process is still undergoing experimentation to arrive at optimum processing conditions. The method appears suitable for molding smaller parts with reduced mechanical properties.

Transfer molding is intermediate and may be developed to the point where controlled fiber alignment is a reality. In this case significant increases in strength and modulus will be possible.

For runs of short duration and prototype molding, there are a number of other methods that will provide satisfactory solutions. These include preform-wet molding, cold-molding, and the newer resin injection processes.

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APPENDIX A

MILITARY AND FEDERAL SPECIFICATIONS

A-1 SPECIFICATIONS FOR THERMOSETS

The following Federal or Military Specifications have provisions pertaining to short fiber thermoset molding compounds:

(1) Federal Specification L-P-383, *Plastic Material, Polyester Resin, Glass Fiber Base, Low Pressure Laminated*

(2) MIL-M-14G, *Molding Plastics and Molded Parts, Thermosetting*

(3) MIL-P-43043B (MR), *Plastic Molding Material, Pre-mix, Polyester, Glass Fiber Reinforced*

(4) MIL-P-46069 (MU), *Molding Plastic, Glass/Epoxy Pre-mix*

(5) MIL-P-46169 (MR), *Plastic, Sheet Molding Compound, Polyester, Glass Fiber Reinforced (for General Purpose Applications).*

A-2 SPECIFICATION REQUIREMENTS

The mechanical property requirements for the various material types are summarized in Table A-1. The specifications, in some cases, also include electrical properties and flame resistant properties.

TABLE A-1

MECHANICAL PROPERTY REQUIREMENTS FOR MIL-SPEC MATERIALS

Specification Number	Material Grade and Type	Impact Strength, ft-lb/ in. Notch		Tensile Strength, ksi	Flexural Strength, ksi	Flexural Modulus, psi x 10^6	Compressive Strength, ksi
		Face	Side				
L-P-383	Mat-Polyester	—	—	20.0	25.0	1.4	20.0
MIL-M-14	MFA-30 Asbestos-Phenolic	3.0	3.0	6.0	8.0	—	20.0
	MFG Asbestos-Phenolic	0.84	0.64	4.5	8.0	—	15.0
	MFI-10 Asbestos-Phenolic	1.30	1.30	5.4	8.0	—	18.0
	MF1-20 Asbestos-Phenolic	2.56	2.0	6.0	8.0	—	18.0
	GPI-100 Glass-Phenolic	10.0	10.0	4.5	15.0	—	20.0
	MMI-30 Glass-Melamine	3.0	3.2	5.5	8.5	—	20.0
	MAI-60 Glass-Polyester	10.0	6.0	3.5	12.0	—	18.0
	MAT-30 Glass-Polyester	3.0	3.0	4.0	15.0	—	18.0
	MAI-30 Glass-DAP	3.0	3.0	6.0	14.0	—	20.0
	GDI-30 Glass-DAP	3.0	2.75	4.5	10.0	—	20.0
	GDI-30F Glass-DAP	3.0	2.75	4.5	10.0	—	20.0
	SDG Glass-DAP	0.3	0.3	4.5	9.0	—	16.0
	SDG-F Glass-DAP	0.3	0.3	4.5	9.0	—	16.0
	MSI-30 Glass-Silicone	3.2	3.2	2.0	7.0	—	10.0
MIL-P-43043	Pre-mix Glass-Polyester	12.0	—	13.5	26.0	—	25.0
MIL-P-46069	Pre-mix Glass-Polyester	18.0	—	22.0	50.0	2.6	—
MIL-P-46169	SMC Grade A, Class 1	7.5	—	6.0	16.0	—	—
	2	9.5	—	8.0	20.0	—	—
	3	11.5	—	12.0	24.0	—	—
	4	13.0	—	14.0	26.0	—	—
	Grade B, Class 1	6.5	—	5.5	15.0	—	—
	2	9.5	—	7.5	17.0	—	—
	3	11.5	—	9.5	20.0	—	—
	4	13.0		11.5	22.0		

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Brigadier General, USA
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OFFICIAL:

JOHN LYCAS
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