3rd Edition

Reinforced Plastics Handbook

Donald V Rosato
& Dominick V Rosato

Reinforcements
Plastics
Compound constructions
Fabricated processes
Markets/ Products
Designing
Engineering Analyses
Selecting Plastic & Process
Summary
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Abbreviations
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ELSEVIER

Reinforced Plastics Handbook

Third edition

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Preface and Acknowledgement

The text is organized and written with useful information in the World of Reinforced Plastics to provide a source and reference guide for fabricator, mold maker, material supplier, engineer, maintenance person, accountant, plant manager, testing and quality control individual, cost estimator, sales and marketing personnel, new venture type, buyer, user, educator/trainer, workshop leader, librarian/information provider, lawyer, consultant, and others.

It will be useful for those using reinforced plastic (RP) composites as well as those contemplating their use. People with different interests will gain knowledge by focusing on a subject and interrelate across subjects that they have or do not have familiarity. Information and data presented includes some important history, detailed up dates, and what is ahead. As explained throughout this book, this type of understanding is required in order to be successful in the design, prototype, and manufacture of the many different, marketable, fabricated products worldwide. This approach provides potential innovations concerning materials of construction, fabricating techniques, improved products performance to cost, and designing new products.

The book provides an understanding that is concise, practical, and comprehensive and that goes from "A–to–Z" on the subject of RP. Its concise information for either the technical or the non-technical reader goes from interrelating and understanding basic factors starting with the materials of construction and plastics melt flow behavior during processing.

This third edition has been written to update the subject of reinforced plastics in the World of Reinforced Plastics. By updating the book, there have been changes with extensive additions to over 75% of the 2nd Edition's content. Many examples are provided of processing different plastics and relating them to critical factors that range from product designs-to-meeting performance requirements-to-reducing costs-to-zero defect targets.

More information that is basic has been added concerning present and future developments, resulting in the book being more useful for a long time to come. Detailed explanations and interpretation of individual subject matters (3000 plus) are provided using many figures and tables. Information ranges from basic design principles to designs of different size fabricated products by different processes. Throughout the book, there is extensive information on problems and solutions as well as extensive cross-referencing on its many different subjects.

This book continues to represent the encyclopedia on RP. Even though the worldwide industry literally encompasses many hundreds of beneficial computer software programs, this book introduces these programs (ranging from operational training to product design to fabricating to marketing). However, no one or series of software programs can provide the details obtained and the extent of information contained in this single source book with its extensive cross references.

It is important to recognize that a major cost in the production of RP products, ranging from the design concept to the finished molded product, is that of the materials of construction. They range from 40 to 90% of the total product cost. Thus, it is important to understand how best to use the materials based on the appropriate design approach and processing technique. Design is interdisciplinary. It calls for the ability to recognize situations in which certain techniques may be used and to develop problem-solving methods to fit specific design requirements. Many different examples are presented concerning problems with solutions that may develop in different design approaches, fabricating techniques, etc., up to the final product in use.

In the manufacture of products, there is always a challenge to utilize advanced techniques, such as understanding the different plastic melt flow behaviors, operational monitoring and control systems, testing and quality control, and so on. However, these techniques are only helpful if the basic operations of fabricating are understood and characterized, to ensure the elimination or significant reduction of potential problems.

What makes this book unique is that the reader will have a useful reference of pertinent information readily available as summarized in the Table of Contents and Index. As past book reviewers have commented, the information contained in this book is of value to even the most experienced designers and engineers, and provides a firm basis for the beginner. The intent is to provide a complete review of all aspects of the RP process that goes from the practical to the theoretical and from the elementary to the advanced.

This book can provide people, not familiar with RP, an understanding of how to fabricate products in order to obtain its benefits and advantages. It also provides information on the usual costly pitfalls or problems that can develop, resulting in poor product performances or failures. Accompanying the problems are solutions. It will enhance the intuitive skills of those people who are already working in plastics.

From a pragmatic standpoint, any theoretical aspect that is presented has been prepared so that it is understood and useful to all. The theorist, for example, will gain an insight into the limitations that exist relative to other materials such as steel, wood, and so on. Based on over a half century of worldwide production of all kinds of low to high performance RP products, they can be processed successfully, meeting high quality, consistency, and profitability. As reviewed in this book, one can apply the correct performance factors based on an intelligent understanding of the subject.

This book has been prepared with the awareness that its usefulness will depend on its simplicity and its ability to provide essential information. With the authors experience gained in working in the RP industry worldwide and in John Murphy's work in preparing the 1st and 2nd editions, we are able to provide a useful book. The book meets the criteria of providing a uniquely useful, practical reference work.

The material properties information and data presented are provided as comparative guides; readers can obtain the latest information from material suppliers, industry software, and/or as reviewed in this book's **Bibliography** section. Our focus in the book is to present, interpret, analyze, and interrelate the basic elements of RP to processing plastic products. As explained in this book, even though there are many reinforcements and plastic materials worldwide, selecting the right reinforcement/plastic requires applying certain factors such as defining all product performance requirements, properly setting up or controlling the RP process to be used, and intelligently preparing a material specification purchase document and work order to produce the product. Extensive selection information is provided.

With all types of plastics that include primarily RPs, an opportunity will always exist to optimize its use, since new and useful developments in materials, processing, and design continually are on the horizon requiring updates. Examples of these RP developments are in this book, providing past to future trends in the World of Reinforced Plastics.

Recognize that with the many varying properties of the different RPs, there are those that meet high performance requirements such as long time creep resistance, fatigue endurance, toughness, and so on. Conversely, there are RPs that is volume and low cost driven in their use. As explained in this book, each of the different materials requires their specific RP processing procedures.

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In preparing this book and ensuring its completeness and the correctness of the subjects reviewed, use was made of the authors worldwide personal, industrial, and teaching experiences that total over 100 years, as well as worldwide information from industry (personal contacts, conferences, books, articles, etc.) and trade associations.

The Rosatos
2004

Acknowledgement

As the reinforced plastic industry worldwide continues to grow and expand its capabilities material wise, process wise, design wise, and product wise, so does the literature. This Third Edition of the *Reinforced Plastics* book and the *Reinforced Plastics* magazine published by Elsevier Advanced Technology provides important information.

This Third Edition is a tribute to John Murphy for the excellent work presented in the First and Second issues. Following Murphy's work the Rosatos' continue to provide updates and information on what is ahead.

About the Authors

Donald V. Rosato has extensive technical and marketing plastic industry business experience from laboratory, testing, through production to marketing, having worked for Northrop Grumman, Owens-Illinois, DuPont/Conoco, Hoechst Celanese, and Borg Warner/G.E. Plastics. He has written extensively, developed numerous patents within the polymer related industries, is a participating member of many trade and industry groups (Plastics Institute of America, Plastics Pioneers Association, Society of Plastics Engineers, Society of Plastics Institute, etc.), and currently is involved in these areas with PlastiSource, Inc., and Plastics FALLO. He received a BS in Chemistry from Boston College; MBA at Northeastern University; M.S. Plastics Engineering from University of Massachusetts Lowell (Lowell Technological Institute); Plastics Engineer of Society of the Plastics Engineers and Ph.D. Business Administration at University of California, Berkeley.

Dominick V. Rosato since 1939 has been involved worldwide principally with plastics from designing through fabricating through marketing products. They have been used on and in land, ocean/water, and air/space. Products in many different markets worldwide ranged from toys to electronic devices to transportation vehicles to aircraft to space vehicles products. Experience includes Air Force Materials Laboratory (Head Plastics R&D), Raymark (Chief Engineer), Ingersoll-Rand (International Marketing Manager), and worldwide lecturing. He is a past director of seminars and in-plant programs and adjunct professor at University Massachusetts Lowell, Rhode Island School of Design, and the Open University (UK). He has received various prestigious awards from USA and international associations, societies (SPE Fellows, etc.), publications, companies, and National Academy of Science (materials advisory board). He is a member of the Plastics Hall of Fame. He received American Society of Mechanical

Engineers recognition for advanced engineering design with plastics. He is a senior member of the Institute of Electrical and Electronics Engineers and licensed professional engineer of Massachusetts. He was involved in the first all plastics airplane (1944/RP sandwich structure). He worked with thousands of plastics plants worldwide, prepared over 2,000 technical and marketing papers, articles, and presentations and has published 28 books with major contributions in over 45 other books. He received a BS in Mechanical Engineering from Drexel University with continuing education at Yale, Ohio State, and University of Pennsylvania.

Abbreviations

AAM	American Architectural Manufacturers
ABL	Allegheny Ballistic Laboratory
ABC	acrylonitrile-butadiene-styrene
	acetal (*see* POM)
abs.	absolute
ABS	acrylonitrile-butadiene-styrene
AC	advanced composite
AC	alternating current
ACA	Automotive Composites Alliance
ACC	Automotive composites Consortium
ACCS	advanced composite construction system
ACG	Advanced Composites Group
ACMA	American Composites Manufacturers Association
ACN	acrylonitrile
ACTC	Advanced Composite Technology Consortium
ADC	allyl diglycol carbonate (also see CR-39)
adh.	adhesive
AEC	acrylonitrile-ethylene-styrene
AF	Air Force
AF	aramid fiber
AFML	Air Force Materials Laboratory
AFRP	aramid fiber reinforced plastic
Al	aluminum
AMBA	American Mold Builders Association
ANFI	Assoc. of the Nonwoven Fabrics Industry
ANSI	American National Standards Institute
ANTEC	Annual Technical Conference (SPE)
APC	American Plastics Council, unit of American Chemistry Council
APPR	Assoc. of Postconsumer Plastic Recyclers

ARMI	Assoc. of Rotational Molders International
ARP	advanced reinforced plastics
ASA	acrylic-styrene-acrylonitrile
ASA	American Standard Association
ASM	advanced stitching machine
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
atm	atmosphere
B	boron
bbl	barrel
Be	beryllium
BeCu	beryllium copper
BF	boron fiber
BM	bag molding
BM	blow molding
BMC	bulk molding compound
BO	biaxial-oriented
bpd	barrels per day
BPF	British Plastics Federation
BPO	Benzoyl peroxide
BS	British Standard
BSI	British Standard Institute
Btu	British thermal unit
Buna	polybutadiene
Butyl	butyl rubber
C	carbon
C	Celsius
C	Centigrade (preference Celsius)
C	composite
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacture
CAT	computer-aided testing
cal	calorie (see also C)
CAR	carbon fiber
CAT	computer-aided testing
CBA	chemical blowing agent
CCA	cellular cellulose acetate
CCPIA	China Plastics Processing Industry Assoc.
CCV	Composite Concept Vehicle
CEO	chief executive officer
CF	carbon fiber
CFA	chemical foaming agent

CFC	chlorofluorocarbon
cfm	cubic foot per minute
CFRP	carbon fiber reinforced plastics
CFRTP	continuous fiber reinforced thermoplastics
cg	center of gravity
CLTE	coefficient of linear thermal expansion
cm	centimeter
CM	compression molding
CNC	computer numerical control
CO	carbon monoxide
CO_2	carbon dioxide
cP	centipoise
CP	Canadian Plastics
CPE	chlorinated polyethylene
CPET	chlorinated polyethylene terephthalate
CPVC	chlorinated polyvinyl chloride
Cr	chromium
CR	compression ratio
CR-39	diethylene glycol bis-allyl carbonate
CRP	carbon reinforced plastics
CSM	continuous strand mat
cu	cubic
Cu	copper
3-D	three dimension
D	diameter
3-D	three-dimensional
DIN	Deutsches Institut fur Normung (German Standard)
DMC	dough molding compound
DMC-12	DeLorean motor car (plastic body)
DN	Deutscher Normenausschus
DNA	deoxyribonucleic acid
DOD	Department of Defense
DSQ	German Society for Quality
DV	design verification
DVR	design value resource
DVR	Dominick Vincent Rosato
DVR	Donald Vincent Rosato
E	modulus of elasticity (Young's modulus)
EC	European Community
EEC	European Economic Community
E-glass	glass fiber
EI	modulus (times) moment of inertia (stiffness)
EMI	electromagnetic interference

EP	epoxy
EPA	Environmental Protection Agency
EPS	expandable polystyrene
ER	epoxy resin
EUROMAP	European Committee of Machine Manufacturers for the Rubber & Plastics Industries (Zurich, Swiz.)
EVAL	ethylene-vinyl alcohol copolymer (or EVOH)
F	force
F	Fahrenheit
FALLO	Follow ALL Opportunities
FDA	Food & Drug Administration
FEA	finite element analysis
FP	fluoroplastic
FPL	Forrest Products Laboratory
fpm	feet per minute
FRP	fiber glass reinforced plastic
FRTP	fiber reinforced thermoplastic
FRTS	fiber reinforced thermoset
ft	foot
FW	filament winding
g	gram
G	giga (10^6)
G	torsional modulus
gal	gallon
GDP	gross domestic product (see also GNP)
GF	glass fiber
GFRP	glass fiber reinforced plastic
GLARE	GLAss fiber-REinforced aluminum
GM	General Motors
GM	glass mat
GMRP	glass mat reinforced thermoplastic
GMT	glass mat thermoplastic
GNP	gross national product (GDP replaced GNP in US 1993)
GP	general purpose
gpd	grams per denier
gpm	gallons per minute
GR	glass reinforced
GS	glass sphere
GSP	Generalized System of Preferences
h	hour
H_2	hydrogen
HDBK	handbook
HDPE	high density polyethylene (also PE-HD)

HDT	heat distortion temperature
H_2O	water
hp	horsepower
HRc	hardness Rockwell cone
Hz	Hertz (cycles)
I	moment of inertia
IDSA	Industrial Designers Society of America
IM	infusion molding
IM	injection molding
IMM	injection molding machine
in.	inch
I/O	input/output
J	joule
JF	jute fiber
JIS	Japanese Industrial Standard
JIT	just-in-time
JSW	Japan Steel Works
JV	joint venture
K	Kelvin
K	Kunststoffe (plastic in German)
Kg	kilogram
l	length
L	liter
lb	pound
LCTE	linear coefficient of thermal expansion
LDPE	low density polyethylene (also PE-LD)
LF	long fiber
LFP	long fiber prepreg
LLDPE	linear low density polyethylene (also PE-LLD)
LMDPE	linear medium density polyethylene
LPE	linear polyethylene
m	matrix
m	metallocene (catalyst)
m	meter
mg	milligram
M	mega
M	million
$\underline{M}_m$	micrometer (see also μm)
MA	Manufacturers Alliance
MAD	molding area diagram
MD	machine direction
MDAFRPCA	Material Development Alliance of the FRP Composites Industry

MDPE	medium density polyethylene (also PE-MD)
MEK	methyl ethyl ketone
MF	melamine formaldehyde
mg	milligram
Mg	magnesium
MI	melt index
mike	microinch (10^{-6} in.)
mil	milliinch/one-thousand of inch (10^{-6} in.)
ml	milliliter
mm	millimeter
MM	billion
mol.wt.	molecular weight
MPa	mega-Pascal
MPA	Massachusetts Plastics Alliance
MPF	melamine-phenol-formaldehyde
mph	miles per hour
Msi	million pounds per square inch (psi × 10^6)
MT	metric ton
MVD	molding volume diagram
MW	molecular weight
MWD	molecular weight distribution
N_2	nitrogen
NA	not available
NAM	National Association of Manufacturers
NBR	nitrile-butadiene rubber
NBS	National Bureau of Standards (since 1980s renamed National Institute of Standards & Technology or NIST)
NC	numerical control
NDT	nondestructive testing
NEAT	nothing else added to it
NEN	Dutch standard
NFPA	National Fire Protection Association
NIBS	National Institute of Building Sciences
nm	nanometer
NPCM	National Plastics Center & Museum
NPE	National Plastics Exhibition (SPI)
NR	natural rubber (polyisoprene)
NTMA	National Tooling and Machining Association
O_2	oxygen
O_3	ozone
OEM	original equipment manufacturer
OSHA	Occupational Safety & Health Administration

%vol	percentage by volume (prefer vol%)
%wt	percentage by weight (prefer wt%)
P	load
P	poise
P	pressure
Pa	Pascal
PA	polyamide (nylon)
PAE	polyarylether
PAEK	polyaryletherketone
PAI	polyamide-imide
PAK	polyester alkyd
PAM	modified acrylic fiber
PAM	polyacrylamide
PAN	polyacrylonitrile
Pb	lead
PBA	physical blowing agent
PBI	polybenzimidazole
PC	personal computer
PC	polycarbonate
PC	printed circuit
PC	process control
PE	polyethylene
PE	polythene
PEEK	polyetheretherketone
PEEKK	polyetheretherketoneketone
PEK	polyetherketone
PEKEKK	polyetherketoneetherketoneketone
PEKK	polyaryletherketoneetherketone
PEKK	polyetherketoneketone
PET	polyethylene terephthalate
PETG	polyethylene terephthalate glycol
PEX	cross-linked polyethylene (or XLPE)
PF	phenol formaldehyde (phenolic)
Phr	parts per hundred
pi	$\pi = 3.141593$
PI	isoprene rubber
PI	polyimide
PIA	Plastics Institute of America
PLTA	Plastic Lumber Trade Association
POM	polyacetal
PP	polypropylene
ppb	parts per billion
pph	parts per hour

ppm	parts per million
ppm	parts per minute
PPS	polyphenylene sulfide
PS	polystyrene
psi	pounds per square inch
psia	pounds per square inch, absolute
PTFE	polytetrafluoroethylene (TFE)
PU	polyurethane (PUR)
PUR	polyurethane (PU)
PVA	polyvinyl acetate
PVAB	polyvinyl acetal butyral
PVAL	polyvinyl alcohol (PVOH)
PVF	polyvinyl fluoride
pVT	pressure-volume-temperature (also P-V-T or pvT)
QC	quality control
QPL	qualified products list
R	Rankin
R	Reynold's number
R	Rockwell (hardness)
R&D	research & development
radome	radar dome
RF	radio frequency
RFI	radio frequency interference
RFI	resin film infusion
r.h.	relative humidity
RIM	reaction injection molding
RM	rotational molding
ROI	return on investment
RP	reinforced plastic
RP/C	reinforced plastics/composites
RP/CI	reinforced plastics/Composites Institute (SPI)
RPMP	reinforced plastic Marco process
rps	revolutions per second
RRIM	reinforced reaction injection molding
RTM	resin transfer molding
RTP	reinforced thermoplastic
RTS	reinforced thermoset
s	second
SAE	Society of Automotive Engineers
SAMPE	Society for the Advancement of Material and Process Engineering
SF	safety factor
SG	specific gravity

SMC	sheet molding compound
SMCAA	Sheet Molding Compound Automotive Alliance
SME	Society of Manufacturing Engineers
SPE	Society of the Plastics Engineers
SPI	Society of the Plastics Industry
SRIM	structural reaction injection molding
S-S	stress-strain
STD	standard
T	temperature
T_g	glass transition temperature
T_m	melt temperature
T_s	tensile strength
T/C	thermocouple
TD	transverse direction
TDI	toluene isocyanate
T_g	glass transition temperature
three-D	3-dimensional (3-D)
TM	trademark
TM	transfer molding
TP	thermoplastic
T_s	temperature, softening
TS	thermoset
two-D	2-dimensional (2-D)
TX	thixotropic
μin.	microinch
μm	micron/micrometer (see also M_m)
UD	unidirectional
UF	urea formaldehyde
UHMPE	ultrahigh modulus polyethylene
UHMWPE	ultrahigh molecular weight polyethylene (or PE-UHMW)
UL	Underwriters Laboratories
UN	United Nations
UP	unsaturated polyester (TS)
URP	unreinforced plastics
UV	ultraviolet
V	volt
VEM	viscoelastic material
VF	vulcanized fiber
VIP	vacuum infusion process
VOC	volatile organic compound
vol	volume

vol%	percentage by volume; if % alone is used, it usually identifies wt%
vs.	versus
WF	woven fabric
wt	weight
wt%	percentage by weight; if % alone is used, it usually identifies wt%
WYSIWYG	what you see is what you get
XL	crosslinked
XLPE	crosslinked polyethylene
Y-axis	axis in the plane perpendicular to X-axis
yr	year
Z-axis	axis normal to the plane of the X-Y axes
ZMC	low viscosity molding compound Z-N
Ziegler-Natta	(ZN)
Z-twist	twisting fiber direction

1 Introduction

Overview

It would be difficult to imagine the modern world without unreinforced (URPs) and reinforced plastics (RPs). Today they are an integral part of everyone's life-style, with products varying from commonplace domestic to sophisticated scientific products. In fact, many of the technical wonders we take for granted would be impossible without these versatile and economical materials.

Information and presented data includes some important history, detailed dates, and what is ahead. As explained throughout this book, this type of understanding is required in order to be successful in the design, prototype, and manufacture of the many different, marketable, fabricated RP products worldwide. This approach provides potential innovations concerning materials of construction, fabricating techniques, improved products performance to cost, and designing new products.

RPs is a separate major and important segment in the plastic industry worldwide. Industry continues to go through a major evolution in RP structural and semi-structural products meeting performance and cost requirements in different markets particularly since the 1940s. Many different RPs are used, each with their own capabilities process-wise and performance-wise. RPs have been developed to produce exceptionally strong materials that perform in different environments (Figure 1.1 and Table 1.1). The RP products normally contain from 10 to 40 wt% of a plastic (usually called resin) matrix, although in some cases, plastic content may go as high as 60% or more (Tables 1.2 and 1.3).

In the past, the RP industry has grown about 6.5% annually or about twice the growth rate of USA economy. During this period gross domestic product (GDP/USA consumer represents two-thirds of GDP) tripled,

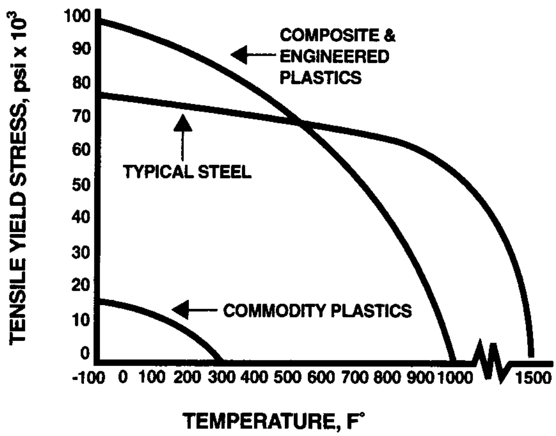


Figure 1.1 Guide on strength vs. temperature of plastics and steel (courtesy of Plastics FALLO)

Table 1.1 Mechanical and physical properties of materials

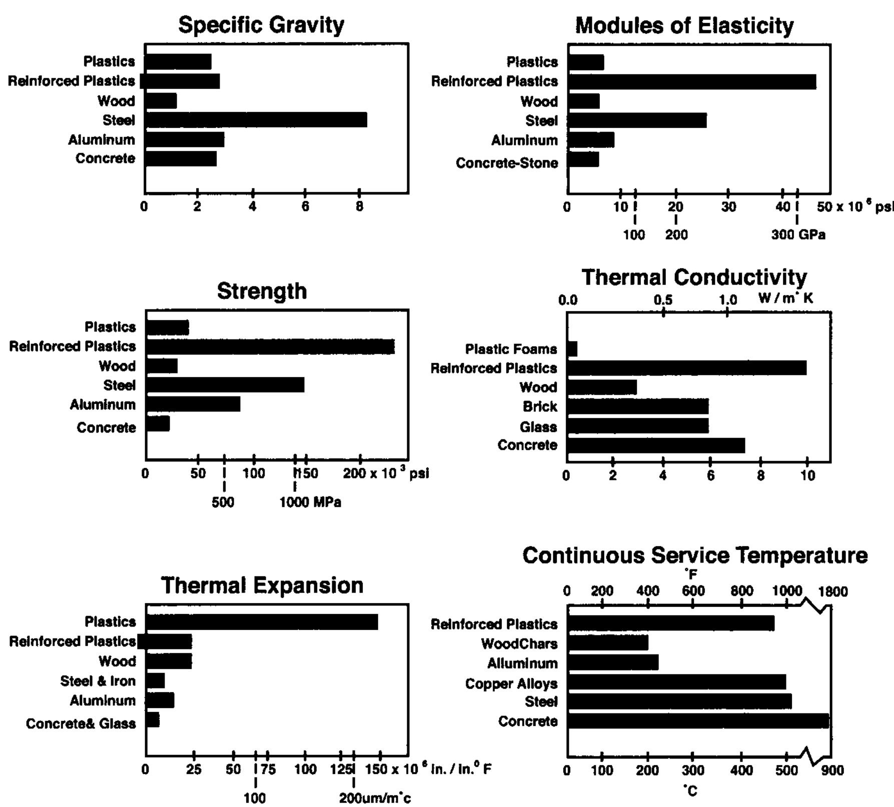


Table 1.2 Properties of RP thermoplastic resins with different amounts of different fibers

Resin	*Specific gravity*	*Tensile strength, MPa*	*Tensile modulus, GPa*	*Elongation, %*	*Flexural strength, MPa*	*Flexural modulus, GPa*	*Izod impact notched, J/m*	*Deflection temperature under load, C*
Nylon-6,6								
Unreinforced	1.14	83	2.9	60	119	2.8	53	90
30% glass fibers	1.39	172	9.0	4	248	9.0	107	252
30% carbon fibers	1.28	227	20.7	3	324	20.7	85	263
40% mineral filler	1.50	92	5.5	3	155	7.2	48	249
40% glass-mineral	1.49	124	7.6	3	207	9.7	64	246
Polypropylene								
Unreinforced	0.9	34	1.4	11		1.6	51	53
30% glass fibers	1.13	52	5.5	2.5	65	4.1	64	137
30% glass fibers chemically coupled	1.13	83	5.9	2.3	110	5.5	107	151
40% mica	1.23	31	4.8	4	48	4.1	37	96
40% talc	1.25	29	3.1	4	48	3.1	27	76
Polycarbonate								
Unreinforced	1.20	65	2.4	7	93	2.3	801[e]	132
30% glass fibers	1.43	131	9.0	2.5	138	7.6	160	143
30% carbon fibers	1.33	152	17.2	1.8	220	15.2	107	149
5% stainless steel	1.27	68	3.1	5	110	3.1	69	146
Polyesters								
30% glass fibers (PBT)	1.51	121	6.9	4	200	8.7	96	206
30% glass fibers (PET)	1.56	158	8.7	3	234	9.1	107	224

Table 1.3 Properties of TS polyester RPs with different amounts of glass fiber

	Glass Fiber (wt %)						
Property	*0*	*10*	*20*	*30*	*40*	*50*	*60*
Specific gravity	1.14	1.21	1.28	1.37	1.46	1.57	1.70
Specific volume $m^3/mg \times 10^{-10}$	24.3 8.8	22.9 8.3	21.6 7.8	20.1 7.3	19.0 6.9	17.6 6.4	16.3 5.9
Tensile strength MPa	12 83	13 90	19 131	25 172	31 214	32 221	33 228
Tensile elongation (%)	60	3.5	3.5	3.0	2.5	2.5	1.5
Flexural strength MPa	15 103.	20 138	29 200.	34 234.	42 290.	46 317.	50 345
Flexural modulus GPa	4.0 28	6.0 .41	9.0 .62	13 .90	16 1.10	22 1.52	28 1.93
Compressive strength MPa	4.9 33.8	13 89.6	23 158.6	27 186.2	28 193.1	29 200.0	30 206.9
Heat deflection temperature at °C	150	470	475	485	500	500	500
Thermal expansion mm/mmK × 10^5	4.5 8.1	1.6 2.9	1.4 2.5	1.3 2.3	1.2 2.2	1.0 1.8	0.9 1.6
Water absorption, 24 h (%)	1.6	1.1	0.9	0.9	0.6	0.5	0.4
Mold shrinkage	15	6.5	5	4.0	3.5	3.0	2.0

steel consumption doubled, aluminum consumption tripled, and RP shipments grew 15 times (Chapter 6). RP growth unfortunately follows economic recessions such as the last that started during 2001.

Important developments have occurred and continue to occur in USA, UK, Germany, Italy, England, Sweden, Japan, and other countries. Throughout this book, examples of past, present and future developments are reviewed. The past developments continue to provide the basis for present and future developments. For example, in England, the British Standard Institute issued a code for storage tanks and vessels in 1973. It used relatively simple formulas for stresses under service loads and for RP design. These methods could be developed for vehicle components. A significant research effort at the British National Physical Laboratory developed design-analysis methods for anisotropic materials at an intermediate level between a standard formula and full computer analysis. This work concentrated on rectangular plates under various support and loading conditions, and could be applied to RP panel structures that contain components of an approximately rectangular shape such as a car door. Results reported at that time-included work on design procedures for RP plates under flexural loading, on optimum design of laminated glass fiber RP (GFRP) materials, and on an interactive mini-computer program for plate design analysis.

During 1941, USA produced bulletins HDBK ANC-17 on reinforced plastics and HDBK ANC-23 on sandwich constructions that included RPs. Based on this type information the all RP sandwich monique constructed airplane was designed and built by the USA Air Force. It flew during 1944. This advanced RP technology of 1944 was demonstrated in the fabricating (hand-lay-up bag and autoclave molding) of this two-seater glass fiber/TS polyester airplane. Later, Grumman built 50 of this type of airplane under A.F. contract (Chapter 6).

The term RP refers to composite combinations of resin and reinforcing materials that provide significant property and/or cost improvements than the individual components that can produce products. To be structurally effective, there must be a strong adhesive bond between the resin and reinforcement.

Reinforcements usually come in continuous or chopped fiber forms as in woven and nonwoven fabrics. Both thermoplastic (TP) and thermoset (TS) resins are used in RPs (Chapter 3). At least 90 wt% of all RPs use glass fiber (E-type) materials (Chapter 2). At least 55 wt% of all RPs use TPs even with their relatively lower properties compared to reinforced TSs (RTSs). Practically all reinforced TPs (RTPs) with short or long glass fibers are injection molded at very fast processing cycles; producing

Table 1.4 Comparing mechanical properties of glass fiber/thermoset and thermoplastic RPs with different metals

	Reinforced plastics (selected)				*Steel*			*Aluminum*		*Magnesium*	*Zinc*
	UPSMC	*UP hand lay-up*	*PA66 30% glass*	*PPS 40% glass*	*HSLA Cold roll*	*Low carbon Cold roll*	*Stainless*	*Wrought*	*Diecast*	*Diecast*	*Diecast*
Glass fiber %	30	30	30	40	–	–	–	–	–	–	–
Specific gravity	1.85	1.37	1.48	1.64	7.75	7.86	8.03	2.74	2.82	1.83	6.59
Tensile strength											
MPa	82.8	86.25	158.7	151.8	448.5	331.2	552.0	338.1	331.2	227.7	282.9
10^3 psi	12.00	12.50	23.00	22.00	65.00	48.00	80.00	49.00	48.00	33.00	41.00
Tensile modulus											
GPa	1173	6.9	8.28	14.145	207	207	193.2	70.38	71.07	448.5	75.21
10^6 psi	1.70	1.00	1.20	2.05	30.00	30.00	28.00	10.20	10.30	65.00	10.90
Elongation %	<1.0	1.3	1.9	3.0	22.0	37.0	40.0	23.0	2.5	3.0	10.0
Flexural strength											
MPa	179.4	193.2	241.5	255.3				137			
10^3 psi	26.00	28.00	35.00	37.00							
Flexural modulus											
GPa	11.04	5.175	5.52	13.11				68.6			
10^6 psi	1.60	0.75	0.80	1.90							
Compressive strength											
MPa	165.6	151.8	182.85	144.9	422.5	331.2	552	338.1	331.2	277.7	6.9
10^3 psi	24.00	22.00	26.50	21.00	65.00	48.00	80.00	49.00	48.00	33.00	1.00
Izod impedance											
J/m	854.4	694.2–801	117.48	80.1							
Ft-lb/in	16.00	13–15	2.20	1.50							
Hardness Rockwell	68[1]	50[1]	M-95	R123	B-80	B-50	B-88	R-80	85[2]	85[2]	82[2]

[1]Barcol hardness; [2]Brinell hardness.

high performance products used in different environments Table 1.4 introduce RP properties.

Higher performing fibers that are used include organic and inorganic high performance glass (other than the usual E-glass), aramid, carbon, graphite, and boron (Table 1.5). Other fibers used to meet different performance requirements and/or costs include natural (cotton, sisal, jute and other cellulosics), synthetic (nylon, polyester, acetate, rayon). When more than one fiber is used, the reinforcement is termed a hybrid.

Table 1.5 Comparison of commonly used reinforcing fibers

Fiber/grade	*Density ($g\ cm^{-3}$)*	*Tensile strength (MPa)*	*Flexural modulus (GPa)*	*Specific modulus (Mm)*
Carbon HT	1.8	3500	160–270	90–150
Carbon IM	1.8	5300	270–325	150–180
Carbon HM	1.8	3500	325–440	180–240
Carbon UHM	2.0	2000	440+	200+
Aramid LM	1.45	3600	60	40
Aramid HM	1.45	3100	120	80
Aramid UHM	1.47	3400	180	120
E-glass	2.5	2400	69	27
R-glass	2.5	3450	86	34
Quartz glass	2.2	3700	69	31
Aluminum	2.8	400	72	26
Titanium	4.5	930	110	24
Steel (bulk)	7.8	620	207	26
Steel (extruded)	7.8	2410	207	26
Steel (stainless)	7.9	1450	197	25

Also available are whisker reinforcements with exceptional high performances (Chapter 2). Also used are non-fibrous materials, such as steel wire (Table 1.6), and surface-treated mineral fillers that include mica platelets, talc, fibrous and finely divided minerals, glass flakes, and hollow and/or solid glass micro spheres. Lightweight expanded materials, such as sheets of reinforced foam or honeycomb, are used as cores in sandwich structures (Chapter 7).

Based on contents of an RP other terms are used to identify an RP. Examples include glass fiber reinforced plastic (GFRP), aramid fiber reinforced plastic (AFRP), carbon fiber reinforced plastic (CFRP), graphite fiber reinforced plastic (GFRP), boron fiber reinforced plastic (BFRP), etc.

Table 1.6 Relative weights vs. equal tensile strength for different materials based on 100% for steel structures

	Relative weight (%)
Steel	100
Aluminum	65
E-glass fiber RP	38
Carbon fiber RP (CFRP)	29
High strength CFRP	8
Aramid fiber RP (AFRP)	26
High strength AFRP	8
S-glass fiber RP	8

The mechanical properties of the RPs are largely determined by the type of reinforcement, its form, and positioning (orientation) (Chapter 7). A high content of fibrous reinforcement produces a high tensile strength (which increases with the length of the fiber), but does not necessarily confer higher rigidity. A high mineral content in the plastic may give high rigidity but relatively poor tensile strength. A combination of the two is often used but, to improve the bonding between the various components, it may also be necessary to introduce a sizing or processing aid. The balance between resin and reinforcement (known as the resin/reinforcement ratio) is a major factor determining the properties of an RP structure.

Both RTSs and RTPs can be characterized as high performance engineering plastics, competing with engineering unreinforced plastics. When comparing processability of RTSs and RTPs, the RTPs are usually easier to process and permit faster molding cycles.

RPs can also be characterized by their ability to be molded into either extremely small to extremely large structurally loaded shapes well beyond the basic capabilities of other materials or processes at little or no pressure. In addition to shape and size, different RPs posses other characteristics that make them very desirable in designing engineering products. The other characteristics include lightweight, high strength and modulus, directional properties (Figure 1.2), high strength-to-weight ratio, creep and fatigue endurance, high dielectric strength, corrosion resistance, long term durability, ease of fabrication, simplified installation, aesthetic appeal, cost reduction, and the potential to be combined with many other useful qualities.

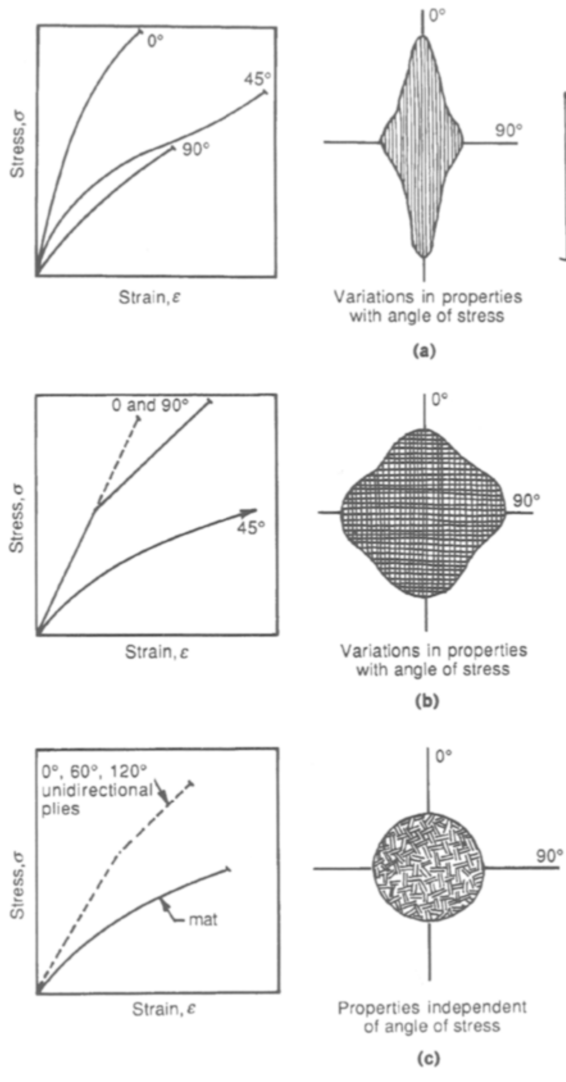


Figure 1.2 Directional properties of reinforced plastics

The form the RP takes, as with URPs, is determined by the product requirements. It has no inherent form of its own so it must be shaped. This provides an opportunity to select the most efficient forms for the application. Shape can help to overcome limitations that may exist in using a lower-cost material with low stiffness. As an example, underground fuel tanks can include ribs to provide added strength and stiffness to the RP orientation in order to meet required stresses at the lowest weight and production cost.

The formability of these products usually leads to one-piece consolidation of constructed products to eliminate joints, fasteners, seals, and other costly or potential joining problems. As an example, formed building RP fascia panels eliminate many fastenings and seals. Examples of design characteristics, gained by using RP materials to produce RP products, are reviewed in this book.

RPs, also called plastic composites or composites, are tailor-made materials that provide the designer, fabricator, equipment manufacturer, and consumer engineered flexibility to meet different environments and create different shapes (Table 1.7). They can sweep away the designer's frequent crippling necessity to restrict performance requirements of designs to traditional monolithic materials. The objective of an RP is to combine similar or dissimilar materials in order to develop specific properties related to desired characteristics. They can be designed to provide practically any variety of characteristic. For this reason, practically all industries use them. Economical, efficient, and sophisticated parts are made, ranging from toys to bridges to preserving historic buildings, to reentry insulation shields to miniature printed circuits to missiles/rockets.

Table 1.7 Examples of different composite systems

Matrix Material	*Reinforcement material*	*Examples of properties modified*
Thermoset plastic, Thermoplastic	Glass, aramid, carbon, graphite, whisker, metal, etc.	Mechanical strength, wear resistance, elevated temperature resistance, energy absorption, thermal stability
Metal	Metal, ceramic, carbon, glass fiber, etc.	Elevated temperature strength, thermal stability, etc.
Ceramic	Metallic and ceramic particles and fibers	Elevated temperature strength, chemical resistance, thermal resistance, etc.

It is acknowledged that these RP materials used to fabricate different products have not come close to realizing their full potential in a multitude of applications (Chapter 10). They could be both more efficient and cost effective. Meanwhile they are used widely and successfully. Utilizing the laws of physics, chemistry, and mechanics, theoretical values can be determined for different materials. For steel, aluminum, and glass, the theoretical and actual experimental values are practically the same, whereas plastics have the important potential of reaching values that are far superior to those of other materials. Their structural properties together with lightweight are demonstrated by their use in aircraft, boats, water skis, surfboards, boat docks, and the list goes on used in underwater, on land, to space.

The electrical insulation property of RPs results in their effective use in electrical and electronic housings, printed circuit boards, hardware for the electrical utility industry, shatterproof light globes, cherry picker boom with 'people bucket' for high voltage wire electrical lines, ladders, etc. RP components and pole-line hardware have contributed greatly to the aims of beautifying and providing safety in the electric utility industry.

In addition to their excellent dielectric properties, RPs provide necessary strength with reduced silhouette and weight. The corrosion resistant, smooth, hard surfaces also resist the embedment of contaminants. Since at least the 1940s utility companies have used components that include pole-top pins, adjustable tension braces, guy-strain insulators, line spacers, insulator pins, upsweeps, double-insulator standoff brackets, switch control rods, hot sticks, and switchgear components.

Thermal insulation properties are typically used in motor transport, refrigerator railroad cars, and unwrapped (uninsulated) process vessels and piping.

The ability of RPs to be formed into complex shapes and irregular contours is demonstrated in a variety of products (aircraft parts, boats, chairs, public transportation vehicles, automotive parts, truck bodies and components, park benches, truck and railcar hoppers, etc.).

Successful corrosion resistant applications are extensive. For many years, they have included chemical processing piping, fume collection hoods, scrubbing towers, handling equipment in the electroplating industry, and stack liners inside chimneys. A specific example of the latter is an installation in Utah that used 600 metric tons of glass fiber roving reinforcement with a TS polyester matrix. Double liners were installed inside a 207.8 m high reinforced concrete chimney. Filament wound field-fabricated sections were 13.7 m long with an 8.5 m diameter. Thirty-six sections were installed. These types of liners have been used since the 1970s.

Many RP water-filtration systems are found throughout the world. Different designs are used depending on the particular filtration system used, i.e., very large and deep RP tanks have circulating and stirring arms, etc. An example of a large closed-designed water filtration system is glass fiber/TS polyester RP. It is 6.1 m (20 ft) diameter by 9.8 m (32 ft) high and was low-pressure molded. It was shipped in one assembled and bonded structure by water barge to its destination.

High strength-to-weight ratios have been demonstrated in primary and secondary structures and components of aircraft, rocket engine cases, large underground and overground storage tanks, portable oxygen tanks for fire fighters, etc. Weather resistance is another necessary property of decorative panels for residential and commercial buildings, patio roofs, highway signs, protective shields in transcontinental communication systems, aircraft and ground radomes, antennas, etc. Other RP products include shipping pallets, organic fiber RP filtration membranes, wall panels that absorb the impact of bullets, waterfront piers/pilings, and aerial booms.

Since the 1940s, the aeronautical and aerospace technologies have soared, with all types of RPs playing major roles in both pragmatic improvements and dramatic advances. RPs lightweight and durability provide savings on fuel consumption and the ability to stand up to stress (creep, fatigue, etc.) and varied environments.

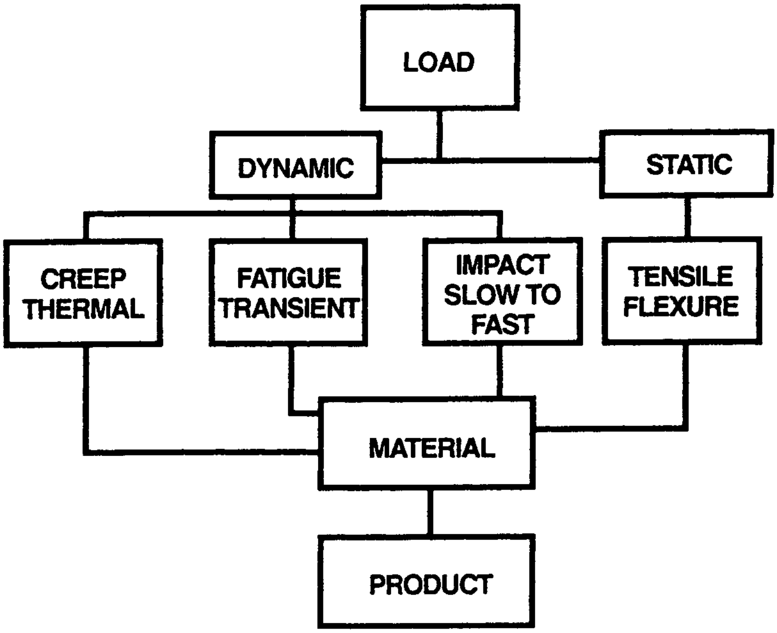
The Chevrolet Corvette was one of the first major applications of RPs in the automotive field (USA 1953). The body was made of short E-glass fibers with TS-polyester RP molded largely by the low-pressure hand lay-up and matched die molding (Chapter 5).

The list of accepted applications could continue endlessly covering products used for all industries and people of all ages. Each product contributes to the worldwide plastic industry's technical growth. Information on production of products is reviewed throughout this book.

Designing different products demonstrated a variety of performances RPs provide such as a range of static to dynamic loads (Table 1.8), aesthetics, environments, recycling, shapes, assemblies or joining, etc. These performances are reviewed in this book (Chapters 6, 7, 8, etc.). In order for the designer to be successful, it is important that all the product performance requirements be obtained and understood. This does not always occur. Once the requirements are obtained including time schedules and quantity needed, the designer can proceed to determine if an RP is required, the material of construction to be used, and the manufacturing process to be utilized. The designer should know possible shaping limitations based on materials and process to be used and if the shape can be determined based on the best design or engineering approach.

There are different designs and engineering basic and practical approaches reviewed in this book (Figure 1.3). Others are available in different design textbooks that are included in the Bibliography section.

Table 1.8 Static and dynamic loads (courtesy of Plastics FALLO)



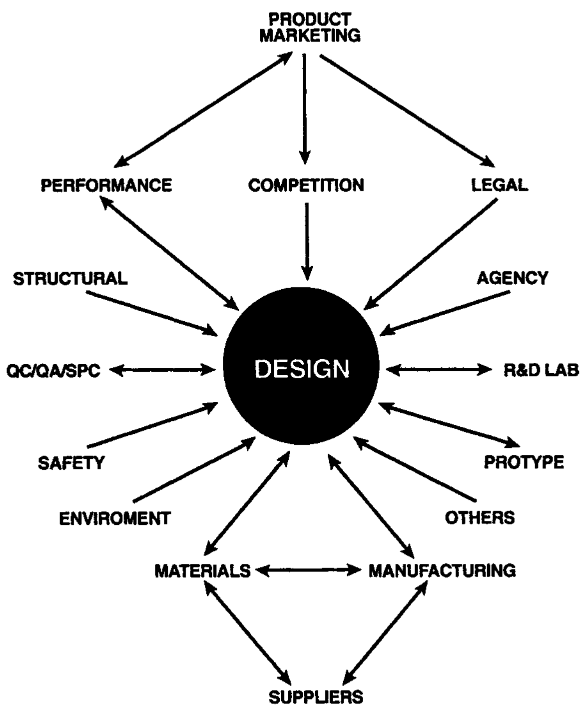


Figure 1.3 Examples of factors that influence the design challenge (courtesy of Plastics FALLO)

As reviewed in this book, designing products range from using simple to complex approaches. However and fortunately, people we know did not have to design the human body. The human body is the most complex structure ever "designed" with its so-called 2,000 parts (with certain parts being replaced with plastics) and having recirculating all the blood in the body every 20 minutes, pumping it through 60,000 miles of blood vessels, etc. Thus, the designer of the human body had to be extremely creative; some of us know who designed the human body.

Commodity and Engineering Plastics

Of the URPs, about 90 wt% of all plastics can be classified as commodity plastics (CPs), the others being engineering plastics (EPs). The EPs such as polycarbonate (PC) representing at least 50wt% of all EPs; others include nylon, acetal, etc. EPs include most reinforced plastics. The EPs are characterized by improved performance in higher mechanical properties, better heat resistance, and so forth when compared to CPs.

The EPs demand a higher price. Just over a half century ago, the price per pound was at 20¢ and above; at the turn of the century it started at $1.00, and now higher. When CPs with certain reinforcements and/or alloys with other plastics are prepared, they become EPs.

Performances

All TP or TS matrix property can be improved or changed to meet varying requirements by using reinforcements. Typical thermoplastics used include TP polyesters, polyethylenes (PEs), nylons (polyamides/PAs), polycarbonates (PCs), TP polyurethanes (PURs), acrylics (PMMAs), acetals (polyoxymethylenes/POMs), polypropylenes (PPs), acrylonitrile butadienes (ABSs), and fluorinated ethylene propylenes (FEPs). The thermoset plastics include TS polyesters (unsaturated polyesters), epoxies (EPs), TS polyurethanes (PURs), diallyl phthalates (DAPs), phenolics (phenol formaldehydes/PFs), silicones (SIs), and melamine formaldehydes (MFs). RTSs predominate for the high performance applications with RTPs fabricating more products. The RTPs continue to expand in the electronic, automotive, aircraft, underground pipe, appliance, camera, and many other products.

Fiber strengths have raised to the degree that 2-D and 3-D RPs can be used producing very high strength and stiff RP products having long service lives. RPs can be classified according to their behavior or performance that varies widely and depends on time, temperature, environment, and cost. The environment involves all kinds of conditions such as amount and type of loads, weather conditions, chemical resistances, and many more. Directly influencing behaviors or performances of RPs involve factors such as type of reinforcement, type of plastic, and process used (Chapter 2, 3, and 5). These parameters are also influenced by how the product is designed. Examples of design performances of RPs follow with more details in the other Chapters:

Thermal Expansion
URPs generally have much higher coefficients of linear thermal expansion (CLTE) than conventional metal, wood, concrete, and other materials. CLTEs also vary significantly with temperature changes. There is RPs that does not have these characteristics. With certain types and forms of fillers, such as graphite, RPs can eliminate CLTE or actually shrink when the temperature increases.

Ductility
Substantial yielding can occur in response to loading beyond the ductility limit of approximate proportionality of most stress-to-strain in URPs. This action is referred to as ductility. Most RPs does not exhibit such behavior. However, the absence of ductility does not necessarily result in brittleness or lack of flexibility. For example, glass fiber-TS polyester RPs do not exhibit ductility in their stress-strain behavior, yet they are not brittle, have good flexibility, and do not shatter upon impact (Chapter 7). The RPs do not shatter upon impact like sheet glass.

TS plastic matrix is brittle when unreinforced. However, with the addition of glass or other fibers in any orientation except parallel, unidirectional, the fibers arrest crack propagation. This RP construction results in toughness and the ability to absorb a high amount of energy. Because of the generally high ratio of strength to stiffness of RPs, energy absorption is accomplished by high elastic deflection prior to failure. Thus, ductility has been a major factor promoting the use of RPs in many different applications since the 1940s. Some unreinforced TPs such as polycarbonate (PC) and polyethylene (PE) do yield with ductility prior to failure, exhibiting similar stress-strain behavior to mild steel.

Toughness
The generally low-specific gravity and high strength of reinforcement fibers such as glass, aramid, carbon, and graphite can provide additional benefits of toughness. For example, the toughness of these fibers allows them to be molded into very thin constructions. Each fiber has special characteristics. For instance, compared to other fiber reinforcements,

aramid fibers can increase wear resistance with exceptionally high strength or modulus to weight.

Tolerance/Shrinkage
RTPs and RTSs combined with all types of reinforcements and/or fillers are generally much more suitable for meeting and retaining tight dimensional tolerances than are URPs. As an example for injection molded products, they can be held to extremely close tolerances of less than a thousandth of an inch (0.0025 cm) or effectively down to zero (0.0%). Achievable tolerances range from 5% for 0.020 in. (0.05 cm), to 1% for 0.500 in. (1.27 cm), to ½% for 1.000 in. (2.54 cm), to ¼% for 5.000 in. (12.70 cm), and so on.

Some URPs change dimensions and/or shrink immediately after fabrication or within a day to a month due to material relaxation and changes in temperature, humidity, and/or load application. RPs can significantly reduce or even eliminate this dimensional change after fabrication.

When comparing tolerances and shrinkage behaviors of RTSs and RTPs there is a significant difference. Working with crystalline RTPs can be yet more complicated if the fabricator does not understand their behavior. Crystalline plastics generally have different rates of shrinkage in the longitudinal, melt flow direction, and transverse directions. In turn, these directional shrinkages can vary significantly due to changes in processes such as during injection molding (IM). Tolerance and shrinkage behaviors are influenced by factors such as injection pressure, melt heat, mold heat, and part thickness with shape. The amorphous type materials can be easier to balance (Chapter 3).

Composites

As reviewed a composite is a combination of two or more materials with properties that the components do not have by themselves. They are made to behave as a single material. Nature made the first composite in living things. Wood is a composite of cellulose fibers held together with a matrix of lignin. Most sedimentary rocks are composites of particles bonded together by natural cement; and many metallic alloys are composites of several quite different constituents. On a macro scale, these are all homogeneous materials. There are steel reinforced concrete, medical pills, and more. Included is RPs.

The term composite started to be used in the RP industry during the 1940s. The Society of the Plastics Industry (SPI) during the 1940s started the Low pressure Industries Division and shortly there after was called the Reinforced Plastics Division with energetic Charlie Condit at the helm of this growing industry for the SPI. D. V. Rosato during 1950, as a Board Member of the Reinforced Plastics Division of SPI, was finally successful at expanding the name of the Division to Reinforced Plastics/Composite Division (1954). The original product was only glass fiber-TS polyester plastic RPs. In the mean time, other reinforcements and plastics were being used; thus the name change. Other name changes have been made such as the Composites Institute of SPI (1988), etc. It is now a more powerful and useful organization for the RP industry called the American Composites Manufacturers Association (ACMA). Its president is Richard Morrision (Morrision Fiber Glass Co., Ohio, USA).

Recognize that composites identify literally many thousands of different material combinations not containing plastics. There are:

aggregate-cement matrix (concrete)
aluminum film-plastic matrix
asbestos fiber-concrete matrix
carbon-carbon matrix
carbon fiber-carbon matrix
cellulose fiber-lignin/silica matrix
ceramic fiber-matrix ceramic (CMC)
ceramic fiber-metal matrix
ceramic-metal matrix (cermet)
concrete-plastic matrix, fibrous-ceramic matrix
fibrous-metal matrix
fibrous-plastic matrix
flexible reinforced plastic
glass ceramic-amorphous glass matrix
laminar-layers of different metals
laminar-layer of glass-plastic (safety glass)
laminar-layer of reinforced plastic
laminar-layers of unreinforced plastic
metal fiber-metal matrix
metal matrix composite (MMC)
microsphere glass-plastic matrix (syntactic)
particle-ceramic matrix
particle-metal matrix
particle-plastic matrix
potassium nitrate-charcoal-sulfur matrix (blasting powder)
plastic adhesive bonding metal-to-metal
plastic-coated fabric
plastic-plastic (coextruded coinjection, laminated)
silver-copper-mercury matrix (dental amalgram)
steel-rod-concrete matrix
whisker-metal matrix
whisker-plastic matrix
wood-plastic matrix, reinforced plastic

and thousands more that do not include plastics. At the atomic level, all elements are composites of nuclei and electrons. At the crystalline and molecular level, materials are composites of different atoms. In addition, at successively larger scales, materials may become new types of composites, or they may appear to be homogeneous.

In this review, RPs is considered to be combinations of materials differing in composition or form on a macro scale. However, all of the constituents in the plastic composite retain their identities and do not dissolve or otherwise completely merge into each other. This definition is not entirely precise, and it includes some materials often not considered composites. Furthermore, some combinations may be thought of as composite structures rather than composite materials. The dividing line is not sharp, and differences of opinion do exist.

Thus the name composite literally identifies many thousands of different combinations with very few that include the use of plastics. In using the term composites when plastics are involved the more appropriate term is plastic composite. However, the more descriptive and popularly used worldwide term is reinforced plastic (RP).

Advantages and Limitations

As a construction material, RPs provides practically unlimited benefits to the fabrication of products, but unfortunately, as with other materials, no one specific RP exhibits all these positive characteristics. The successful application of their strengths and an understanding of their weaknesses (limitations) will allow producing useful products. With any material, (plastic, steel, etc.) products fail not because of its disadvantage(s). They failed because someone did not perform their material and process selection in the proper manner and/or incorrectly processed the material (Chapter 9).

There is a wide variation in properties among the many commercially available materials classified as RPs. They now represent an important, highly versatile group of engineering materials. Like steel, wood, and other materials, specific groups of RPs can be characterized as having certain properties. As with other materials, for every advantage cited for a certain material, a corresponding disadvantage can probably be found in another.

Many RPs that are extensively used worldwide are typically not as strong or as stiff as metals and they may be prone to dimensional changes especially under load or heat. Regardless they are used extensively instead of metals because their performances meet product requirements. There are RPs that meet dimensional tight requirements (includes those that meet zero change), dimensional stability, and are stronger or stiffer based on product shape than other materials including steel.

In most cases, a basic beam structure can be used in the design of parts. Conventional designs with other materials are based on single rectangular shapes or box beams because generally, in timber and in steel, they are produced as standard shapes. Their use in RP components is often accompanied by a wasteful use of material, as in large steel sections. Using RP, the hollow channel such as I- and T-shapes designed with generous radii (and other basic plastic flow considerations during processing) rather than sharp comers, are more efficient on a weight basis. They use less material that might cause a high second moment of inertia. The moment of inertia of such simple sections possibly causing stresses and deflections is a matter of basic calculations using very simple theories (Chapters 7 and 8).

Such non-rectangular sections are common in many RP or unreinforced plastic components. Channels, T-sections, and hollow corner pillars are found in crates and stacking containers, and inverted U-sections and cantilevers that are common in parts such as street lamp housings to aircraft structural parts.

Where such latitude exists in designing shapes, as is found in RP materials, designs using large amounts of materials are not necessarily the best, nor do they give the best mechanical and physical performance per unit weight of material. For example, sometimes quite minute amounts of material judiciously placed in, as an example, an injection-molded crate can make an important difference in the behavior of crates when stacked.

Processing any plastics, reinforced or unreinforced, into curved panels is relatively easy and inexpensive. Panels fit the structural theory that curved shaped can be stiffer to bend than flat shapes of the same weight. However, to withstand external pressure, a square section component will usually be heavier than one that is circular and of the same volume. Both single- and double-curvature designs are widely used to ensure a more effective use of RP materials.

An example of single curvature in a structural element is the RP translucent corrugated roofing panel that is inherently much stiffer than material of the same volume used as a flat sheet. The stiffness of corrugated panels under loading conditions can be calculated. To improve stiffness further, the corrugated panels can sometimes be slightly curved along the length of the corrugations.

Double-curved shells can take the form of special domes, be saddle shaped, or use hyperbolic shapes, as featured in architectural design textbooks. These shapes can be made similar in modular forms molded with RP, thereby providing an efficient structural shape with a higher buckling resistance than special shapes of comparative curvature and thickness. Structural benefits are derived from using RP-faced sandwich designs in different shapes.

In addition to shape and size, RPs often possess characteristics that make them desirable from a design engineering approach, such as cost reduction, ease of fabrication, simplified installation, weight reduction, aesthetic appeal, and the potential to be combined with many other useful qualities. Cost reduction is reviewed throughout this book. The form the RP takes is determined by the designer's conception or product requirements. It has no inherent form of its own so it must be shaped. This provides an opportunity to select the most efficient forms for the application. Shape can help to overcome limitations that may exist in using a lower-cost material with low stiffness. Tanks and vessels are shaped and ribbed to provide added strength and stiffness to oriented RPs in order to meet required stresses at the lowest cost. Their shape is selected for greatest efficiency. Enclosures of all types can be shaped to meet the requirements of its contents.

Where electrical properties, particularly high resistivity are important, such as in insulating hangers for high-voltage electrical lines, RPs can be a logical choice compared to glass and other materials. When minimal strength requirements are to be met, URPs may be adequate. In contrast to the high electrical resistivity of most plastics, graphite fibers, and other fiber materials can provide electrically conductive RP materials.

The generally low-specific gravity and high strength of reinforcement fibers such as glass, aramid, carbon, and graphite can provide other benefits. For example, the toughness of these fibers allows them to be molded into very thin constructions. Each have special characteristics, i.e., aramid fibers have increased wear resistance. Information on fiber reinforcements are reviewed in Chapter 2.

Industry has learned that the high cost of corrosion in manufacturing can be reduced significantly using well-designed and well-applied RPs. There are a number of factors that have a marked influence on the service life of RP equipment that is used in corrosion service environments. These are:

1. the type of matrix plastic
2. the type of reinforcement
3. the sequence of fabrication of layers
4. the controlled distribution of plastic and reinforcement within the laminate
5. the proper design of the laminate to meet the stress requirements of the structure
6. well-controlled fabrication techniques to assure adequate cure (TS) of the plastic system and minimize faults such as voids and pinholes,

7. frequently applying a protective surface plastic layer ranging from 10 to 15 mils in thickness.

The importance of the fabrication technique cannot be adequately stressed. In an appropriate application, a well-prepared RP laminate utilizing the proper materials will guarantee satisfactory performance. Laminates or structures containing the correct plastic matrix and reinforcement combination, but made poorly, will generally not meet expectations.

Plastic matrices are largely immune to the electrochemical corrosion to which metals are often susceptible. Consequently, they can frequently be used profitably to contain water and corrosive chemicals that would attack metals (such as chemical tanks, water treatment plants, and piping to handle drainage, sewage, and water supplies).

Plastics are subject to attack by some aggressive fluids and chemicals. However, not all plastics are attacked by the same materials. It is generally possible, therefore, to select a plastic matrix to meet a particular condition. Some plastics, such as high-density polyethylene (HDPE), are immune to almost any commonly found solvents. A few such as polytetrafluoroethylene (PTFE) are immune to almost any corrosive conditions.

Tolerances should not be specified tighter than necessary for economical production. However, after production starts, the target is to mold as 'tight' as possible to be more profitable by using less material, reducing molding cycle time which results in lower fabrication cost.

Serviceability limits are considered to determine performance of the product when subjected to service loads and environments. Service conditions represent those maximum or limiting conditions that are expected in service. Examples of serviceability limits that should be considered in the design of RPs include residual deformation, buckling or wrinkling, deflection and deformation, thermal stress and strain, crazing, and weeping.

All plastics can be destroyed by fire, like other organic structural materials such as wood. Some burn readily, others slowly and with difficulty. There are those that do not support combustion upon removal of the flame. The URPs and RPs can be rated in standard codes for varying degrees of combustibility, but none is completely resistant to fire. In certain applications, such as aircraft and transportation vehicles, codes specify a time period prior to flame developing.

Since fuel, oxygen, and heat are needed for fire, attempts to reduce the flammability of URPs and RPs center upon suppressing one or more of these factors. The two most common approaches are the incorporation of flame-retardant functional groups in the molecular structure, and the use of additives. Frequently, both of these approaches operate in combination with reactive combustion promoting free radicals given off during combustion.

Additives operate in several ways. The mineral types are resistant to fire and absorb heat. Because they are likely to be good heat conductors, they carry heat rapidly away from local hot spots, thus preventing or delaying the possibility of temperatures rising to the ignition point. There is hydrated alumina whose evaporation retards the raising of temperature until the water evaporates. Some chemical formulation additives, such as aromatics, sometimes form char in cellular forms that insulate the substrate against heat and access by oxygen, thus reducing the chance of fire. In addition, other additives and fillers are used to influence the degree of flammability.

Smoke and other volatile combustion products may be as important as, or more important than flame. Gases may be completely innocuous, such as water and carbon dioxide generated by hydrocarbons which burn in sufficient oxygen. When oxygen is deficient, toxic carbon monoxide may be generated with organic plastics and other organic materials used extensively. Depending upon their chemical structure, gases may be noxious or toxic, and dense smoke may not be generated. Some of the most effective flame suppressants promote the formation of smoke. Thus, the designer may have to make a choice between flame and smoke. Sometimes the most effective fire retardants diminish the durability of the plastic matrices when the product is exposed to the outdoors. Again, it may be necessary to make a choice between requirements.

Highly favorable conditions such as less density, strength through shape, good thermal insulation, a high degree of mechanical dampening, high resistance to corrosion and chemical attack, and exceptional electric resistance exist for certain plastics. There are also those that will deteriorate when exposed to sunlight, weather, or ultraviolet light, but then there are those that resist such deterioration.

For room-temperature applications, most metals can be considered truly elastic. When stresses beyond the yield point are permitted in the design permanent deformation is considered a function only of applied load and can be determined directly from the usual static and/or dynamic tensile stress-strain diagram. The behavior of most plastics is much more dependent on time of application of the load, history of loading, current and past temperature cycles, and environmental conditions. This dependency relates to temperature, time, and load. Ignorance of these conditions has resulted in the appearance on the market of plastic products that were improperly designed (Chapter 7).

Responsibility Commensurate with Ability

Recognize that people have certain capabilities; the USA law says that people have equal rights (so it reads that we were all equal since 1776) but some interrupt it to mean equal capabilities. So it has been said via Sun Tzu, The Art of War, about 500 BC that now the method of employing people is to use the avaricious and the stupid, the wise and the brave, and to give responsibilities to each in situations that suit the person. Do not charge people to do what they cannot do. Select them and give them responsibilities commensurate with their abilities.

People meet an endless succession of challenges in the workplace, at home, and elsewhere. Since this book concerns reinforced plastics, the target is to have qualified people with the willingness to get things done in the World of Reinforced Plastics. These types of people provide strength in the World of RP technology that provides company profits both financially and product performances. This technology is explained throughout this book.

2 Reinforcements

Overview

Many combinations of reinforcements and plastics are used by the plastic industry to affect a diversity of performance and cost characteristics. These may be in layered form, as in typical thermoset (TS) polyester impregnated glass fiber mat, fabric and melamine-phenolic impregnated paper sheets, or molding compound form such as in glass fiber or cotton-filled/TS polyester, phenolic, urea, or nylon RPs. Inline compounds are prepared by injection molding or extruding with short and long glass (and other) fibers. As an example, chopped glass fibers (rovings, etc.) can be fed into an injection-molding machine or a single to twin-screw extruder where principally TP is melted and bonded to the fibers providing an excellent mix. All these resulting plastic RPs have many properties superior to the component materials (Chapter 4).

Reinforcements can significantly improve the structural characteristics of a TP or TS plastics. They are available in continuous forms and chopped forms having different lengths, or discontinuous in form (whiskers, flakes, spheres, etc.) to meet different properties and/or processing methods. Glass fiber represents the major material used in RPs worldwide. Others provide higher structural performances, etc. The reinforcements can allow the RP materials to be tailored to the design, or the design tailored to the material (Figures 2.1 and 2.2 and Tables 2.1 to 2.3).

The large-production reinforcing fibers used today are glass, cotton, cellulosic fiber, sisal, jute, and nylon. Specialty reinforcing fibers are carbon, graphite, boron, aramid, whiskers, and steel. They all offer wide variations in properties, weight, and cost.

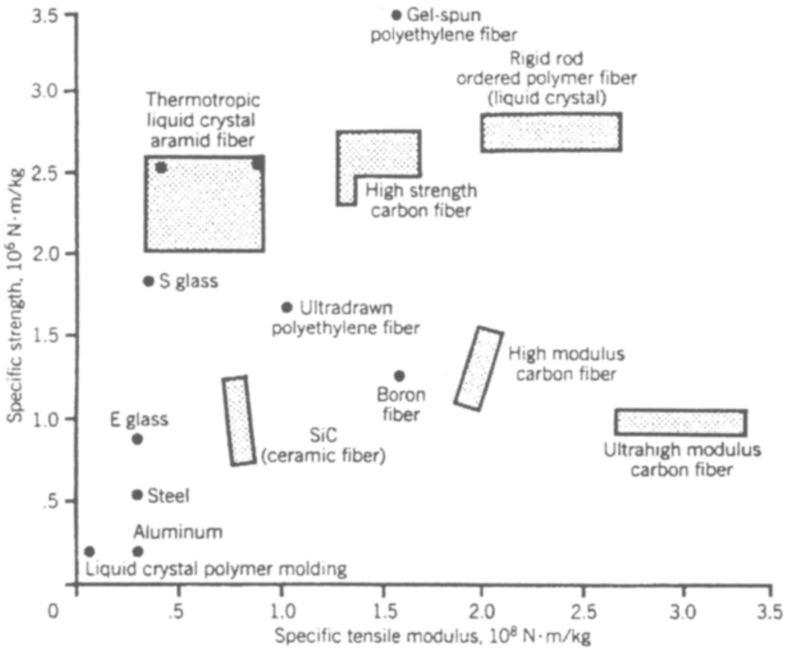


Figure 2.1 Comparison of specific strength vs. specific modulus of RPs. Specific properties are normalized by RP density (Pa or N/m^3 divided by kg/m^3)

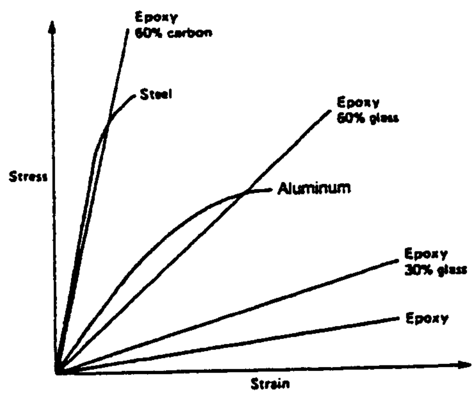


Figure 2.2 Tensile stress-strain curves for different fiber/epoxy and aluminum and steel materials

Fibers in RPs are primarily used to reinforce a resin by transferring the stress under an applied load from the weaker resin matrix to the much stronger fiber. Plastics provide valuable and versatile materials for use as matrices, but other materials, such as metals, ceramics, and cements, are