

Studies on Castor Oil-Based Polyurethane/Polyacrylonitrile Interpenetrating Polymer Network for Toughening of Unsaturated Polyester Resin

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ABSTRACT: Tricomponent interpenetrating polymer network (IPN) systems involving castor oil, toluenediisocyanate (TDI), acrylonitrile (AN), ethylene glycol diacrylate (EGDA), and general-purpose unsaturated polyester resin (GPR) were prepared with various compositions. The structures of the IPNs at various stages were confirmed using FTIR. The thermal stability of the IPNs was studied using TGA, which indicated that the polyurethane/polyacrylonitrile/GPR (PU/PAN/GPR) IPN underwent single-stage decomposition, showing perfect compatibility at the IPN composition of 10 : 90 (PU/PAN : GPR). The mechanical prop-

erties such as tensile, flexural, impact, and hardness for the IPNs with various compositions were determined. It was found that the tensile strength of the GPR matrix was decreased and flexural and impact strengths were increased upon incorporating PU/PAN networks. The swelling properties in water and toluene were also studied. The morphology of the IPNs was studied using SEM. © 2004 Wiley Periodicals, Inc. *J Appl Polym Sci* 92: 817–829, 2004

Key words: resins; interpenetrating networks (IPNs); FTIR; thermal properties; morphology

INTRODUCTION

General-purpose unsaturated polyester resin (GPR) are among the most important thermosetting materials for composite applications because they are relatively inexpensive, offer advantages such as light weight, and possess reasonably good mechanical properties.¹ Nonetheless they suffer a number of limitations. Particularly relevant is their brittleness. These resins are frequently toughened by the incorporation of a tough and flexible elastomer,^{2–5} such as reactive rubber,⁶ carboxyl- and hydroxyl-terminated acrylonitrile butadiene copolymers,⁷ or high-performance thermoplastics.^{8–10} However, the flexible elastomeric phase separates from the matrix during curing, leading to phase-separated morphologies.^{2–5} Also the improvements in the impact strength and strains to failure have invariably been at the expense of stiffness and glass-transition temperature (T_g). GPRs have an extremely broad glass-transition region starting just above room temperature.^{11,12} Thus the mechanical properties, especially the elastic modulus, deteriorate rapidly above room temperature. Incorporation of a rigid polymer matrix like bismaleimide or PAN would improve the T_g values of the polyester matrix.¹³

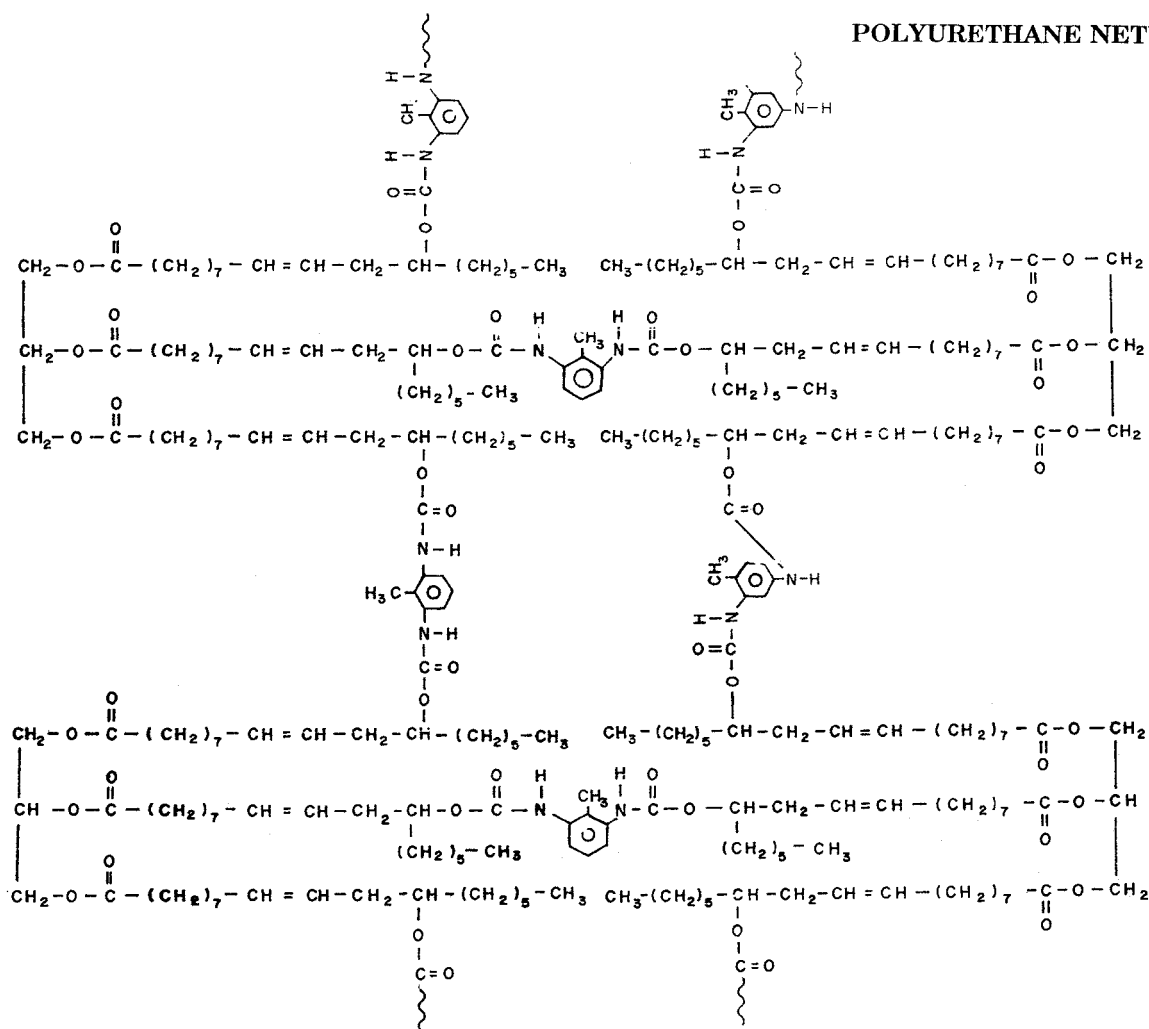
The above facts indicate that the modifications made to the polyester matrix system should allow it to

retain the stiffness, chemical resistance, and at the same time have better impact resistance and increased strain to failure. A GPR system with the above-mentioned properties could be tailor-made by blending it with an elastomeric polymer like polyurethane and a rigid polymeric phase like PAN. Synthesis of an interpenetrating polymer network (IPN), consisting of flexible polyurethane and a rigid PAN network in the GPR network, was considered as an attractive way to achieve this goal.

IPNs constitute a relatively new type of polymer blends consisting of two or more crosslinked polymers in which at least one network is synthesized in the presence of the other.¹⁴ IPNs possess several attractive characteristics compared to those of thermoplastic polymer blends. In the IPN formation, blending is accomplished in conjunction with crosslinking. Phase demixing is limited by permanent interlocking of network chains.^{15–17} Formation of IPNs is the only route to intimately combine crosslinked polymers with limited phase separation. Since the historical synthesis of IPNs, a tremendous amount of work on IPNs has emerged from the laboratories of Sperling et al.,³ Frisch et al.,¹⁷ Hourston et al.,^{18–20} and Hermant and Meyer.²¹ A great deal of research has also been devoted to the toughening of polyester resin by polyurethane incorporation as a secondary phase to form an IPN.^{22–24}

Chou et al.⁵ reported that the reaction sequence during the IPN formation is an important factor in determining the phase mixing and phase morphology of the IPNs. It was found that simultaneous reaction of

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Structure 1

the two reacting systems resulted in a cocontinuous structure that provided enhanced tensile properties and impact strength. Hence, in the present work it was proposed to make simultaneous IPNs rather than sequential IPNs. In recent years, with petroleum production facing exhaustion, potential substitutes from natural products like castor oil are being exploited to synthesize industrially useful polymers. It is used as a polyfunctional alcohol and reacts with isocyanates to form polyurethane. Based on the above facts, the present work was designed to improve the toughness of GPR without loss of stiffness by interpenetrating with castor oil-based polyurethane (PU) and polyacrylonitrile (PAN). The mechanical, thermal, swelling, and morphological properties of the IPNs are discussed.

EXPERIMENTAL

Materials

General-purpose unsaturated polyester resin (GPR), methyl ethyl ketone peroxide (MEKP) in dibu-

tylphthalate (catalyst), and cobalt naphthenate in dibutylphthalate (accelerator) were obtained from Naphtha Resins (Bangalore, India). Polyvinyl alcohol (PVA, releasing agent) was obtained from Central Drug House Chemicals (Bombay, India). Acrylonitrile (AN), benzoyl peroxide (BPO), and acrylic acid (AA) were obtained from Ranbaxy Fine Chemicals (Bombay, India). Castor oil was obtained from the local market (hydroxyl value 127, 2.12 OH groups per mol).²⁵ Toluene diisocyanate (TDI) and dibutyltindilaurate (DBT) were obtained from Sigma-Aldrich (St. Louis, MO). Benzoyl chloride (BC), hydroquinone (HQ), and ethylene glycol (EG) were obtained from E. Merck (Darmstadt, Germany).

Synthesis of acryloyl chloride

Acryloyl chloride (AC) was prepared by distilling a mixture of BC and AA taken in a 3 : 1 ratio along with HQ as inhibitor in a round-bottom (RB) flask fitted with a distillation setup. AC was collected in an RB flask with HQ. It was purified by redistillation and the

TABLE I
Composition and Notations of the Various PU/PAN/GPR IPNs

Sample	Composition of PU prepolymer ^a weight (g)		Composition of PAN prepolymer (mL)		Composition of PU/PAN/GPR IPN ^b (wt %)		Notation
	Castor oil ^c	TDI	AN	EGDA ^d	PU/PAN prepolymer	Polyester (GPR)	
1	64	23	6	1	3 (15) ^e	97	IPN 3
2	64	23	6	1	5 (15) ^e	95	IPN 5
3	64	23	6	1	8 (15) ^e	92	IPN 8
4	64	23	6	1	10 (15) ^e	90	IPN10
5	64	23	6	1	12 (15) ^e	88	IPN12
6	64	23	6	1	15 (15) ^e	85	IPN15
7	64	23	6	1	20 (15) ^e	80	IPN20
8	64	23	8	2	10 (10) ^e	90	IPN B
9	64	23	12	3	10 (7) ^e	90	IPN C
10	64	23	16	4	10 (5) ^e	90	IPN D
11	68 ^f	23	6	1	10 (15) ^e	90	IPN E
12	72 ^g	23	6	1	10 (15) ^e	90	IPN F
13	60 ^h	23	6	1	10 (15) ^e	90	IPN G

^a Few drops of DBT, as catalyst.

^b Resin : accelerator : catalyst = 100 : 1 mL of 1% solution : 1 mL of 1% solution.

^c Samples. 1–10: castor oil content (NCO/OH = 3.17).

^d 1.0 g of BPO per 100 mL of AN, EGDA.

^e PU/PAN mass ratio.

^f NCO/OH = 2.944.

^g NCO/OH = 2.285.

^h NCO/OH = 4.415

fraction boiling at 75–80°C was collected and stored in a cool place with HQ.

Synthesis of ethylene glycol diacrylate (EGDA)

EGDA was prepared as follows: 180 mL of distilled EG and 358.6 mL of triethyl amine were charged to a 2-L three-neck RB flask fitted with a mechanical stirrer and a condenser. AC (208.4 mL) was charged to an addition funnel and added slowly to the above mixture with continuous stirring. Stirring was continued for 1 h, after the addition was complete. The product was filtered to separate the triethyl amine hydrochloride. EGDA was further purified by redistillation under reduced pressure in the presence of HQ.

Synthesis of PU prepolymer

The polyurethane prepolymer was prepared by reacting 64 g of castor oil with 23 g of TDI (NCO/OH ratio = 3.17) using DBT as the catalyst (Table I). In a typical reaction, castor oil and TDI with a few drops of DBT were charged to a beaker and stirred. The reaction was carried out at room temperature (28 ± 1°C) with continuous stirring for 5–10 min to complete it to such an extent that the polyurethane prepolymer was obtained as a thick syrup (Network A).

Synthesis of PU/PAN prepolymer mixture

Required amounts of AN monomer, EGDA crosslinker, and BPO initiator (Table I) were charged

to a beaker and mixed thoroughly until a homogeneous solution was obtained. A specified amount of this mixture was added to the urethane prepolymer in the form of a viscous solution. The mixture was stirred at room temperature for 10 min to form a homogeneous viscous mass. The compositions having higher amounts of PU prepolymer were highly viscous and the air entrapped during mixing was removed by applying a vacuum. On the other hand, the composition rich in AN was heated to 70°C to initiate the polymerization of AN for different intervals of time until an optimum viscosity was obtained. The structure of the crosslinked polymer is given as Network B.

Synthesis of simultaneous PU/PAN/GPR IPN

Preliminary studies carried out on the cure time (gelation time) of the PU system (castor oil, TDA, DBTDL), PAN system (acrylonitrile, ethylene glycol diacrylate), and the GPR system (general-purpose polyester, ethyl methyl ketone peroxide, cobalt naphthenate) reveal that all three systems take approximately equal time for gelation. Hence, the IPNs consisting of PU, PAN, and GPR networks with various compositions were synthesized by a simultaneous method and the formulations are given in Table I. The cured structure of GPR is given as Network C.

The required amount of GPR was charged to a beaker, after which specified amounts of the synthesized PU/PAN precursor were added and stirred well for 20 min using a mechanical stirrer at a speed of 250 rpm. A 1% solution of cobalt naphthenate in dibu-

PAN / EGDA NETWORK (B)



Structure 2

tylphthalate was added to the above mixture (1 mL for 100 mL of resin), stirred well, and 1% solution of MEKP (1 mL for 100 mL of resin) in dibutylphthalate was added with constant stirring. The mixture was degassed by placing in a vacuum desiccator for 10 min. Then the mixture was poured into a mold and cast into sheets.

Fabrication

For casting, two glass sheets of 6 mm thickness having dimensions of 30 × 30 cm were used. One side of each of the glass sheets was coated with PVA and an inert polymer film (to prevent phase separation attributed to the reaction of unreacted hydroxyl groups of PVA with isocyanate to produce polyurethane and to enhance smoothness and glossiness of the surface of the sheet) was placed over the PVA film as a support. These two glass plates were placed one over the other with a leather spacer of 3 mm thickness, in such a way that the polymer films lie inside facing one another. Then the glass sheets were clamped tightly together on three sides and one side was kept open for pouring

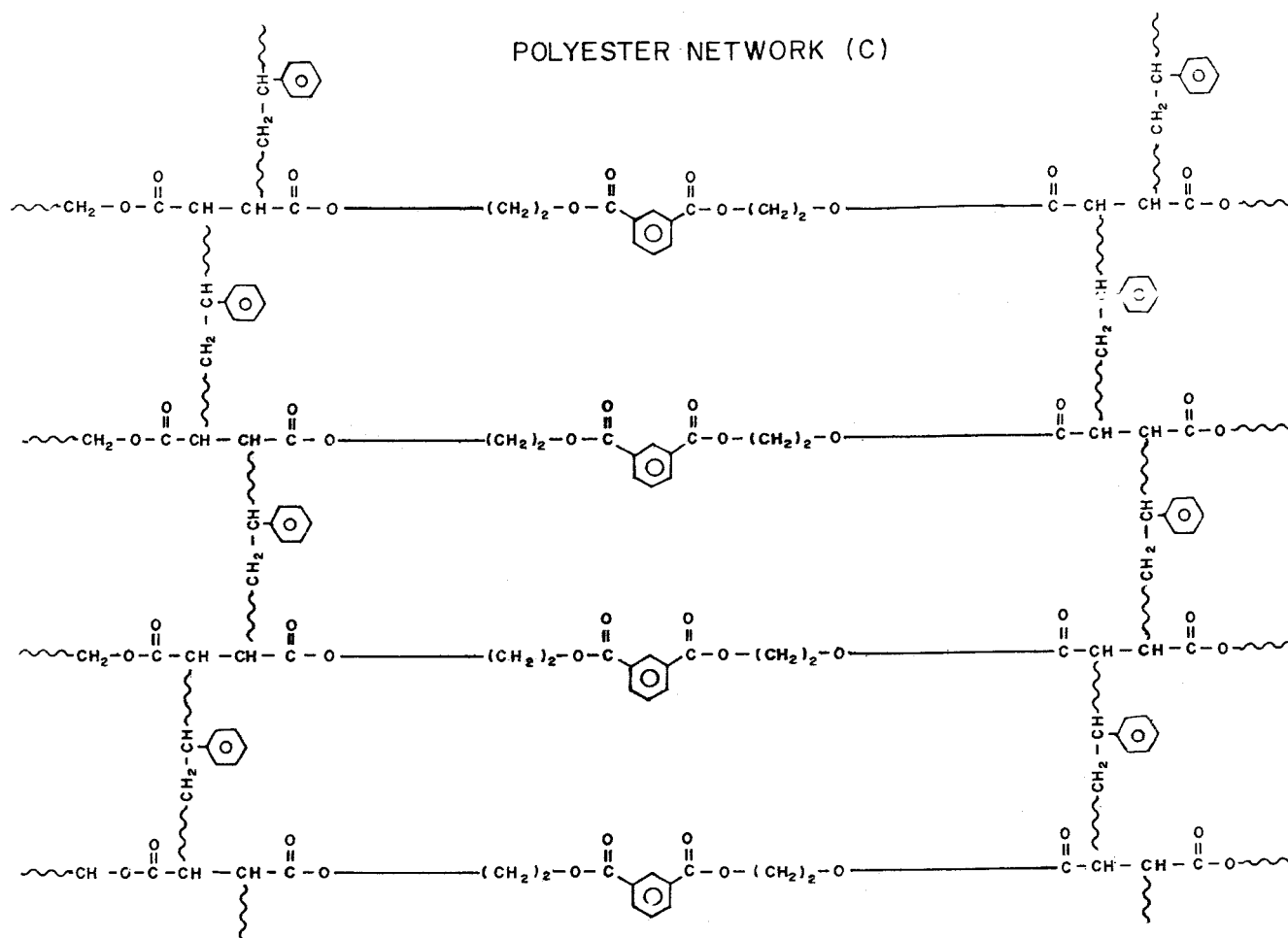
the resin into the mold. The IPN prepolymer mixture was then poured into the mold and allowed to stand for 12 h for complete curing. After that, the sample piece was removed and cut into required specimen size, according to ASTM standards for studying the mechanical properties such as tensile strength, flexural strength, impact strength, and hardness. Adopting the above procedure, IPN 3–IPN 20 and IPNs B to G were cast into sheets and cut into test specimens. At least four specimens of each type were made, subjected to testing, and the average was taken.

FTIR studies

The FTIR spectra of PU/PAN IPN and PU/PAN/GPR IPN were obtained by using a Nicolet Avatar 360 model (Nicolet Analytical Instruments, Madison, WI). The samples were ground with KBr and taken in pellet form.

Testing of IPN network

The tensile (crosshead speed 0.5 mm/min; ASTM D 638) and flexural (crosshead speed 0.5 mm/min;



Structure 3

ASTM D 790) properties were determined using a Universal testing machine (HTE-S Series-H 50K-S model; Hounsfield Test Equipment, UK). The impact strength (ASTM D 265) of all IPNs was measured using an impact tester (type 1997, S.N.117; International Engineering Industries, Bombay, India). The hardness (ASTM D 2240) of the IPNs was studied using Tree Durometer/Shore D hardness tester (Blue Steel Engineer's Pvt., Bombay, India).

Thermogravimetric analysis

The thermal stability and compatibility of the IPNs were determined using a Perkin-Elmer thermogravimetric analyzer (model TACD 7; Perkin Elmer Cetus Instruments, Norwalk, CT) in N_2 at a heating rate of $20^\circ\text{C}/\text{min}$.

Swelling studies

The swelling behavior of the IPNs in water and toluene was studied. The specimens (dimensions: $1 \times 1 \times 0.3$ cm) were kept immersed in water and toluene

for 48 h. Then the specimens were blotted with filter paper to remove the solvent and weighed. The weight difference was used to determine the extent of swelling of the various IPNs in the respective solvents.

Morphological studies

Microphotographs of fractured surface of the IPNs were taken using a scanning electron microscope [SEM (model S-415A; Hitachi, Osaka, Japan), equipped with a 6×7 in. Mamiya camera, having maximum of 25,000 (25K) time magnification capacity]. The tensile fractured surfaces were coated with a thin layer (i.e., 200–250 Å) of a gold-palladium alloy to prevent cracking while imparting energetic electron beams using an HBA/2 Carl Zeiss vacuum system (Zeiss, Jena, Germany) at about 10^{-5} Torr and then mounted vertically on an SEM stub using silver adhesive paste.

RESULTS AND DISCUSSION

Reaction of hydroxyl groups of castor oil with TDI yielded liquid isocyanate terminated prepolymer PU

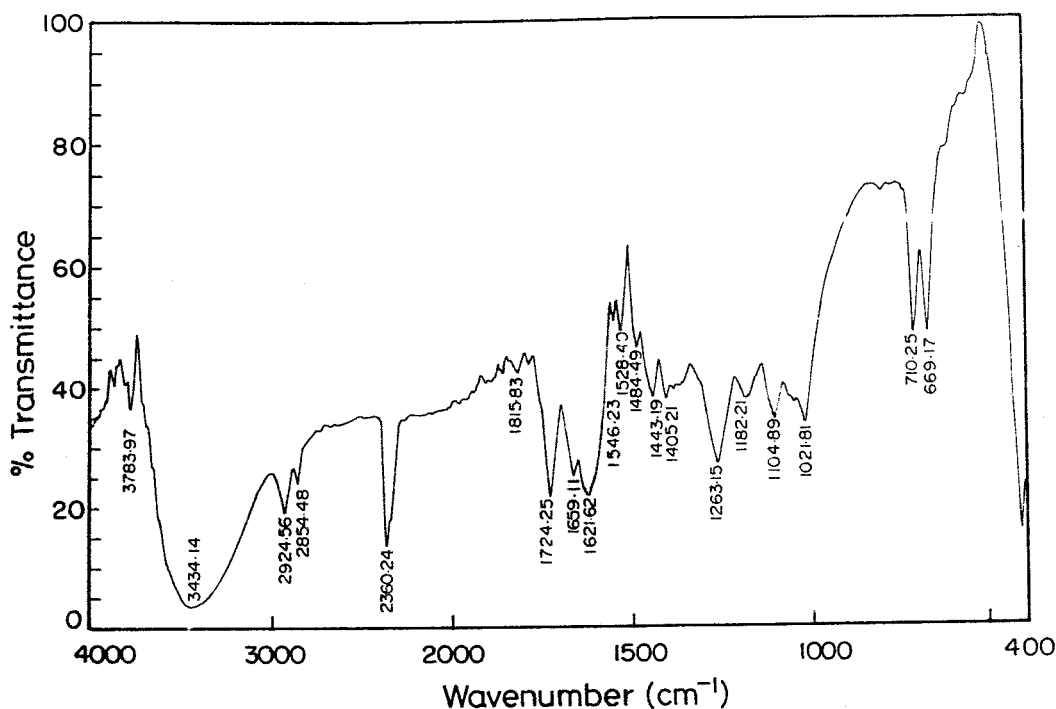


Figure 1 IR spectrum of PU/PAN IPN.

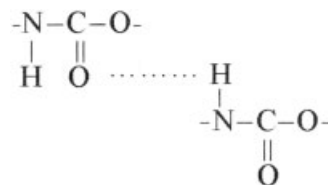
with different NCO/OH ratios. Initially, the prepolymers were soluble in organic solvents such as acetone, dioxane, toluene, and dimethyl formamide because of meager crosslink density. However, upon standing at room temperature, the prepolymer continued to crosslink, resulting in an insoluble mass, but swollen by common organic solvents. Reaction of this soluble urethane prepolymer (before being extensively crosslinked) with a mixture of AN monomer, EGDA crosslinker, and BPO initiator yielded a syrupy liquid prepolymer of PU/PAN IPN, which was also soluble in acetone and toluene. (When this liquid was allowed to stand for about 2 h, an insoluble solid PU/PAN IPN was formed.) The PU/PAN IPN prepolymer was combined with a mixture of GPR, catalyst, and accelerator and allowed to stand, which resulted in the formation of PU/PAN/GPR IPN.

FTIR spectra

The FTIR spectrum of PU/PAN IPN (Fig. 1) indicates characteristic frequencies of urethane linkage around 1724 cm^{-1} for $>\text{C}=\text{O}$ stretching. N—H stretching vibrations of the urethane linkage led to a broad band centered at 3434 cm^{-1} . The in-plane bending vibrations of C—H bonds in the aromatic ring (of TDI) appear as weak bands at 1021, 1104, 1182, and 1263 cm^{-1} . The bands at 1404, 1443, and 1484 cm^{-1} are attributed to the C=C stretching vibrations within the aromatic ring. The out-of-plane ring-bending vibrations appear as sharp bands at 710 and 668 cm^{-1} . The

spectrum also displays sharp bands at 2924 and 2854 cm^{-1} attributed to the asymmetric and symmetric stretching vibrations of the methylene group of PAN. The CN group of PAN gives a sharp band at 2360 cm^{-1} . The bands at 1182 and 1263 cm^{-1} may be attributed to $>\text{CH}_2$ wagging and scissoring.

The FTIR spectrum of PU/PAN/GPR IPN is shown in Figure 2. The broad bands at 3434 and 1723 cm^{-1} may be assigned to the N—H and $>\text{C}=\text{O}$ stretching vibrations of the urethane linkage, respectively. The intermolecular hydrogen-bonded carbonyl appears at 1639 cm^{-1} . Thus in the system under investigation the following type of hydrogen-bonding interactions occurred. Hydrogen bonding involving carbonyl as acceptors and $-\text{NH}_2$ groups as donors cannot be entirely ruled out.



The spectrum also displays absorption bands attributed to in-plane bending vibrations of C—H in the aromatic (1071 , 1126 , and 1279 cm^{-1}) ring, out-of-plane (703 , 743 , and 648 cm^{-1}) ring bending, and C=C stretching (1449 and 1490 cm^{-1}) vibrations within the aromatic ring. A weak band appears at 2360 cm^{-1} attributed to the CN group of PAN and shoulders

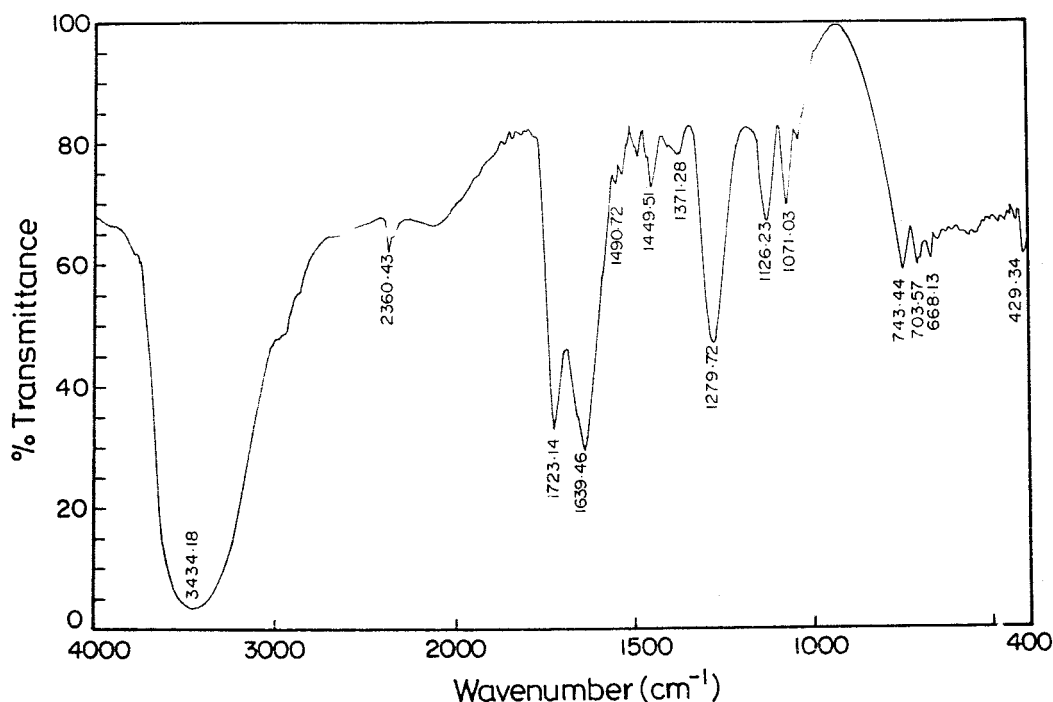


Figure 2 IR spectrum of PU/PAN GPR IPN.

appearing on the high-frequency side of N—H stretching band are attributed to asymmetric and symmetric stretching of the $>CH_2$ group of PAN. The ester $>C=O$ stretching vibrations are overlapped in the bands between 1639 and 1723 cm^{-1} .

Thermal analysis

The thermal stability of the PU, PAN, and PU/PAN IPN and that of PU/PAN/GPR IPN were studied from the TGA curves shown in Figures 3 to 6. Their initial and maximum decomposition temperatures are listed in the respective figures. The PU/PAN IPN starts decomposing at about 225°C. Two-stage decomposition was observed; the first weight loss (maximum) occurring at 388°C (PU) is attributed to the decomposition of urethane linkage and the second weight loss (maximum) occurring at 340°C (PAN) is attributed to the decomposition of PAN. The PU/PAN/GPR IPN (IPN 10) undergoes single-stage decomposition, initial decomposition occurring at 120°C and maximum weight loss occurring at 415°C. Single-stage decomposition shows excellent compatibility between the various constituents of the IPN with this particular composition.

Mechanical properties

The results of mechanical testing—tensile strength, tensile modulus, flexural strength, flexural modulus, impact strength, and hardness—are presented in Fig-

ures 7 to 10. It can be seen from the results that the inclusion of the PU/PAN network in the GPR matrix increased the flexural strength and decreased the tensile strength and elongation at break (IPN 3 to IPN 10). The tensile and flexural moduli remained almost unaffected with the increasing amount of PU/PAN prepolymer added to the GPR (IPN 3 to IPN 8), although IPN 10 has a higher modulus. These results can be explained by assuming that the hard and rigid PAN network in the IPN compensates the softening effect of the PU component. PU/PAN prepolymer undergoes extensive crosslinking reactions during curing of the GPR matrix through the double bonds of castor oil.

Because of this grafting between castor oil-based PU with GPR the morphology of the ternary IPN system was nearly a continuous phase, or at least the phase separation would be a minimum particularly for IPN 10, given that at this composition the mutual interpenetration between the three components was optimum. Such a process enhanced the modulus of IPN 10, and thus the softening effect of PU was less pronounced. Also in IPN 10, the content of the hard and rigid PAN was high, causing the matrix to acquire a high modulus. A similar type of results was obtained by Abbate et al.²⁴ for the toughening of GPR with unmodified rubber. Although the unmodified rubber decreased both the tensile and flexural modulus of GPR, the modified rubber with maleimide end groups underwent crosslinking reactions with GPR, leading to increased modulus.

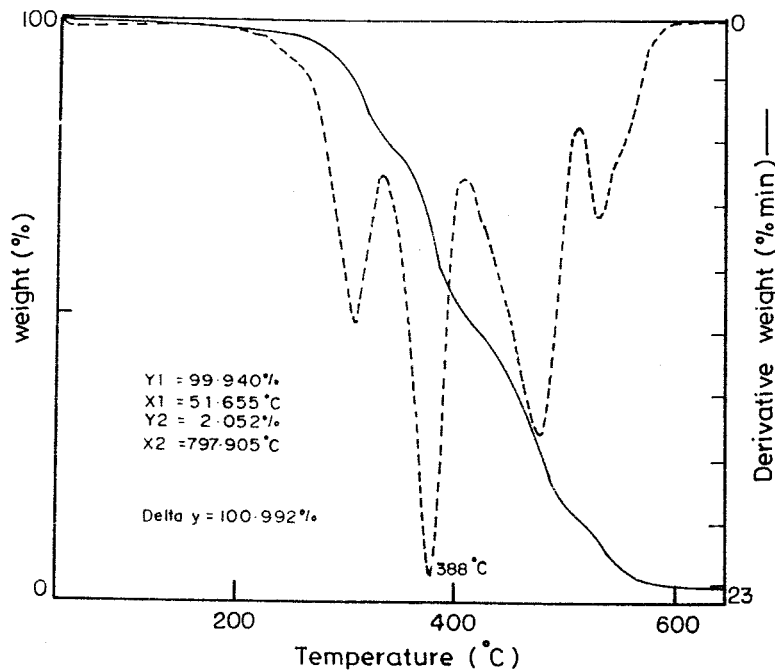


Figure 3 Thermogram of PU.

When the PAN component was increased (IPN B to IPN D), keeping the PU content constant, significant increases in tensile strength, flexural strength, tensile modulus, and flexural modulus were observed. This is contrary to the expectation that the modification of GPR matrix with elastomeric materials should lead to loss of stiffness. The above surprising observation can

be attributed to the presence of PAN matrix in the IPN. When the hard and rigid PAN matrix is also included in the IPN, the stiffness loss was minimized while maintaining the impact strength. Similar to our report, other authors¹³ also reported on the improvement in the stiffness of GPR matrix using a hard and rigid bismaleimide as the reactive second component.

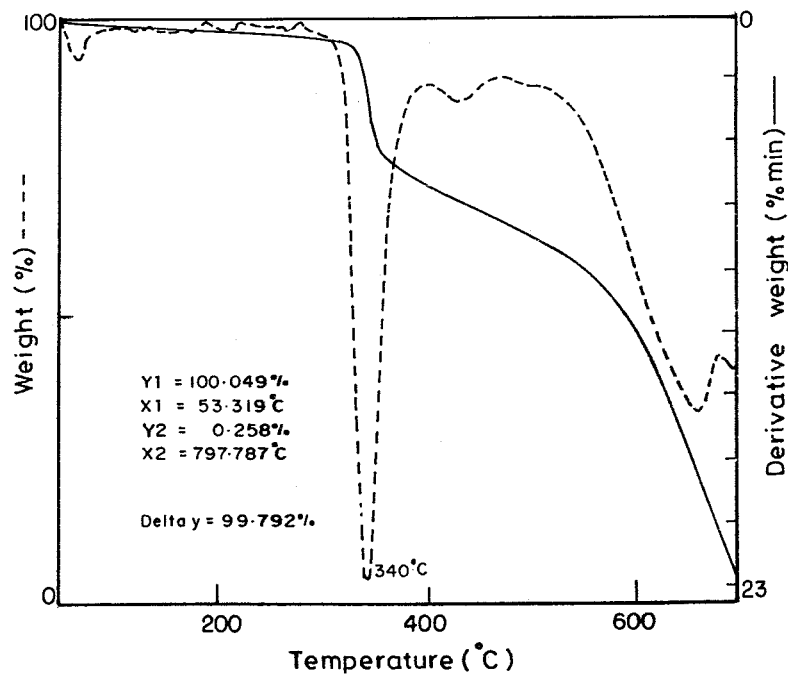


Figure 4 Thermogram of PAN.

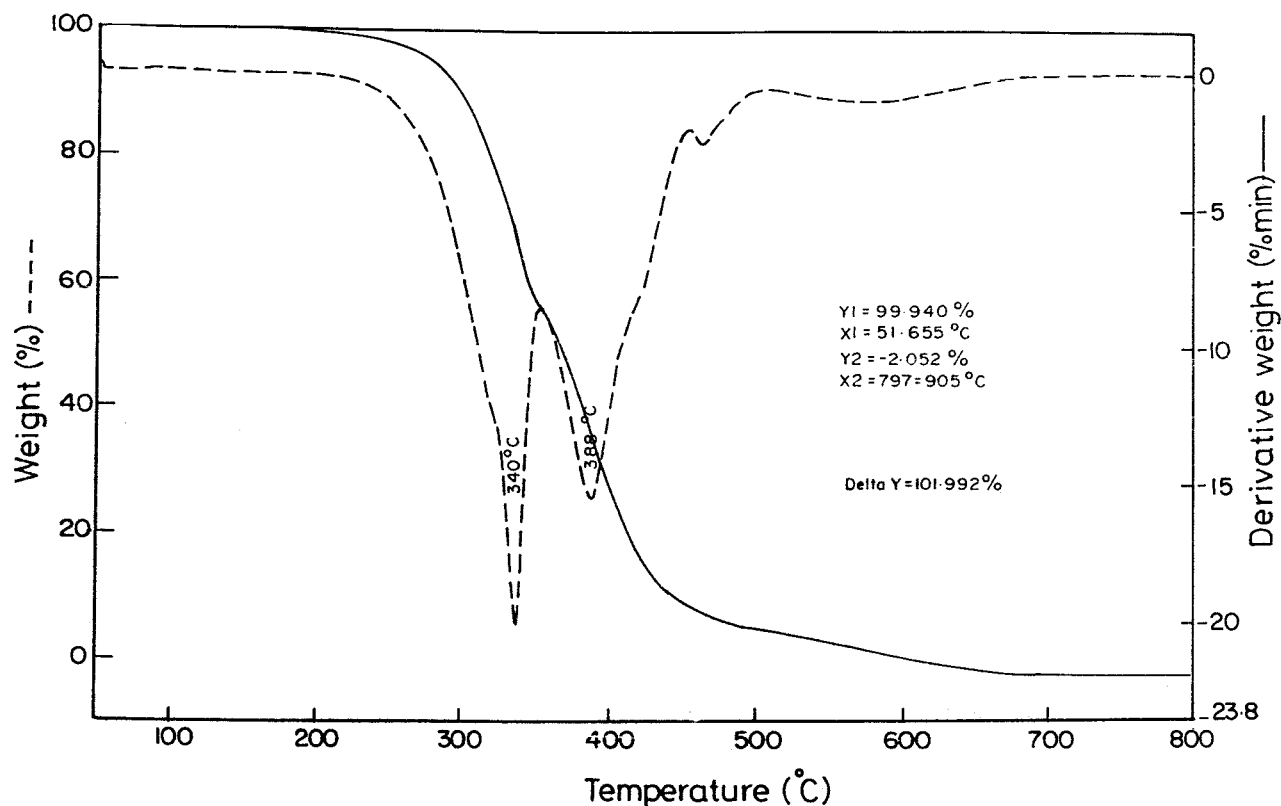


Figure 5 Thermogram of PU/PAN.

With increasing hydroxide (castor oil) content in the PU component of the IPN, the strength and moduli increased (IPN E to IPN G). This may be attributable to the increased crosslinking density in the network through the double bonds in the castor oil. The tensile elongation decreased on incorporating PU/PAN components in the GPR matrix.

The impact strength of the IPNs is greater than that of the pure GPR (Fig. 10). This is in accordance with the expectation that the inclusion of elastomeric PU matrix in the GPR matrix should enhance its impact strength. A similar type of results was obtained for PU/GPR IPNs.⁵ Akay and coworkers²⁶ reported the improved impact strength of PU/PMMA IPNs compared to that of the homopolymer PMMA. It was also reported⁵ that the reaction sequence during the IPN formation is an important factor in determining the phase mixing and phase morphology of the IPNs. It was found that simultaneous reaction of the two reacting systems resulted in a cocontinuous structure that provided enhanced tensile properties and impact strength. In the present work also simultaneous IPNs were made rather than sequential IPNs and the above-mentioned improvements in properties were observed. With increasing PAN content and hydroxide content the impact strength of the IPNs increased.

Hardness

The durometer hardness values of the various IPN-modified GPR composites are given in Figure 10. The values indicate that the GPR and IPN-modified GPR have comparable hardness.

Swelling studies

Swelling studies of IPNs are significant when either of or both of the polymers involved are hydrophilic. The swelling behavior of semi-IPNs of PU and PAN were found to be dependent on the composition and degree of crosslinking of IPNs. When immersed in water both PU and PAN form hydrogen bonds with water, which weaken the interaction between PU and PAN. Hence, water molecules can readily penetrate into the blends, causing them to swell.

From Table II it can be seen that the swelling of IPN in water decreases with increasing PU/PAN content (IPN 3 to IPN 10) because in these compositions there may be good compatibility between the PU/PAN and polyester. At higher contents of PU/PAN in the IPN (IPNs 12, 15, and 20) swelling increases because at these compositions phase separation occurs, which decreases the stability of the network and thus it swells more. In Table II, the effect of increasing the AN

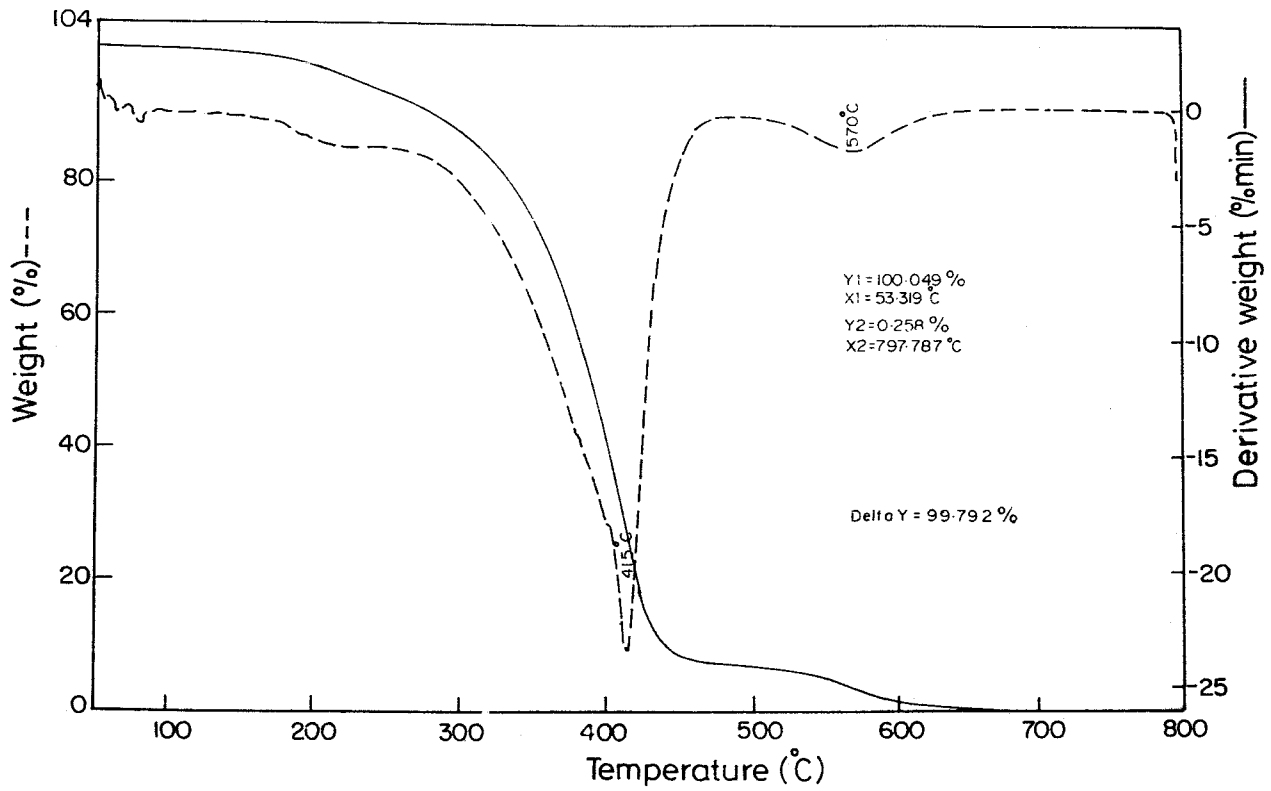


Figure 6 Thermogram of PU/PAN GPR.

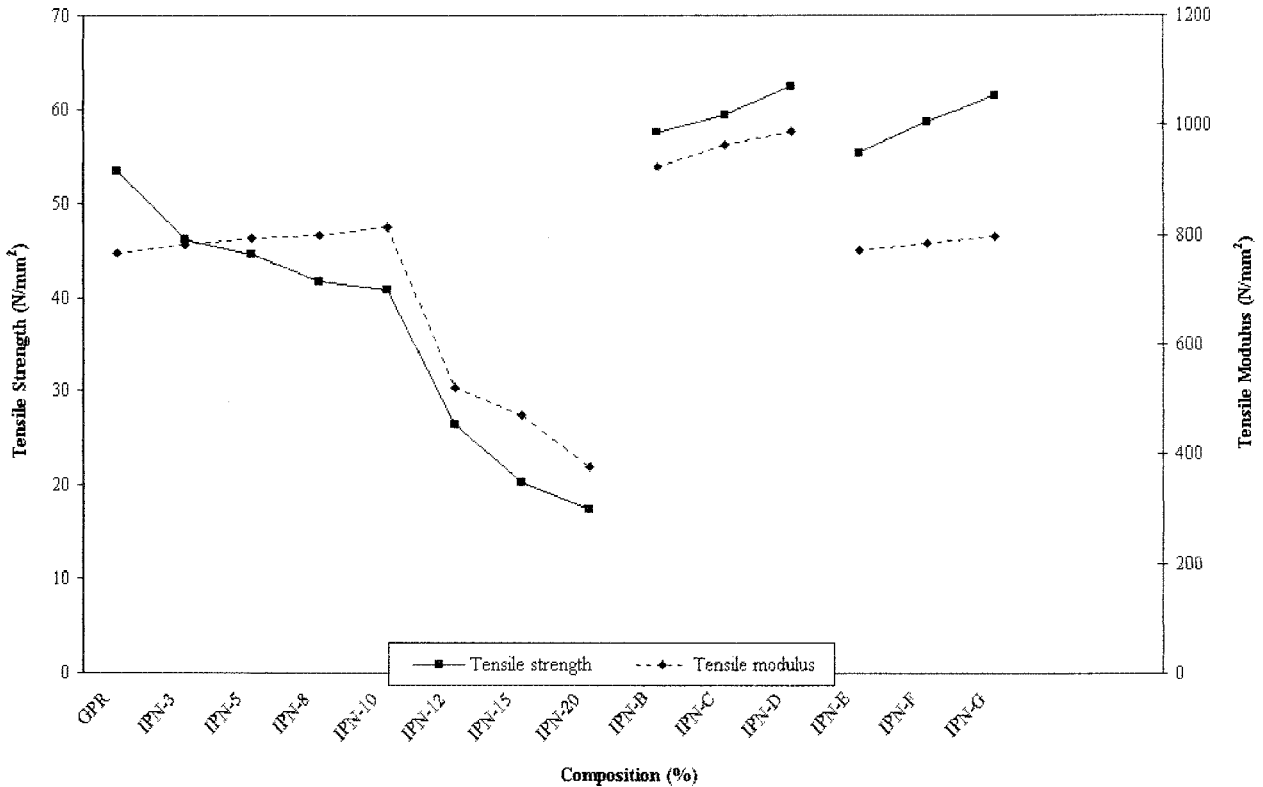


Figure 7 Plots of tensile properties of IPN-modified GPR composites.

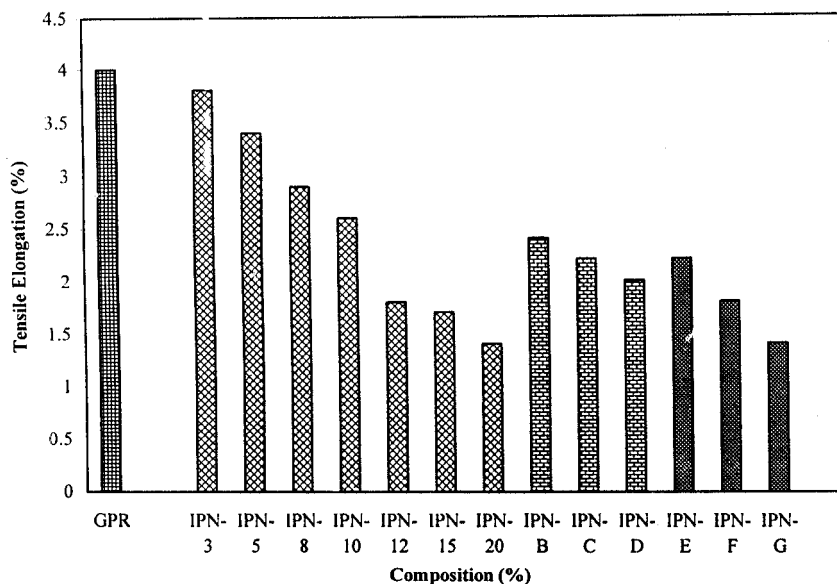


Figure 8 Tensile elongation of IPN-modified GPR composites.

content on the swelling of IPNs is presented (IPN B, IPN C, and IPN D): the extent of swelling increased with AN content, which may be attributed to greater intermolecular hydrogen bonding between nitrile groups and water molecules that facilitate the water penetration into the matrix. The effect of increase in the NCO/OH ratio on the swelling properties of IPNs is also given in Table II. It is evident that swelling increases as this ratio increases, which may be attributed to the decreased crosslinking density at lower

castor oil content (the higher the ratio, the lower the castor oil content).

All IPNs were synthesized as tough sheets. The color of these IPNs varied from golden yellow to dark yellow. The IPNs were insoluble in most of the solvents and their densities were higher than that of water. However, in toluene a considerable weight loss was noticed, given that polyester matrix swells in toluene (the styrene part of the polyester matrix swells readily in toluene), attributed to the solubility of poly-

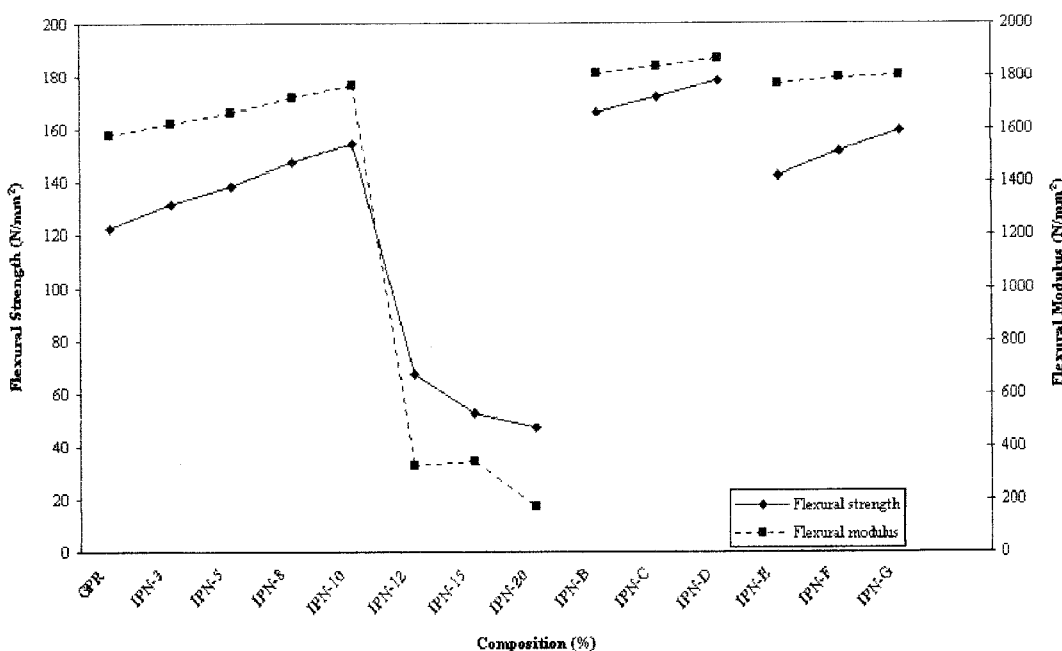


Figure 9 Plots of flexural properties of IPN-modified GPR composites.

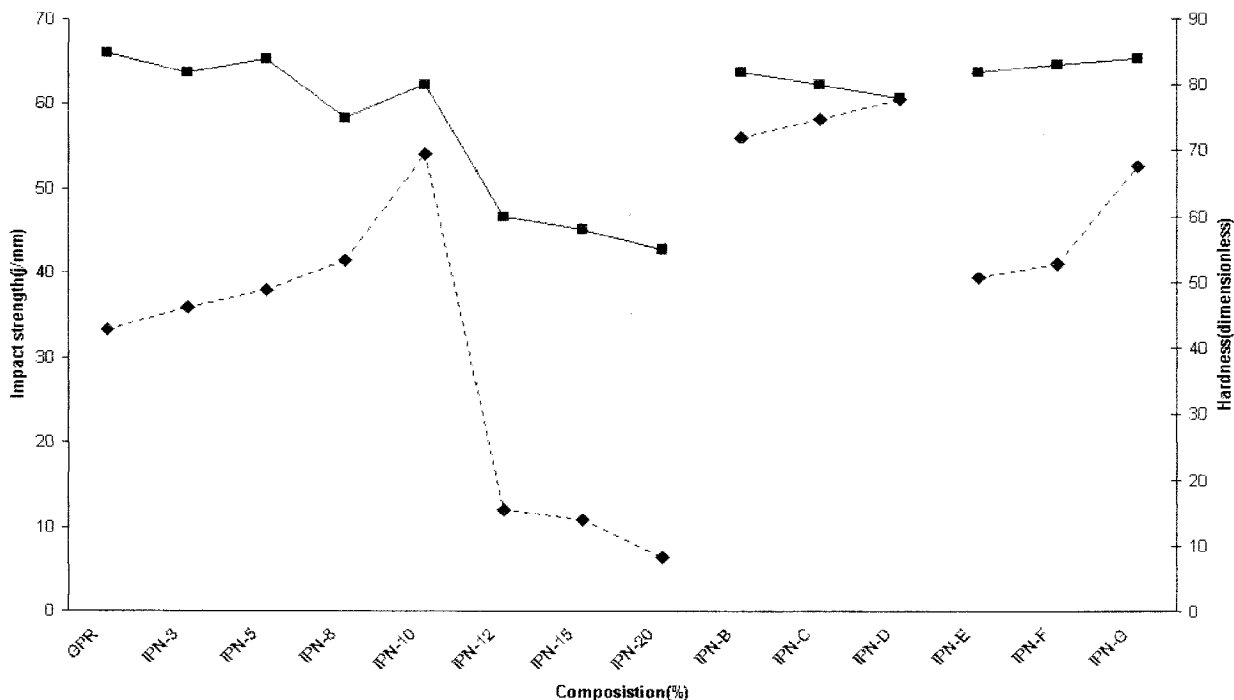
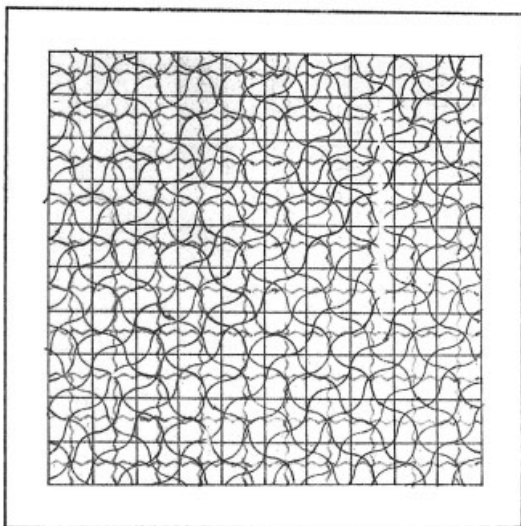
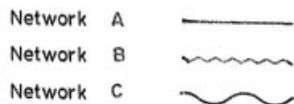


Figure 10 Plots of impact and hardness properties of IPN-modified GPR composites.

styrene in toluene. The percentage weight loss of IPNs was determined in toluene and the results are shown in Table II. With an increase in percentage of PU/PAN, the percentage of weight loss of the IPNs was decreased from IPN 3 to IPN 10. With further increase

in PU/PAN content, weight loss was increased from IPN 10 to IPN 20.

The effect of increasing the AN content on the swelling characteristics in toluene was studied and the results are given in Table II. The percentage weight loss was increased significantly, indicating enhanced solubility in toluene in the presence of higher amounts of PAN. From Table II, it is evident that with increasing NCO/OH ratio in the IPN (IPNs E, F, and G), the percentage weight loss is comparatively less, indicating decreased solubility.



Structure 4

TABLE II
Swelling in Water and Toluene (48 h)

Sample	Gain in weight in water (g)	Loss in weight in toluene (g)
IPN 3	0.0286	0.0171
IPN 5	0.0235	0.0161
IPN 8	0.0200	0.0131
IPN 10	0.0064	0.0100
IPN 12	0.0175	0.1304
IPN 15	0.0206	0.1745
IPN 20	0.0304	0.1800
IPN B	0.0069	0.2098
IPN C	0.0105	0.5858
IPN D	0.0255	0.5228
IPN E	0.0035	0.0141
IPN F	0.0024	0.0800
IPN G	0.0169	0.0048

Morphologies of modified and unmodified GPR system

The morphology of the cured unmodified and IPN-modified polyester matrix was investigated by SEM and the resulting micrographs are given in Figures 11 and 12. The tensile fractured surface of the unfilled resin (Fig. 11) shows a brittle failure. The tensile fractured surface of IPN-modified GPR with the particular composition (IPN 10) is smooth at the magnification of 500 \times , thereby showing perfect compatibility and improved phase distribution compared to that of the pure GPR matrix. However, in the pure GPR system the surface is rough. This would indicate a compositional homogeneity on a microscopic scale with respect to the IPN-modified system.

CONCLUSIONS

- Castor oil, a renewable resource, was used in the synthesis of IPNs.
- The FTIR spectra of the PU/PAN and PU/PAN/GPR IPNs indicate formation of IPNs.
- The tensile strength of GPR matrix was decreased on incorporating PU/PAN networks.
- The flexural strength of IPNs was found to be higher than that of pure GPR.
- The flexural modulus for the IPNs decreased with increasing PU content, although an increased modulus was observed at higher PAN contents.
- The impact strength of IPNs was found to be higher than that of the pure GPR.
- The IPNs and the pure GPR resins were found to have comparable hardness values.
- With increasing PU/PAN content in the GPR matrix, swelling in water and loss of weight in toluene were observed.
- The PU/PAN/GPR IPN undergoes single decomposition, showing ideal compatibility at this composition (IPN 10).



Figure 11 SEM micrograph of pure GPR.

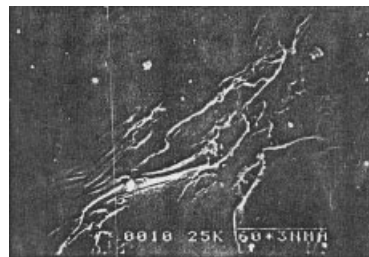


Figure 12 SEM micrograph of PU/PAN/GPR IPN (IPN 10).

- The morphologies of the IPNs show compatibility and good phase distribution.

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