

# New Ultraviolet-Curable Formulations for Bonding Poly(vinyl chloride)-Coated Fiberglass Wire Mesh for Reinforcement Applications

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**ABSTRACT:** The advantages of the ultraviolet (UV)-curing process are numerous, including a rapid cure, conservation of energy, environmental and user friendliness, and superior finish properties such as a high gloss and chemical and scuff resistance. In addition, the UV-curing process offers flexibility suitable for sensitive substrates and complete screen stability because UV ink dries on exposure only to a UV-energy source and not to ambient UV-light sources such as sunlight or fluorescent shop lights. Industrial methods apply traditional heat setting to form mesh reinforcement structures from poly(vinyl chloride)-coated fiberglass wires. The main defects of this method are the inefficiency and inconsistency of the process plus the huge consumption of power needed to generate the necessary

thermal energy to bond the wire mesh. The heating process also causes quicker degradation of the wire and shortens the lifetime of the product. The purpose of this current innovative work is to replace this defective heat-setting method with the more efficient and very advantageous method of applying UV-curable coatings for this task. The obtained results are prospective for this endeavor, covering the issues of energy conservation, the economy of the process, and the improved mechanical properties of the finished product. © 2008 Wiley Periodicals, Inc. *J Appl Polym Sci* 111: 3058–3064, 2009

**Key words:** coatings; curing of polymers; lithography; photopolymerization; poly(vinyl chloride) (PVC)

## INTRODUCTION

The application of coated fabrics as architectural membrane materials for lightweight structures has grown dramatically. As flexible materials, coated membrane materials have very little bending stiffness and therefore have only tensile resistance. Polyester yarn coated with poly(vinyl chloride) (PVC) has been reported to have better mechanical properties as the thickness of the PVC coating increases.<sup>1</sup> PVC-coated fiberglass wire mesh is found in many application areas as well. A screen made of these wires is an open mesh that is placed in concrete during the fabrication of cement board or backer board. The cement board is screwed to the floor or wall, and then the tile is glued to the cement board. This kind of mesh is placed on the top and bottom of the concrete, increasing the strength of the cement board. The traditional method for bonding these PVC-coated fiberglass wires uses radiant heaters. This method is inefficient and requires enormous power to generate the necessary thermal energy to

bond the wire mesh. In addition to being inefficient, the current heaters also transfer a large amount of heat to the working environment, resulting in poor working conditions. The radiant heaters also fail to heat the mesh uniformly across its surface area. The heating process causes the PVC to soften, and this in turn can cause gaps in the PVC coating, exposing the fiberglass wire to the outer circumference. This causes quicker degradation of the wire and shortens the lifetime of the product. The task of this work is to rectify this problem by finding a more efficient method than heat setting for bonding the wire mesh while lowering the amount of heat released into the surroundings and improving the quality of the mesh itself.

The traditional inefficient heat-setting method for bonding PVC-coated wire mesh can be solved in a variety of ways. The initial problem has four different characteristics: energy inefficiency, excessive heating of the working environment, reduced product quality, and a lack of standardized guidelines. The lack of standardized guidelines means that some of the heaters in the traditional heat-setting method are running at full capacity, whereas others are not; this leads to rough results. The ideal situation is to be able to set all the heaters to the same intensity and obtain the same results every time. A possible solution is to replace the traditional radiant

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heating elements with ceramic heating elements. These elements have an extremely efficient design, transferring almost all their input power. Along with their increased efficiency, the black body ceramic heaters offer the ability to emit certain wavelengths of infrared radiation specifically. This capability allows the heaters to be tailored to whatever material they are heating. Because the heating elements can be tailored to emit the wavelength best absorbed by PVC, the total energy required to bond the wire mesh can be reduced. This decreases the amount of heat that has to be wasted to bond the mesh, and this lowers the ambient temperature around the looms. One drawback of the black body ceramic heater is their fragility. The ceramic heater is much more susceptible to fracturing and breaking due to both static and dynamic stress than the radiant process heater. Because the heating elements and their housings take some abuse throughout the weaving process, the susceptibility to fracture presents a problem for the ceramic heater. The unit can sometimes receive serious dynamic impacting stress from the loom, which could potentially shatter the ceramic heating element.

Another way of bonding the PVC-coated wire mesh could be achieved with the ultraviolet (UV)-curing method. The UV-curing process requires a light source, which directs UV or visible light onto the formulated product. Photoinitiators absorb the UV energy from the light source, setting in motion a chemical reaction that quickly, in fractions of a second, converts the liquid formulation into a solid, cured film. The bulk of the formulation is made up of monomers and/or oligomers. Monomers are low-molecular-weight materials that can be monofunctional or multifunctional molecules, depending on the number of reactive groups that they possess. Functional monomers become part of the polymer matrix in the cured coating because their reactive functional groups undergo polymerization during exposure to UV light. Therefore, the UV-curing process is dependent on three basic parameters: the UV-irradiation wavelength, the extinction coefficient of the applied photoinitiator, and the UV curability of the monomer/oligomer system incorporated in the process.<sup>2-11</sup> The photoinitiator is a critical component of the UV-curing process as it represents the additive that initiates the polymerization process to quickly reach the final crosslinked product. As UV-light energy is emitted, it is absorbed by the photoinitiator in the mobile coating, causing it to fragment into reactive species. These can be either cationic or free-radical species. The vast majority of systems are based on free radicals, which react with the unsaturated compounds in the liquid formulation and cause them to polymerize. Of equal importance to the photoinitiators, however, is the UV-light source.

Regardless of the type of light source, however, the emission spectra of the lamp must overlap the absorption spectrum of the chosen initiator. The UV-curing lamps are typically much more energy-efficient than the radiant heating elements. On average, the UV-curing bank of lights uses 10–30% of the energy used by radiant heating elements. In addition, because UV curing does not rely on radiating heat to accomplish the bonding, the temperature of the working environment would be much lower than that with the heat-setting method. UV curing leaves the PVC coating intact and does not in any way expose the fiberglass wire. This lowers the number of imperfections in the wire and greatly improves the life and quality of the product. In addition, UV curing is a more dependable process that allows the operators to set all lamps to the same settings on the looms and achieve the same results. The UV-curing process has several advantages. First, the UV-curing system uses irradiation and chemicals and does not rely on copious amounts of heat to bond the wire mesh; this improves the working environment. Second, because the PVC is not melted and then solidified, the chance of exposing the fiberglass wire is significantly less with UV curing than with radiant heat curing, and this in turn would increase the lifetime of the wire mesh by sheltering the fiberglass wire from elements that might degrade its strength. The UV-curing process also has multiple disadvantages; among them, there are several safety concerns that must always be met during the process, and the UV lamps steadily degrade during their lifetimes, producing less UV energy. The estimated life of a UV lamp is typically the number of hours until the output energy of the lamp reaches 90% of the initial maximum output. This problem can be solved by overdesign of the lamp requirements so that the energy required by the process is 90% or less of the actual output of the UV lamp chosen. The main disadvantages of UV curing are the safety considerations and hazards coming from either the UV-light source or the monomers involved in the chemical reaction. However, the overall advantages of using the UV-curing technique overwhelm its drawbacks.

## EXPERIMENTAL

### Materials

The two monomers applied in this study were ethoxylated (30) bisphenol A diacrylate (CD9038) and ethoxylated (20) trimethylolpropane triacrylate (SR415); both were purchased from Sartomer Co., Inc. (Exton, PA) Irgacure 754, a phenylglyoxylate-based free-radical photoinitiator, was provided by Ciba Specialty Chemicals Corp. (Mobile, AL). It is a mixture of oxyphenyl-acetic acid-2-(2-oxo-2-phenyl-

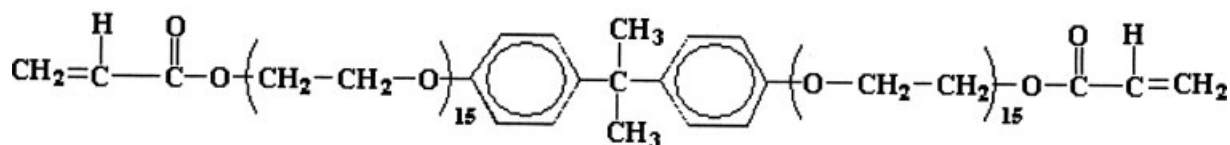


Figure 1 Chemical structure of CD9038.

acetoxy-ethoxy)-ethyl ester and oxyphenyl-acetic-2-(2-hydroxyl-ethoxy)-ethyl ester photo-initiators. Solvents such as methanol and toluene were purchased from Sigma-Aldrich Co. (Milwaukee, WI) and were used without further purification. The chemical structures of CD9038 and SR415 are shown in Figures 1 and 2.

### Curing conditions

All test samples studied in this work were prepared through the curing of their formulations by the addition of 2.0 wt % Irgacure 754 to the monomer formulation and irradiation by a UV-light source with an output wavelength of 365 nm and a total output power of 2400 W. The velocity of the conveyor belt was set at 5 ft/min for a total distance of 33 in. with an HC6-400 UV-curing station (UV Connection Inc., Spring, TX), as shown in Figure 3. For selecting the best monomer, both CD9038 and SR415 monomers were tested separately first by the coating of  $5 \times 7$  in.<sup>2</sup> mesh sections. The method of monomer application was changed from brushing to spraying to reduce the amount of monomer consumption. The coated wire-mesh sections were mounted onto a fixed-size aluminum frame that was designed especially for this purpose to prevent the monomer from pooling and filling the open mesh, which is undesired action. Samples were then subjected to UV curing under the specified curing conditions. To make sure that the curing was complete, all test samples were passed into the UV-curing station two or three times. After UV curing and drying overnight at the ambient temperature, the cured samples were cut into 35-in.<sup>2</sup> sections at a 45° wrapped angle and tested for the tensile strength characteristics (see Figs. 3–5).

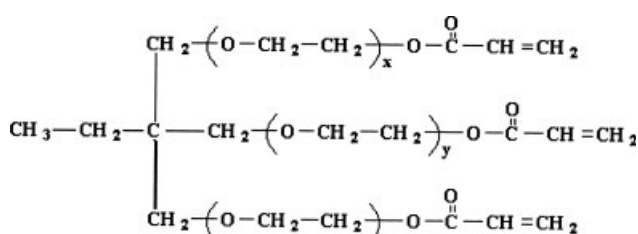


Figure 2 Chemical structure of SR415.

## RESULTS AND DISCUSSION

### Introduction to UV curing and definition of the term

The growth of UV curing in the past few decades has been phenomenal, and as a result, it has become an established industrial process. The marketplace makes its demands, chemists continue to strive for coatings to suit the criteria of new products, machine builders continue to produce even faster and complex machines, and UV-lamp suppliers produce lamps with even higher power levels. UV-curing processing has become one of the most rapidly developing fields in the entire coatings industry, and this has placed it far ahead of the general coatings field in terms of annual growth, despite the existence of initial problems. The transformation of a reactive liquid into a solid by irradiation, leading to polymerization and in most cases also to crosslinking, is termed *curing*. Infrared-, microwave-, and

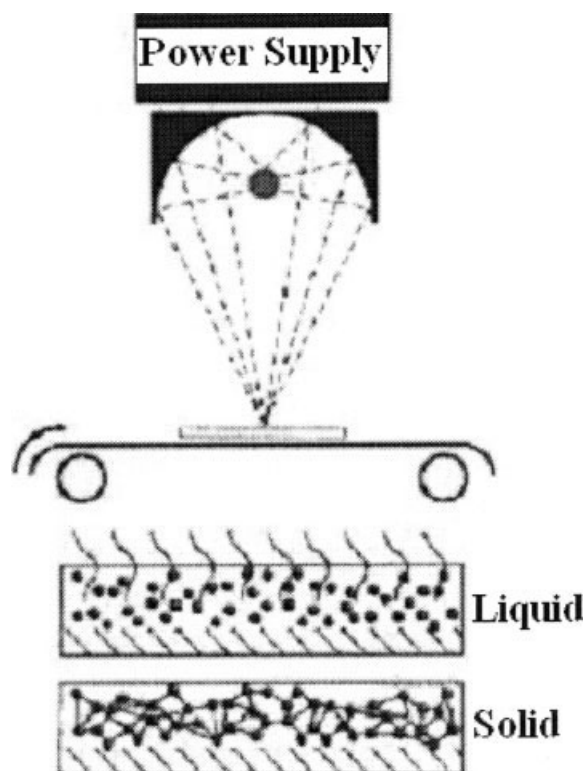
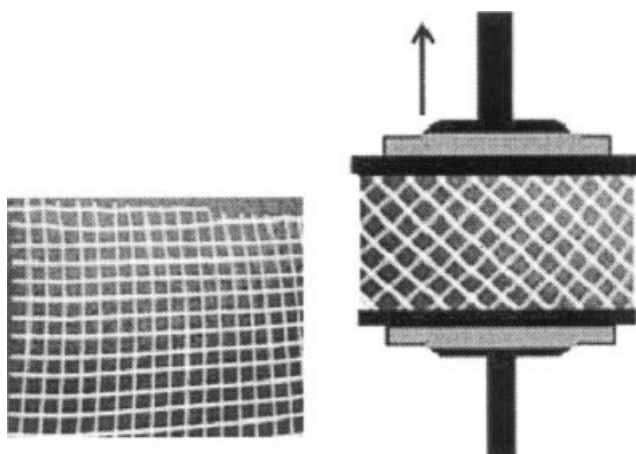


Figure 3 Sketch of the UV-curing station.



**Figure 4** PVC-coated fiberglass mesh with a  $5 \times 7$ -in.<sup>2</sup> section cut at  $45^\circ$  declined angles with respect to the thread direction.

radio-frequency radiation initiates thermal curing, whereas UV and electron-beam irradiation work via electronic excitation, and ionization leads to nonthermal curing. This simple definition refers to the well-known fact that organic molecules become electronically excited or ionized after energy absorption. Energies between 2 and 8 eV are typically needed to transform organic molecules from a ground state to an excited state. The excited molecules are able to undergo chemical reactions, which may lead to chemically reactive products, which initiate the fast transformation of the liquid into a solid.<sup>12</sup>

### Components of UV curing

#### UV source

UV light is part of the optical region of the electromagnetic spectrum and is generally recognized as being between the wavelengths of 200 and 400 nm. Visible light from 400 to 760 nm and infrared energy

from 760 nm to 1 m are also components of the optical region. Industrial UV lamps produce energy across the full spectral range of the optical region.

#### Chemical formulation

A UV formulation is a blend or mixture of a number of chemical components designed to meet the properties required by the production method and the finished product. It is the task of the UV chemist to choose the components of the formulation to achieve the required properties of the finished product. There are two categories of UV-curable chemistries, free-radical and cationic.

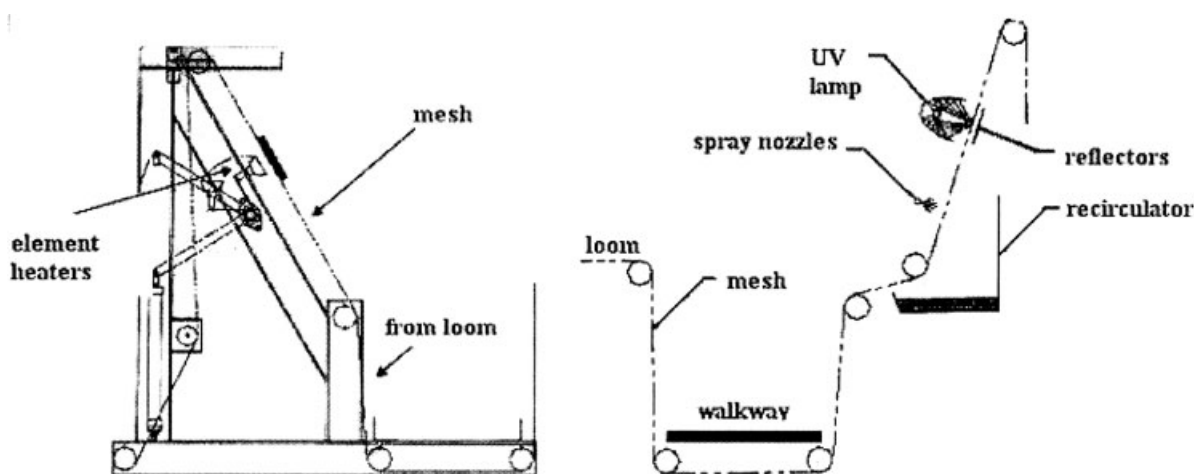
#### Free-radical photoinitiator

UV light does not usually have sufficient energy levels to interact with the reactive groups of the molecules within the coating and generate free radicals. Instead, a photoinitiator is added to the formulation, which when exposed to UV light of a specific wavelength absorbs the UV light and produces free radicals, which start the crosslinking process; this results in virtually instant polymerization.

#### Cationic photoinitiator

As with free-radical UV chemistry, the same principles of formulation component selection apply. Although different monomers and oligomers are normally required for this type of chemistry, the main difference lies within the photoinitiator selection. Cationic photoinitiators, generally aryl sulfonium salts, form an acid catalyst when exposed to UV light and consequently start the cationic chemical reaction.

Unlike free-radical UV chemistry, it is generally accepted that cationic curing is not affected by the



**Figure 5** Sketch of the traditional thermal bonding line (left) and the future UV bonding line (right).



**TABLE I**  
Bond Strength Results for the Cured Samples Coated with Monomers in the Absence of Solvents

Pass	Monomer	Monomer consumed (g/ft <sup>2</sup> )	Method applied	Bond strength (lb)
a1	SR415	N/A	Brush	2.1
a2	SR415	5.27	Brush	2.6
a3	SR415	4.16	Brush	2.9
a4	CD9038	7.12	Brush	2.7
a5	CD9038	5.39	Brush	4.3
a6	CD9038	7.12	Brush	5.1
a7	50 : 50 wt % mixture	14.40	Brush	6.5
a8	50 : 50 wt % mixture	6.17	Brush	5.2
a9	50 : 50 wt % mixture	5.06	Brush	4

presence of oxygen, and the reaction continues to proceed even after the removal of the UV-light source.

#### Acrylate monomers and UV-radiation curing

The most commonly used UV- or electron-beam-curable formulations contain the acrylate unsaturation with their characteristic functional group (CH<sub>2</sub>=CR-COOR': R=H = acrylate, R=CH<sub>3</sub> = methacrylate). Methacrylates are known to be less reactive than acrylates and are used in special applications. The polymerization of acrylates is initiated by radicals. Chain propagation and termination as well as crosslinking are radical processes. The polymerization of acrylates is a typical radical polymerization of vinyl monomers.<sup>13</sup> Acrylate double bonds are consumed during the polymerization process. Therefore, the degree of double-bond conversion is a measure of the degree of cure. With experimental methods such as stationary or time-resolved infrared spectroscopy, the double-bond conversion can be either determined after a certain time or followed as a function of time.<sup>8</sup>

#### Bond strength results

The basic task of this study was to replace the traditional and defective heat-setting method for bonding

PVC-coated fiberglass wires with an alternative more efficient and nondegrading method such as coating with UV-curable coatings (see Fig. 4). The key point of this work was to seek the most polar/hydrophilic UV-curable monomers to accomplish the wetting for the polar PVC surfaces and hence ensure better coverage of the surface with the monomer and consequently stronger bonding. The selected monomers were reported to be water-soluble and the most hydrophilic of all UV-curable monomers, which are commonly known by their hydrophobic nature. Both monomers were also reported as low-odor, low-volatile, and low-skin-irritating and as good for free-radical polymerization. The monomers were tested separately and as 50 : 50 wt % mixtures, and all test samples showed successful results. For economic purposes and to obtain the lowest price with acceptable performance balance, the monomer component was diluted with solvents such as toluene and methanol at 50 : 50 wt % and 25 : 75 wt % (monomer/solvent), and it was taken into account that the minimum acceptable bond strength for this task was 2 lb/in.<sup>2</sup>.

Both UV-curable monomers, CD9038 and SR415, were tested separately and in a 50 : 50 wt % mixture and with no solvent and with variable solvent concentrations of toluene and methanol. Finally, we were able to determine the best recipe that showed

**TABLE II**  
Bond Strength Results for the Cured Samples Coated with 50 : 50 wt % CD9038/SR415 Solutions in Toluene

Pass	Monomer solution in toluene	Monomer consumed (g/ft <sup>2</sup> )	Method applied	Sides sprayed	Bond strength (lb)
b1	50 wt %	0.82	Brush	One	2.9
b2	50 wt %	1.09	Brush	One	4.6
b3	50 wt %	0.78	Brush	One	11.5
b4	50 wt %	0.10	Spray	One	5.8
b5	50 wt %	0.06	Spray	One	N/A
b6	75 wt %	0.03	Spray	One	3.6
b7	75 wt %	0.03	Spray	One	1.9
b8	75 wt %	0.02	Spray	One	1.7

**TABLE III**  
**Bond Strength Results for the Cured Samples Coated with 50 : 50 wt % CD9038/ SR415 Solutions in Methanol**

Pass	Monomer solution in methanol	Monomer consumed (g/ft <sup>2</sup> )	Method applied	Sides sprayed	Bond strength (lb)
c1	50 wt %	0.27	Spray	One	0.7
c2	50 wt %	0.14	Spray	One	2.8
c3	50 wt %	0.08	Spray	One	3.6
c4	50 wt %	0.08	Spray	Both	3.7
c5	50 wt %	0.21	Spray	Both	1.8
c6	75 wt %	0.04	Spray	One	3
c7	75 wt %	0.02	Spray	One	3
c8	75 wt %	0.01	Spray	One	1.8
c9	75 wt %	0.03	Spray	Both	3
c10	75 wt %	0.21	Spray	Both	2
c11	75 wt %	0.06	Spray	Both	1.5

the desired bond strength of 2.0 lb/in.<sup>2</sup> and at the same time fulfilled the minimum monomer consumption to meet the economic purpose if applied on an industrial scale. Tables I–III display all the results obtained for the bond strength for all binder compositions studied in this work along with their monomer consumption and the method of application (either brushing or spraying).

We had proven before in our earlier publications that the curing conditions applied in this work were sufficient to cause all the acrylate double bonds to interact and disappear completely from infrared spectra of the cured samples for this category of acrylate monomers.<sup>14–16</sup> The results shown in Table I show that no consistent results were obtainable when the monomers were applied directly without dilution and especially when the brush was used instead of the sprayer as a tool for coating the mesh surface. However, applying the monomer in dilute solutions to the mesh surface helped to improve the quality of the mesh surface coverage and gave results that were more consistent. Applying the monomer directly without dilution was disadvantageous as it led to nonuniform coverage of the mesh plus the overuse of the monomer, which gave a false correlation between the bond strength and the amount of monomer consumed in each pass. Applying dilute solutions of monomer components showed improved results, as indicated by the data in Tables II and III.

Samples b6–b8 and c6–c9, in which the amounts of the monomers consumed were the minimum among the samples (0.01–0.04 g/ft<sup>2</sup>), showed the required bond strength of 2.0 lb/in.<sup>2</sup>, and this indicated the success of the current innovative work.

#### Total Hildebrand solubility parameter [ $\delta$ (MPa<sup>0.5</sup>)]

$\delta$  is a numerical value that is given to both the solvent and polymer to correlate their interactions together.<sup>17–21</sup>  $\delta$  is a result of three intermolecular

forces, the so-called van der Waals forces: dispersion ( $\delta_d$ ), dipole–dipole ( $\delta_p$ ), and hydrogen bonding ( $\delta_h$ ).  $\delta$  can be calculated from these components as follows:

$$\delta = [\delta_d^2 + \delta_p^2 + \delta_h^2]^{0.5}$$

When a solvent and a polymer have solubility parameters that closely resemble each other, the solubility of the solvent in the polymer is high. In this study, the two applied solvents were toluene and methanol:  $\delta$  is 18.2 MPa<sup>0.5</sup> for toluene, 29.6 MPa<sup>0.5</sup> for methanol, and 21.4 MPa<sup>0.5</sup> for PVC polymer. However, because of the hazards of toluene according to its material safety data sheet, we recommended using methanol instead; this is in addition to the advantage of the higher volatility of methanol versus toluene, which renders it the more favorable solvent. The criterion of solvent selection for accomplishing the task of this study most successfully is to find the solvent that dissolves the monomer mixture into a homogeneous solution and at the same time does not attack the substrate surface at any level of chemical or physical interactions. In reference to the values of  $\delta$  for both solvents, it is clear that toluene would be a more drastic solvent than methanol toward the substrate surface of PVC, and so it may cause an undesirable level of deterioration in its thickness during the complete UV-curing process.

This criterion for solvent selection in the current work resembles the art of flexographic printing with UV acrylate-based ink formulations on shrink films such as PVC, oriented polystyrene, and glycol-modified poly(ethylene terephthalate). The solvent selection in flexographic printing is a crucial task, and its effectiveness depends on its ability to adequately dissolve one material while leaving the others unaffected.<sup>22–25</sup> Therefore, toluene as a solvent with  $\delta = 18.2$  MPa<sup>0.5</sup> is expected to attack the PVC substrate surface ( $\delta = 21.4$  MPa<sup>0.5</sup>) more powerfully than methanol as a solvent could ( $\delta = 29.6$  MPa<sup>0.5</sup>).

Ethanol, as an environmentally friendly solvent and with respect to its total Hildebrand value ( $\delta = 26.5 \text{ MPa}^{0.5}$ ), would be the best solvent that could be used in this specific example of a monomer/substrate couple. Although the data given in Tables I–III show the success of the current endeavor, the odd results exhibited by samples b6 and b7 are simply due to the primitiveness of the tools applied in substrate coating using either brushes or sprayers. These primitive tools are expected to be the reason for the inaccurate coating of the PVC substrate surface with the monomer solution. This imperfect coating of the substrate surface with the monomer solution accounts for this false correlation between the amount of monomer consumption and the resulting bond strength for these two specific samples coded as b6 and b7.

Another useful test that must be passed in quality control testing for the final wire-mesh products is the dye test. The dye test examines the proper coating of PVC over the core of fiberglass at the end of the processing and bonding of the wire-mesh products. The test involves the wire-mesh sample being placed in a bath of red dye and left for a period, and then the sample is removed and inspected to see if any dye has wicked into the fiberglass core through any holes in the PVC coating. Although some wicking is typically found in samples made with the traditional heat-setting method, the UV-curing samples were virtually perfect with no wicking. This is more proof promoting the bonding of PVC-coated fiberglass wires with these new UV-curable formulations rather than the traditional heat-setting method.

### CONCLUSIONS

1. The UV-curing technique was successfully tested as an alternative technique for bonding PVC-coated wire-mesh instead of the traditional heat-setting procedure, and it showed prospective results.
2. The desired bond strength of  $2.0 \text{ lb/in.}^2$  for bonding PVC-coated wires was achieved with the application of the minimum amount of the UV-curable monomers.
3. The solvent selection for preparing the dilute monomer solutions is a crucial task, and its criterion resembles that of flexographic printing using UV-curable ink formulations on shrink polymer films.

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