

IMPROVING THE LONG-TERM PERFORMANCE  
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**Abstract.** Since neat PVC is rigid, in all applications a plasticizer is added. Migration of the plasticizer results in brittleness of flexible PVC and environmental pollution. We have used three types of cross-linking agent blended with commercial PVC, plasticizer and thermal stabilizer. Heat treatments at 100 °C, 121 °C and 136 °C were performed. We made tensile tests, dynamic friction tests, wear rate determination, scratch resistance determination, water absorption tests and SEM analysis – to make selection of compositions suitable for sufficient cross-linking for long term applications.

**Keywords:** poly(vinyl chloride), plasticizer containment, PVC thermal stability, PVC scratch resistance.

## 1. Introduction

Poly(vinyl chloride) (PVC) is one of the most widely used synthetic polymers. Its worldwide consumption is around 40 million metric tons – while the average demand for PVC increases about 5% every year.

PVC was first accidentally created by the German scientist Eugen Baumann in 1872.<sup>1</sup> He left overnight a flask with vinyl chloride exposed to sunlight. Next day he found a white solid inside the flask. The material was quite brittle (more on brittleness B below), hence it did not find applications. In 1926 Waldo Semon produced a plasticized PVC,<sup>2</sup> also by an accident. He tried to get an unsaturated polymer that would have good adhesion to metals by boiling PVC in a solvent at a high temperature.

Contemporary flexible PVC exhibits good mechanical properties, high electrical resistivity, and – importantly – it is resistant to corrosive solutions and relatively fire resistant. In addition to these advantages, low cost of PVC makes it a good option for construction

materials, pipes and wire insulators. PVC tubes are used as a reinforcement in recycled aggregate concrete.<sup>3</sup> PVC containing multi-wall carbon nanotubes is used for electromagnetic interference shielding.<sup>4</sup>

However, flexible PVC has a severe flaw: the *migration* of plasticizer is the main reason that aging of PVC is accelerated, its service life shortened. One sees the plasticizer in the form of liquid ‘tears’ on the surfaces of PVC wires and cables; customers complain to the PVC manufacturers about a defective product. Plasticizer leaching not only affects material properties, but also provides environmental pollution and potentially diseases. Heat and pressure are two common environmental factors that may force the plasticizers to move out of PVC matrix and makes PVC-based materials brittle. Such materials will not be able to withstand even relatively small deformations and fractures will occur. Khan and Patil<sup>5</sup> developed for this reason an acoustic method for detection of cracks in PVC pipes.

One puts a plasticizer often into PVC formulations.<sup>6</sup> More than 7 million tons of plasticizer are used annually and about 30% of plasticizers are emitted from PVC into air in an ‘ideal’ experimental chamber.<sup>6</sup> This is still a very large number that people should face, although the real amount of emission may be lower – depending on different environments. Clearly the problem of plasticizer migration must be controlled as soon as possible in order to isolate humans from toxic substances. A relatively less troubling but still substantial problem is that plasticizer migration towards the interface causes an increase of dynamic friction compared to that of the reference PVC.<sup>7</sup> This situation behooves us to deal with at least two issues. We have done work on nontoxic bio-plasticizers for PVC as replacements for conventional toxic plasticizers.<sup>8</sup> The other direction is improvement of thermal stability of PVC; we have done some work in this direction<sup>9</sup> but we feel that more work is warranted. Given the situation described above, we chose the method of chemical cross-linking and three different kinds of cross-linking agents – with the objective of defining the best one. Heat treatments at low, medium and high temperatures were carried out because the temperature is a significant factor that affects the rate of migration in polymers.

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## 2. Experimental

### 2.1. Materials

We have used a PVC resin, plasticizer, three kinds of cross-linking agents and a thermal stabilizer. All of the components are commercially available materials. In the Introduction the purpose of employing a plasticizer and a cross-linking agent have been explained.

We need to explain the reason for using thermal stabilizer. Chlorine atoms are covalently bonded to carbon atoms in PVC structure; however, such bonds are not stable at elevated temperatures. This results in the decomposition of PVC when it is heated – prior to processing. Therefore, a thermal stabilizer is added in order to prevent degradation of PVC.<sup>10</sup>

### 2.2. Sample Preparation

Table 1 shows individual formulae for each kind of sample. Control sample was prepared without a cross-linking agent, while Samples I, II and III contained different cross-linking agents such as Cross-linker 1, Cross-linker 2 and Cross-linker 3, respectively.

In order to prepare homogeneous PVC mixtures, a heater (SCIOGEX MS-H280-Pro) and a stirrer (Cafra Petite Digital Stirrer BDC250U1) were used. First, a batch of pure PVC resin with a thermal stabilizer was preheated at 70 °C and stirred at a speed of 1500 revs/min for 5 minutes. After 5 minutes, temperature was raised to 90 °C. Second, an appropriate amount of plasticizer was added and stirred for another 5 minutes. Third, some droplets of cross-linker were dripped into the mixture and kept stirring it for 5 minutes. Once the composition was well mixed, we fed it to an extruder (Thermo Electron Corporation HAAKE PolyDrive Extruder) which has four zones and one die with different temperatures ranging from 350°C to 400°C. A sheet die with 50 mm gap was used in order to produce sheet samples.

**Table 1.** Compositions of samples

Components	Samples			
	Control	I	II	III
PVC	100 phr	100 phr	100 phr	100 phr
Plasticizer	25 phr	25 phr	25 phr	25 phr
Thermal Stabilizer	3 phr	3 phr	3 phr	3 phr
Cross-linker 1	N/A	4%	N/A	N/A
Cross-linker 2	N/A	N/A	4%	N/A
Cross-linker 3	N/A	N/A	N/A	4%

### 2.3. Heat Treatment

As well known, the temperature is a critical factor affecting the plasticizer migration rate. According to the standard requirements of Underwriters Laboratories Inc., thermoplastic-insulated wires and cables must meet the requirements of UL83 and UL2556: samples that underwent a 7-day heat treatment must maintain at least 45 % of tensile elongation at break when compared to samples not subjected to heat treatment and maintained at room temperature.<sup>11,12</sup> Following these requirements, our samples were placed in an oven (Shellab 1408 economy vacuum oven) – so that they did not touch the walls of the chamber – for 7 days at 100 °C, 121 °C and 136 °C. Table 2 lists the sample names corresponding to different temperatures of heat treatment and surfaces of the samples. We see that the control sample shows darker surface color than the cross-linked samples.

### 2.4. Tensile Tests

Some dog-bone shaped specimens were cut from flatted PVC sheets which were obtained from the extruder. The dimensions of dog-bone specimen are consistent with ASTM D638 type IV standard. Eight specimens were tested for each kind of sample with 5.0 mm/min tensile speed; a MTS® Universal Testing Machine QTEST/5 was used to determine the mechanical properties such as Young's modulus, strain at break and tensile toughness.

### 2.5. Tribological Tests

Tribology is a very broad area that includes the studies of friction, lubrication, wear, adhesion, scratch resistance and any interactions between surfaces.<sup>13,14</sup> Since our goal is providing long term performance to PVC by cross-linking, we need to evaluate the effectiveness of this process. This can be done by determination of dynamic friction.

We have used a tribological tester produced by Nanovea Inc. in the pin-on-disk mode. As the name implies, a specimen is secured on a spinning disk and it is contacted with a stationary pin which is subjected to normally 5.0 N force while the machine is running. A SS302 stainless steel ball with 3.2 mm diameter was used as a pin. During the testing, the total sliding distance is 75.36 m (6000 revolutions and a track with 2 mm radius) and the spinning speed is 200 revs/min.

### 2.6. Surface Profilometry Analysis

The purpose of profilometry analysis is to determine the wear rate, that is an index that describes the degree of abrasion. In other words, lower wear rate refers to a stronger ability to resist against abrasion. The wear rate<sup>13,14</sup> can be expressed as:

$$\text{Wear rate} = u_{sp} = V_{loss} / F \cdot D \quad (1)$$

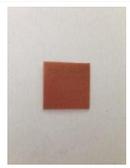
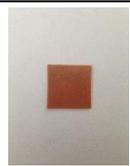
where  $F$  and  $D$  are force and total distance in tribological test, respectively, and  $V_{loss}$  is the volumetric loss of fragments separated from the specimen during testing.  $V_{loss}$  can be approximately calculated as:

$$V_{loss} = \pi \cdot R \cdot A \quad (2)$$

where  $R$  refers to the track radius and  $A$  is the cross-sectional area of a track. By combining Eqs. (1) and (2), one obtains:

$$\text{Wear rate} = u_{sp} = \pi \cdot R \cdot A / F \cdot D \quad (3)$$

**Table 2.** Samples and images of surfaces

Sample	Type of Cross-linker	Heat Treatment	Surface	Sample	Type of Cross-linker	Heat Treatment	Surface
RT-Control	N/A	N/A		RT-II	Cross-linker 2	N/A	
100C-Control	N/A	100 °C		100C-II	Cross-linker 2	100 °C	
121C-Control	N/A	121 °C		121C-II	Cross-linker 2	121 °C	
136C-Control	N/A	136 °C		136C-II	Cross-linker 2	136 °C	
RT-I	Cross-linker 1	N/A		RT-III	Cross-linker 3	N/A	
100C-I	Cross-linker 1	100 °C		100C-III	Cross-linker 3	100 °C	
121C-I	Cross-linker 1	121 °C		121C-III	Cross-linker 3	121 °C	
136C-I	Cross-linker 1	136 °C		136C-III	Cross-linker 3	136 °C	

We have used a Dektak<sup>®</sup> 150 stylus surface profilometer produced by Veeco Instruments Inc. to characterize the surface topology of our samples. The profilometer is a contact-type scanning machine which has a stylus moving across a sample with 1.0 mg force applied and the tip radius of the stylus is 12.5  $\mu\text{m}$ . The scanning length is 1200  $\mu\text{m}$  and the measurement depth is 524  $\mu\text{m}$  – fulfilling the condition that it is larger than the dimensions of every track. After 60-second scanning, the surface features are displayed as a two-dimensional graph and the surface information including the cross-sectional area is calculated by a dedicated program.

## 2.7. Scratching Tests

Viscoelastic recovery is a property that represents the ability of healing for a polymer after it is deformed by external forces in scratch resistance determination. The percentage viscoelastic recovery<sup>14,15</sup> can be written as:

$$\text{Viscoelastic recovery} = \varphi = (P_d - R_d)/P_d \cdot 100\% \quad (4)$$

where  $P_d$  and  $R_d$  are the penetration depth and the recovery depth, respectively. Penetration depth is measured simultaneously by the indenter while the indenter is scratching a specimen. On the other hand, recovery depth is detected by the indenter after a specific time in order to assure the specimen is fully recovered.

The apparatus we employed for scratching test is Micro Combi Tester produced by CSM<sup>®</sup> Instruments. The scratch length is 5.0 mm and scratch speed is 5.0 mm/min. During the scratching process, the load of the indenter linearly increases from 0.03 N to 15.0 N while the allowed recovery time is 2 minutes. We did not see percentage recovery differences of more than 1 % for recovery times longer than 2 minutes.

## 2.8. Water Absorption Tests

For these tests, average weight changes of three specimens of each sample were recorded until no obvious weight increments were observed. The weight change can be simply defined as:

$$\text{Weight change} = (W - W_i)/W_i \cdot 100\% \quad (5)$$

where  $W$  and  $W_i$  represent the current weight and the initial weight of a specimen.

Typically, all specimens stopped absorbing more water on the seventh day of tests; thus, the measurements of weight were carried out at some particular time within 7 days such as 15 minutes, 30 minutes, 1 hour, 3 hours, 6 hours, 12 hours and from the first day to the seventh one. During water absorption tests, each specimen was immersed in a separate beaker filled with hot water at 90 °C. These beakers were covered with aluminum foil in order to prevent the evaporation of water and they were placed in a furnace (Thermolyne<sup>™</sup> Atmosphere Controlled Ashing Furnaces) to maintain at the same temperature for one week.

## 2.9. Scanning Electron Microscope (SEM) Analysis

Quanta 200 SEM, a product from FEI Company, was used to observe the cross-sectional areas after tensile testing. By observing these areas at 1000x magnification, one is able to see how the PVC chains are close-packed and the chain orientations. The working distance of Quanta 200 SEM ranges from 9.4 mm to 12.8 mm and the Everhart-Thornley detector is used – operated in the high vacuum mode with the electron accelerating voltage of 12.50 kV. We could not use higher voltage for higher resolution and magnification since PVC samples could not withstand the irradiation of such high-energy electron beam.

The major damages to polymers resulting from electron beams can be categorized into two types: heat and radiolysis.<sup>15</sup> For electron beam heating, the temperature of specimen raises due to the inelastic collisions of incident electrons and molecules in a specimen. The heating damage causes degradation or even melting of polymers. For radiolysis damage, the electrons in the molecules are excited to higher energy states but do not return to stable states. Consequently, the breakages of chemical bonds are generated and cause mass loss of light atoms such as hydrogen, nitrogen and oxygen.

## 3. Results and Discussion

### 3.1. Mechanical Properties

Fig. 1 shows the tensile Young moduli of all samples after different degrees of heat treatment.

There are two important factors that influence Young's modulus: temperature and cross-linking.<sup>16,17</sup> The first evident conclusion from Fig. 1 is that Young's moduli increase as the temperature of heat treatment increases. This is easily understandable, the evaporation of plasticizer results in the PVC samples becoming more difficult to deform. We expected that adding cross-linking agents could prevent the exudation of the plasticizer and maintaining the flexibility of PVC – as demonstrated below. In Fig. 1, we find some samples containing cross-linking agents that show higher Young's moduli than the control sample; apparently the separate PVC chains were cross-linked and formed a network structure. The network structure leads to an increasing Young's modulus.<sup>18</sup> Generally, the cross-linked sample not only conserve high flexibility but also show improved Young's moduli.

Fig. 2 presents the tensile strain at break  $\varepsilon_b$  values. When the cross-linked samples are compared with the control sample, we find that the former have relatively higher  $\varepsilon_b$  values than the control sample after being sub-

jected to the same heat treatment. This can be explained by the formation of cross-links which improve the ability of stretching PVC chains.

We recall the standard requirements UL83 and UL2556:  $\epsilon_b$  must be at least 45 % after heat treatment at

100 °C, 121 °C and 136 °C. Clearly all samples studied fulfill this requirement.

Tensile toughness is defined as the area under the stress vs. strain curve. In Fig. 3, we see that the toughness increases as temperature increases and also increases after application of cross-linking agents.

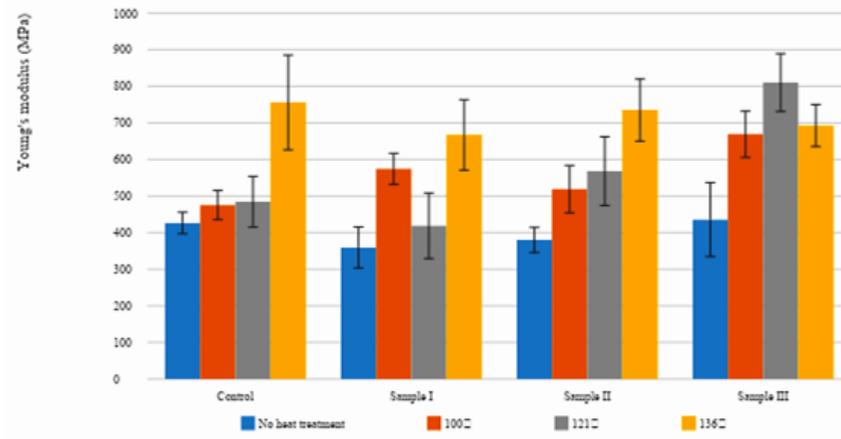


Fig. 1. Tensile Young modulus results

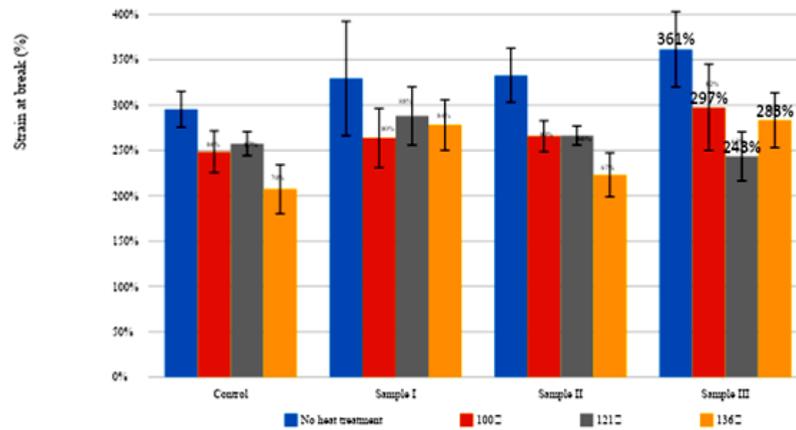


Fig. 2. Comparison of strain at break values

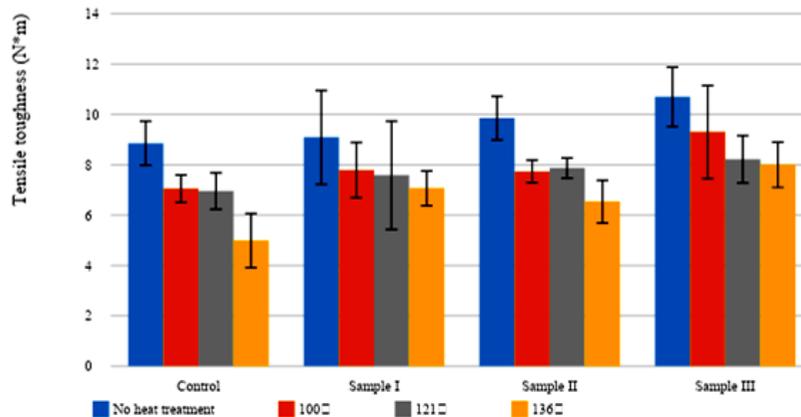


Fig. 3. Comparison of tensile toughness results

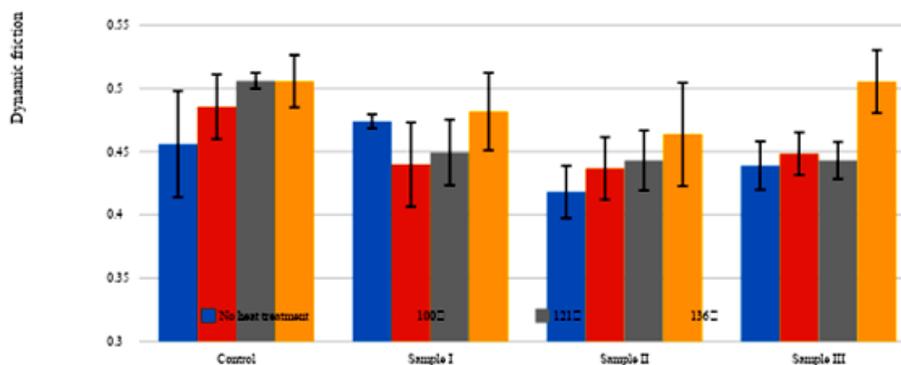


Fig. 4. Dynamic friction results; the colors pertain to the same temperatures as in Fig. 3

### 3.2. Dynamic Friction

We present these results in Fig. 4.

The friction is known to be mainly affected by two factors: nature of the surface and type of the material. The fundamental components of control sample and Sample I, II, and III were the same commercial PVC and plasticizer; thus, the differences of dynamic friction displayed in Fig. 4 are caused by changes of surfaces. Plasticizer is a viscous fluid and it increases the adhesion between two moving parts.<sup>7</sup> When the migration of plasticizer towards the surface occurs, the newly arrived plasticizer changes the surface and increases the dynamic friction.

If we focus on an individual sample in Fig. 4, we find that largely the dynamic friction increases as the temperature of heat treatment increases – since more plasticizer moved toward the surface of sample. However, if all the samples at the same temperature were compared, we discovered that largely the cross-linked samples exhibit lower dynamic friction than the control sample. Moreover, Sample II exhibits the lowest dynamic friction in every case of heat treatment. We find that the cross-links formed between PVC chains clearly mitigate the migration of the plasticizer.

In addition to the above explanation in terms of the effectiveness of cross-linking, we can interpret the dynamic friction results also from a different angle. The threshold temperature at which a significant amount of the plasticizer begins to exudate is seen in Fig. 4. Focusing on the control sample, it is worth to notice that the dynamic friction values at 121 °C and 136 °C differ very little. Apparently, the majority of the plasticizer starts to exudate around 121 °C. On the other hand, differences in dynamic friction values are seen between 121 °C and 136 °C for Sample I, II and III. We infer that a large process of exudation was launched around 136 °C for cross-linked flexible PVC. Thus, the exudation of the plasticizer in the control sample occurs at lower temperatures than in the cross-linked ones. This is another evidence of the ability of cross-linking agents in restricting plasticizer exudation.

### 3.3. Wear Rates

Wear is often an unexpected process from the industrial viewpoint; it costs large amounts of money to maintain worn parts or replace damaged ones. Some ways of decreasing wear are being developed. Cross-linking is one of the methods to decrease the wear rate – as discussed by Galvin and her colleagues.<sup>19</sup> They tell us that ultra high molecular weight polyethylene wear debris is a major cause of long term failure of total joint replacements. We consider the results in Fig. 5 from this point of view.

According to Fig. 5, an increase of wear rate with the treatment temperature is found for all samples. It can be explained that the surface of each specimen is occupied by more plasticizer as the temperature becomes higher. The high density of the plasticizer on the surface results in a higher dynamic friction and a larger amount of debris formed. Thus, controlling the migration of the plasticizer is a crucial way to reduce the wear rate. Aside from the effect of residual plasticizer, the network structure resulting from cross-linking is another factor enhancing wear resistance.<sup>19</sup> The tightly combined chains in cross-linked flexible PVC prevent the mobility and fractures of chains and the detachment of fragment from a specimen. Briefly speaking, the results of wear rate reveal that Sample I, II and III achieve high enough wear resistance, especially when they underwent high-temperature heat treatment. Thus, cross-linked flexible PVC can survive longer without oozing plasticizers and generating damage.

### 3.4. Scratch Resistance and Viscoelastic Recovery

Any polymer is viscoelastic, hence it exhibits simultaneously elastic (solid-like) and viscous flow (liquid-like) under application of a mechanical force.<sup>14</sup> We have determined  $P_d$  and  $R_d$  values as described in Section 2.7. The results are shown in Figs. 6 and 7.

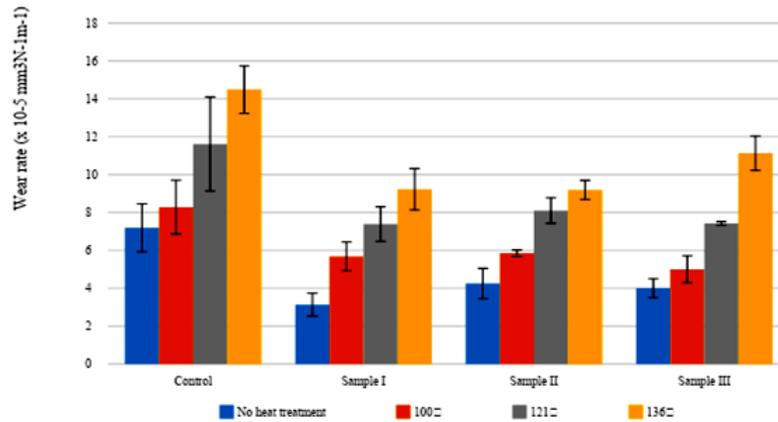


Fig. 5. Comparison of wear rates

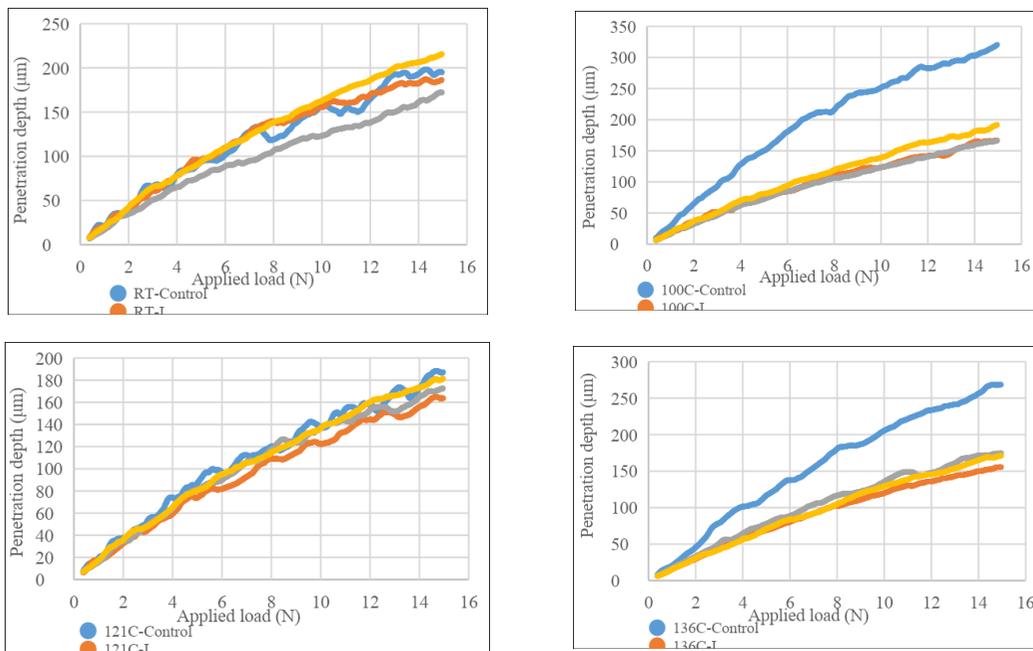


Fig. 6. Penetration depth results

According to Figs. 6 and 7, large differences of penetration depth and residual depth between control sample and cross-linked samples are observed, especially for samples that underwent heat treatment. We can infer that the cross-linked samples retain more plasticizers and higher flexibility – that results in shallower penetration and residual depths.

Fig. 8 presents the viscoelastic recoveries  $\phi$  defined by Eq. (4) explaining the effectiveness of cross-linking. We notice in that Figure for low applied loads some inaccuracies in recovery values. This is understandable since we are dealing with percentage differences between small values.

An equation defining brittleness was formulated,<sup>15,21</sup> namely

$$B = 1/(E' \cdot \varepsilon_b) \tag{6}$$

where  $E'$  is the storage modulus determined in dynamic mechanical testing and  $\varepsilon_b$  is as before the tensile strain at break at the same temperature.

It was demonstrated that  $B$  is inversely proportional to the viscoelastic recovery defined by Eq. (4).<sup>21</sup> Later, it was shown that  $B$  is inversely proportional to the tensile toughness.<sup>22</sup> Therefore, return now to the results of tensile toughness. Cross-linked samples exhibit higher tensile toughness than the control sample. Particularly for the heat treatment at 121°C and 136°C, we observe large differences of tensile toughness between cross-linked samples and control sample. We see in Fig. 8 that the

control sample exhibits relatively lower viscoelastic recovery than the cross-linked samples.

Importantly, we conclude that viscoelastic recovery is improved by cross-linking because more plasticizers are

contained inside the PVC matrix and the flexibility of PVC is maintained. This conclusion from  $\phi$  results is in agreement with results of tensile testing, dynamic friction, and wear rates too.

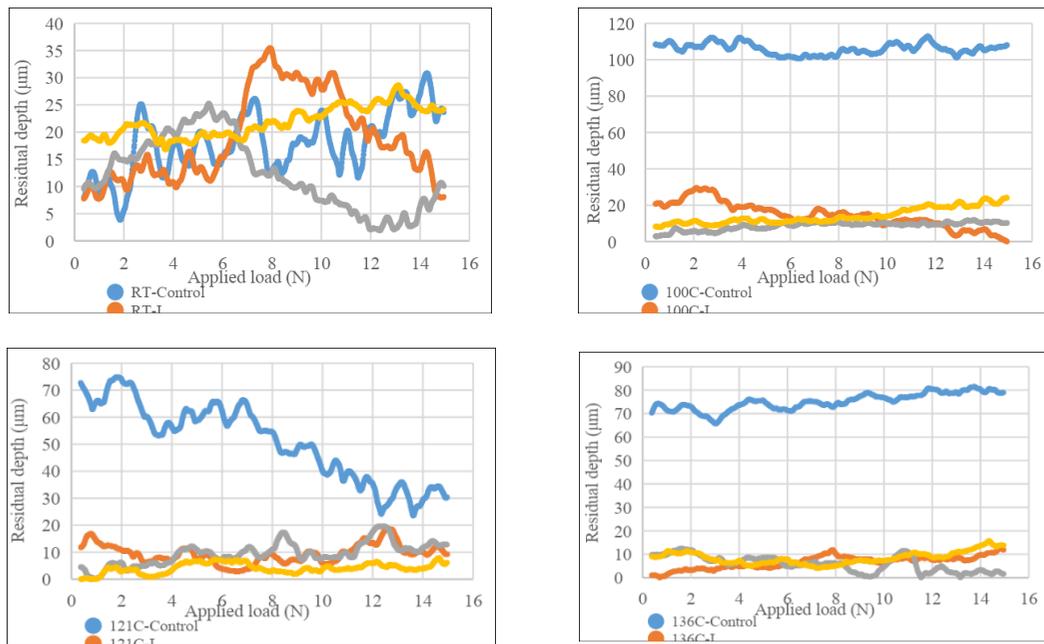


Fig. 7. Residual depth results

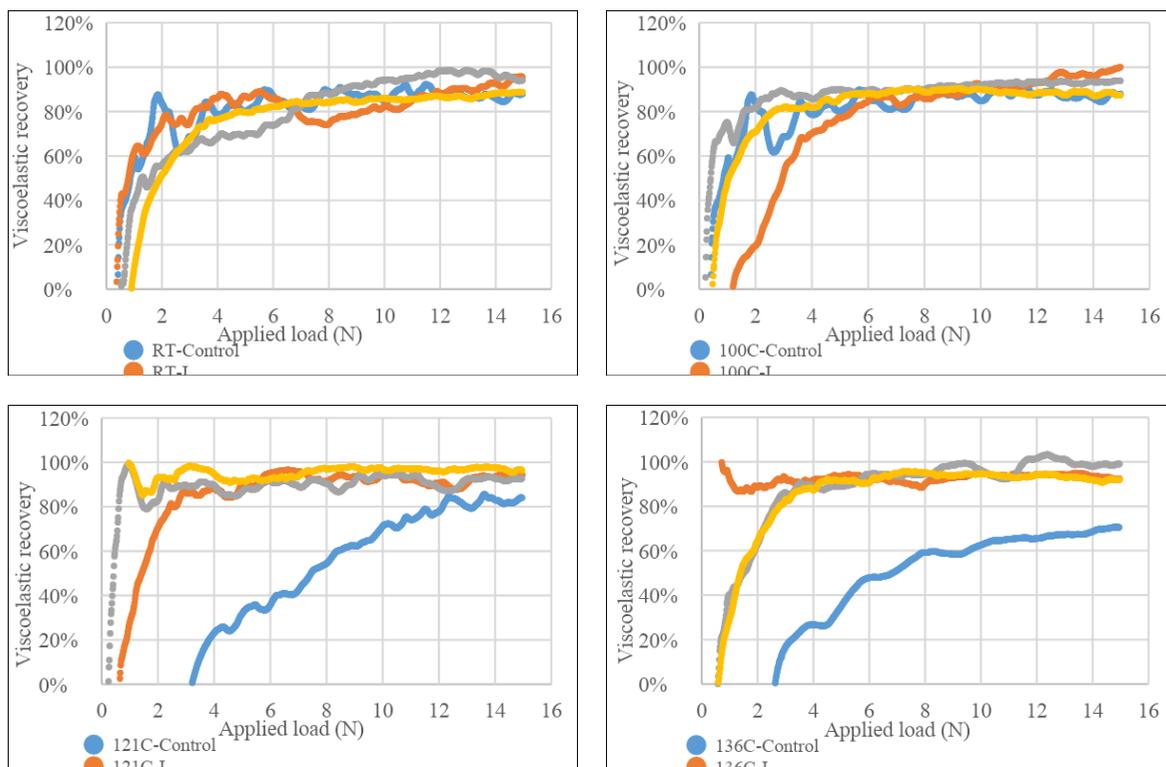
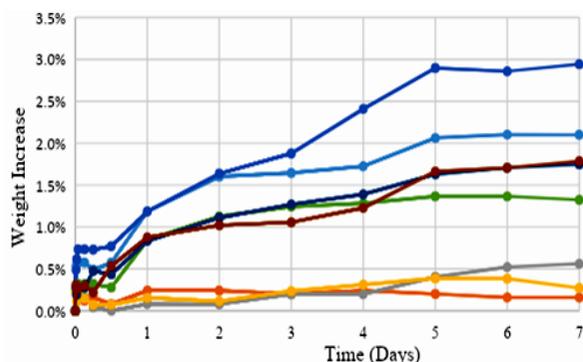


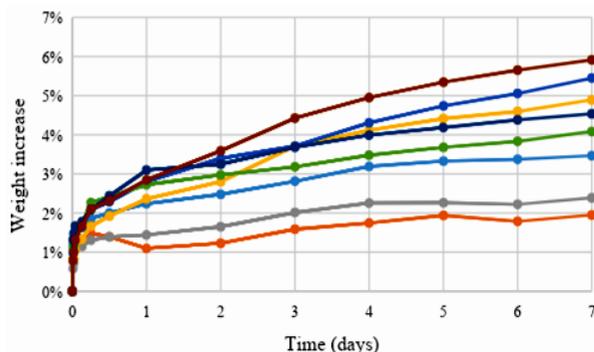
Fig. 8. Viscoelastic recovery results

### 3.5. Water Absorption

In general, flexible PVC is classified as a hydrophobic material, hence water repellent. This is confirmed by results in Figs. 9 and 10. Small amount of water were absorbed by non-cross-linked flexible PVC, between 2 % to 6 % of its initial weight. Apparently, water molecules were attracted by C–Cl bonds in flexible PVC. The polarity of C-Cl bonds is the main reason for water absorption because Coulombic attraction is created between C-Cl bonds and water molecules which are well known as polar.



**Fig. 9.** Weight increase as a function of time for samples without heat treatment and samples with heat treatment at 100°C



**Fig. 10.** Weight increase as a function of time for samples with heat treatment at 121°C and 136°C

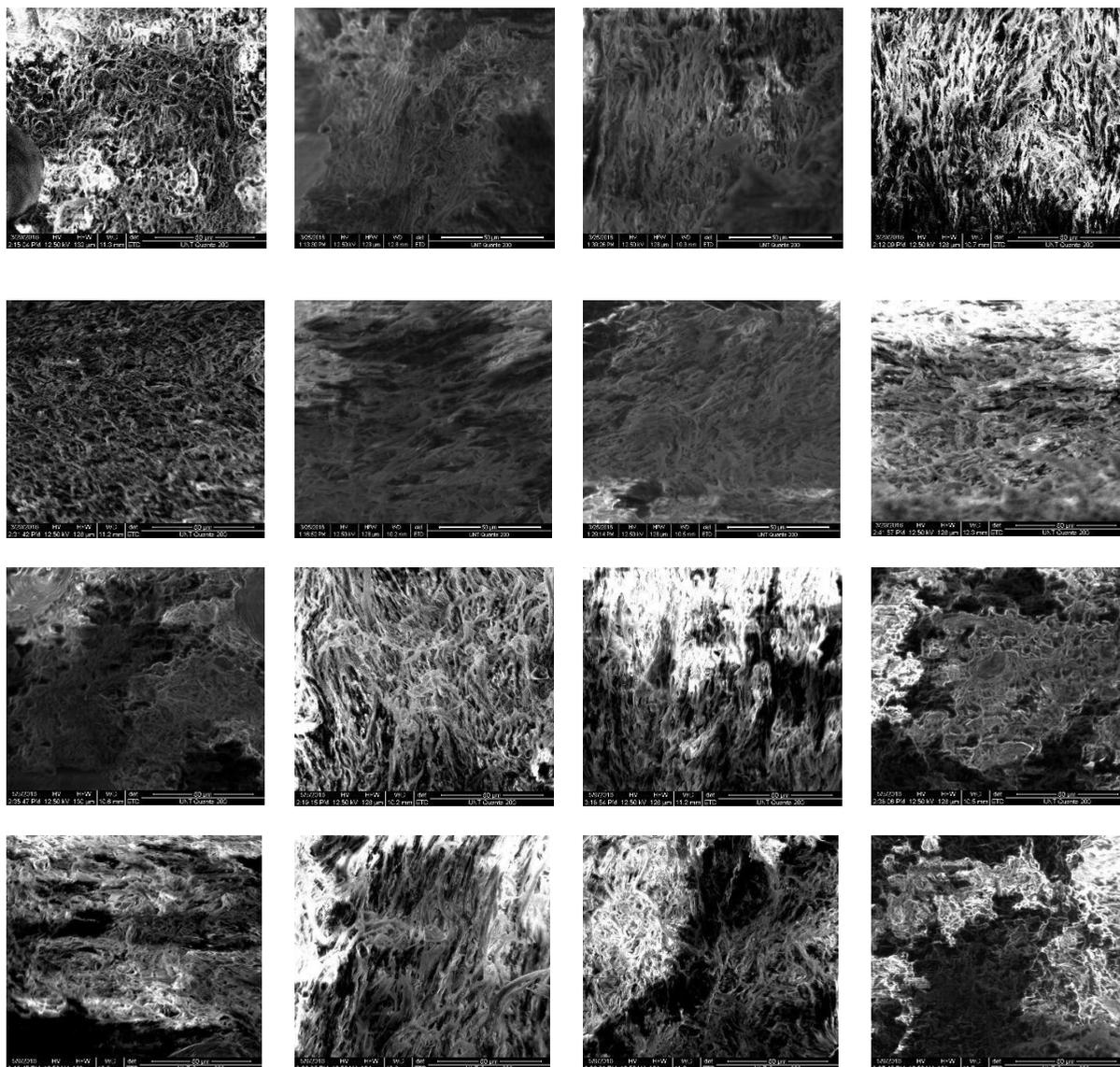
In addition to polarity, the issues of free spaces and cross-links between PVC chains are other factors that influence the results of water absorption tests.<sup>22</sup> As we have already known, cross-links are thought as barriers while the plasticizer molecules are moving. Water molecules are repelled by such barriers and it is difficult for them to occupy the free spaces between PVC chains. The relatively small free spaces limit the amount of water absorbed at saturation by flexible PVC with significant cross-linking.

Consider Fig. 9; the weight increments are: for the control sample we have 2.10 % and 2.94%; for Sample I we have 0.16 % and 1.33%; for Sample II we have 0.56 % and 1.75 %; for Sample III we have 0.27 % and 1.79 %. For samples without heat treatment and with heat treatment at 100 °C, Fig. 9 shows that all cross-linked flexible PVC samples show less water absorption than the control sample does. We infer that there were more free spaces left by the migration of plasticizer and no cross-links were present to hinder the „invasion’ of water molecules into the control sample. On the other hand, in Fig. 10 we notice that Sample I and II maintain low weight increments compared to the control sample, while the weight increments for Sample III exceed those for the control sample at high degrees of heat treatment.

### 3.6. SEM Analysis

SEM is a convenient method to understand how cross-linking agents change the structure of flexible PVC; however, the limit in using high energy electron beam and high magnification is a disadvantage when polymers are concerned. In Fig. 11, we can find some evidences of cross-linking, although the cross-links cannot be directly seen under a microscope. If a specimen is highly cross-linked, it means that there are more chains combined together. As a consequence, numerous wide and white lines are seen in the images of SEM. The other evidence of cross-linking is the orientations of chains. We find that the chains in cross-linked flexible PVC are oriented along a specific direction. As the results of a plasticizer, chains were able to move and stretch along the direction of tensile force before fracture occurred. If such phenomenon of particular orientation was shown in the images which contain specimens with heat treatment, we can conclude that the plasticizers were kept in flexible PVC matrix due to the effectiveness of cross-linking.

By examining the first row in Fig. 11, we find that Sample II and Sample III show wide and white cross-linked chains in the case without heat treatment. Although Sample I does not exhibit such wide cross-linked chains like Sample II and III do, it has a denser packing characteristic than the control sample has. For the second row in Fig. 11, in addition to close-packed chains, oriented chains are present in Samples I, II and III but not in the control sample. As for the third and fourth row in Fig. 11 with severe degrees of heat treatment, Sample I and Sample II still maintain some characteristics of cross-linking. However, we are not able to observe dense chains and orientation in the control sample and Sample III. In summary, Sample I and II can survive in high temperature situations without losing plasticizers and flexibility, while Sample III can only withstand medium temperatures.



**Fig. 11.** SEM images of control sample and Samples I, II and III without heat treatment and with heat treatment at 100°C, 121°C and 136°C

## 4. Conclusions

As noted in the beginning, PVC has a large variety of applications. Thus, Speel and LeMaire<sup>24</sup> used PVC in combination with a conducting polymer called Versicon<sup>TM</sup> to obtain a desired level of direct current electric conductivity. Vasseur and Deymier<sup>25</sup> studied transmission of acoustic waves in two-dimensional composite media composed of arrays of Duralumin cylinders embedded in a PVC matrix. Joneydi and coworkers<sup>26</sup> created superhydrophobic surfaces on PVC-coated architectural fabric using spray coating. Olad and Nosrati<sup>27</sup> mixed in the solution ZnO–polyaniline nanocomposite with PVC; the ternary hybrid provided an anticorrosion coating on iron. Vesely, Kalendova and Manso<sup>28</sup> studied properties of

calcined kaolins in paints in relation to their PVC volume concentration coatings based on water-borne epoxy resin. PVC affected significantly both mechanical properties and corrosion resistance of the coatings. Herbert, Oliver, Lumsdaine and Pharr<sup>29</sup> used the flat punch nanoindentation to measure the constitutive behavior of viscoelastic solids in the frequency and time domain. The material studied was a highly plasticized PVC. We also note the work by Meng and coworkers<sup>30</sup> who applied additives to improve mechanical properties of PVC while at the same time they improved flame retardancy and smoke suppression.

From our results of mechanical testing, tribological properties determination, water absorption tests and SEM analysis, we formulate a general conclusion: our cross-

linked flexible PVC materials including Samples I, II and III exhibit good mechanical properties; Sample II performs outstandingly in tribological tests. Nevertheless, for Sample III, given the inferior performances in water absorption tests and SEM analysis, we infer that that sample cannot maintain the effectiveness of cross-linking and cannot hinder sufficiently the leakage of the plasticizer – after it underwent heat treatment at a temperature above 100°C. Generally, flexible PVC blended with the cross-linker 1 (Sample I) or cross-linker 2 (Sample II) provides highly satisfactory solutions for improving the long-term performance of PVC.

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## ПОКРАЩЕННЯ ДОВГОСТРОКОВОЇ ЕФЕКТИВНОСТІ ПОЛІВІНІЛХЛОРИДУ (ПВХ)

**Анотація.** Оскільки чистий ПВХ є жорстким, у всіх сферах застосування до нього додають пластифікатор. Міграція пластифікатора призводить до крихкості еластичного ПВХ і забруднення довкілля. Ми використовували три типи жируючого агента, змішаного з комерційним ПВХ, пластифікатором і термічним стабілізатором. Проводили термообробку за температури 100, 121 і 136 °С. Ми провели випробування на розтягування, випробування на динамічне тертя, визначення швидкості зношування, визначення стійкості до подряпин, випробування водопоглинання та SEM-аналіз, щоб зробити вибір придатних для достатнього зшивання для тривалого застосування композицій.

**Ключові слова:** полівінілхлорид, утримування пластифікатора, термостабільність ПВХ, стійкість ПВХ до подряпин.