Enhanced process-effective and skin-friendlier solutions for the production of dipped goods using synthetic polyisoprene-based lattices

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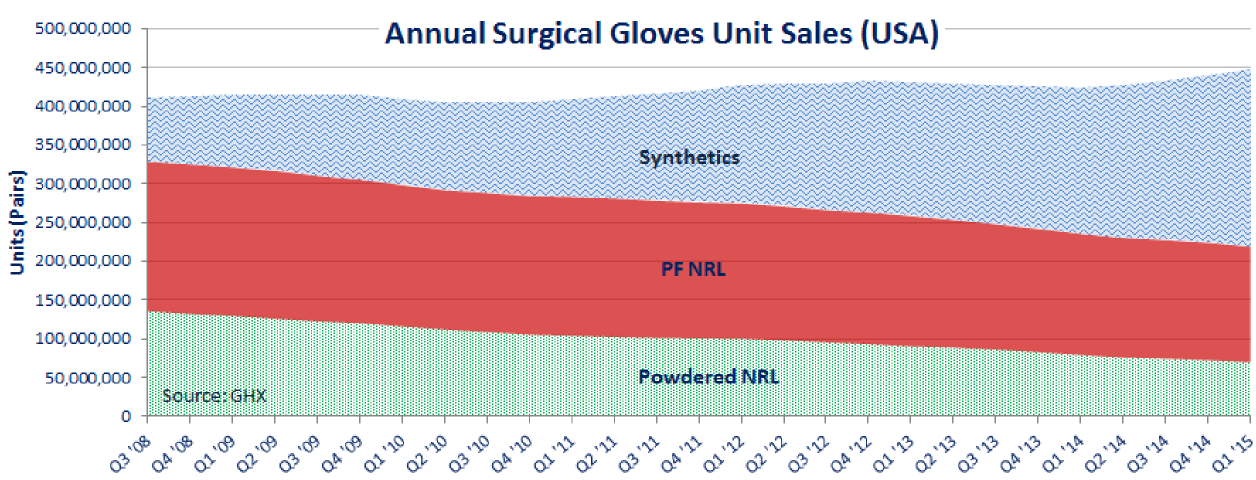
1. Introduction

Pure, Strong and Soft are the key features in our Cariflex® polyisoprene latex (Cariflex® IR0401 latex) which offers the customers an alternative to Natural Rubber Latex (NRL) in dipped goods applications. Our product constitutes a superior alternative to Natural Rubber Latex because it is not made with natural rubber and hence does not contain the natural rubber-related proteins suspected to trigger Type I allergic reactions.

Since its commercialization in 2001, Kraton's Cariflex® IR0401 latex has been used successfully for dipped goods such as surgical gloves and condoms. Such applications require a combination of protection and comfort features, which the most demanding users can find in articles made of Cariflex® IR0401 latex.

This synthetic latex runs consistently on standard dipping lines, and produces goods characterized by an amazing mix of strength and comfort, on top of solving Type I allergies encountered with NRL. Kraton presented a paper on this subject at the Akron's 13th International latex Conference in 2011, and keeps generating more supportive data on the subject.

Having recognized this opportunity, hospitals increasingly embrace the concept of "Natural Rubber Free" operating rooms, when they don't ban NRL altogether in their entire premises. They find that the overall benefits outpace the additional cost associated to the purchase of synthetic articles. This trend translates into growing shares of synthetic surgical gloves in the US, at the expense of Natural Rubber Latex gloves. Today, synthetic surgical gloves represent about 50% of the total US market, and the market share keeps growing.



Yet, the *status quo* is never an option. While our primary objective until a few years back, in full alignment with our customers, has been to grow our polyisoprene latex capacity ahead of the demand curve, the market is now looking forward to the next generation of improvements – safer, nicer, and more efficient solutions.

Having solved the life-threatening Type I allergy, recurrent customer demands now include options to reduce risks associated to Type IV allergies, which are not related to the presence of proteins in the elastomeric raw material but rather to the other vulcanization chemicals.

On the manufacturing front, customers always look for improved productivity or forgiving processes, such as lower temperature curing or longer pot-life.

Finally, in a consumer application such as condoms, the industry seeks nice looking solutions, e.g. better transparency which can be part of the overall consumer experience.

We have investigated multiple compounding options covering these topics and offer our results in this paper.

2. Results and Discussion

We have tested our latex products following the compounding, dipping, curing, and testing methods described in the Appendix.

Table 1 below provides an overview of the various solutions that we have developed. The detailed results are presented and discussed in the sections below.

Table 1: Overview of attributes of Cariflex® latex compounds prepared with different cure packages

	IR0401 with Bostex™851	IR0401with Bostex™862	IR0401with Bostex™909	2GL** Accelerator free	2GL** with Bostex™866
Ingredients	w/ DPG, ZnO, thiurams and S	DPG-free	DPG- and ZnO-free	NO cure chemicals	DPG- and thiuram-free
Cure T	High ~ 130°C	High ~130°C	Low ~ 115°C	Dry and anneal at ~ 120°C	Low ~ 120°C
Film appearance	Opaque	Opaque	Transparent	Transparent	Opaque
Tensile strength*	~25 MPa	~25 MPa	25-30 MPa	20-25 MPa	25-30 MPa
Pot-life (~23°C)* **	7 days	At least 21 days	14-21 days	~ 7 days	At least 28 days
Value	Mainstream technology	DPG-free solution	Transparent films, DPG-free solution, Low heating capacity ovens	Type IV allergy solution	DPG-free, thiuram free solution, Low chemicals & high performance

NOTE: Bostex™ is a trademark of Akron Dispersions

* Tensile strength values stated in the table are for optimized formulations and cure conditions

** 2GL is a developmental product in the Cariflex® line of products (see section 2.5 for details)

*** Pot-life of compounds has been reported based on laboratory dipping conditions

2.1. Evaluation of cure package Bostex^{TM}851

The MSDS of Bostex851 cure formulation states that it contains sulfur, zinc oxide, zinc diethyldithiocarbamate (ZDEC), N,N'-Diphenylguanidine (DPG) and Dipentamethylene thiuram hexasulfide/tetrasulfide (DPTH). IR0401 latex compounds were prepared with 3phr, 5phr and 7phr of Bostex851. All films were cured at 130°C for 20 minutes.

During maturation of the latex compound, intra-particle crosslinking occurs as a result of slow vulcanization within the particles. It is important that the latex particles form a continuous film during dipping/drying/curing processes with sufficient inter-particle crosslinking to have a product with good mechanical properties. Inter-particle crosslinking is hindered if the degree of intra-particle crosslinking is high during maturation. The amount of curatives added to the latex is one of the main factors that determine the balance between intra-particle and inter-particle crosslinking.

Figure 1 shows the tensile strength of IR0401 films prepared with the three compounds mentioned above as a function of maturation time. It can be seen that for compounds containing 5phr and 7phr of Bostex851, the tensile strength is in the range of 25-30 MPa for maturation days 1-4. This is significantly higher than that specified by ASTM D3577 for surgical gloves, which is 17 MPa. Between days 4-7, the tensile strength decreases, but remains above 20 MPa. After day 7, the tensile strength continues to decrease and drops below 17 MPa after 15 days.

This is probably due to the fact that the degree of intra-particle crosslinking is much higher leading to poor film formation as described previously. At 3phr Bostex851, the tensile strength increases to 15-20 MPa after 4 days of maturation, and for this compound also the tensile strength drops below 17 MPa after 15 days.

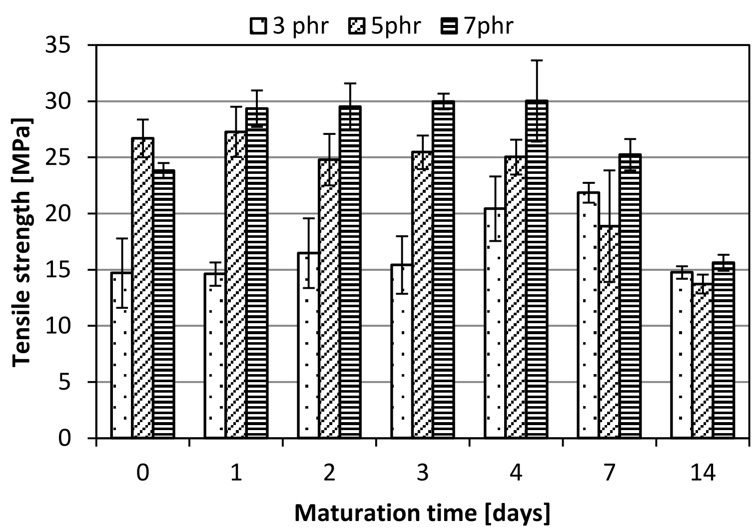


Figure 1: Tensile strength vs. maturation time for IR0401 films cured with Bostex^{TM}851 at three concentrations - 3phr, 5phr and 7phr.

The elongation at break of films made with all 3 compounds as a function of maturation time is shown in Figure 2. As expected, the elongation at break decreases with increasing concentration of crosslinking agent (Bostex851). For compound with 3phr of Bostex851, the elongation at break decreases with maturation time (as the tensile strength increases, elongation at break will decrease). For 5phr and 7phr, the elongation at break remains almost a constant within the range of experimental error.

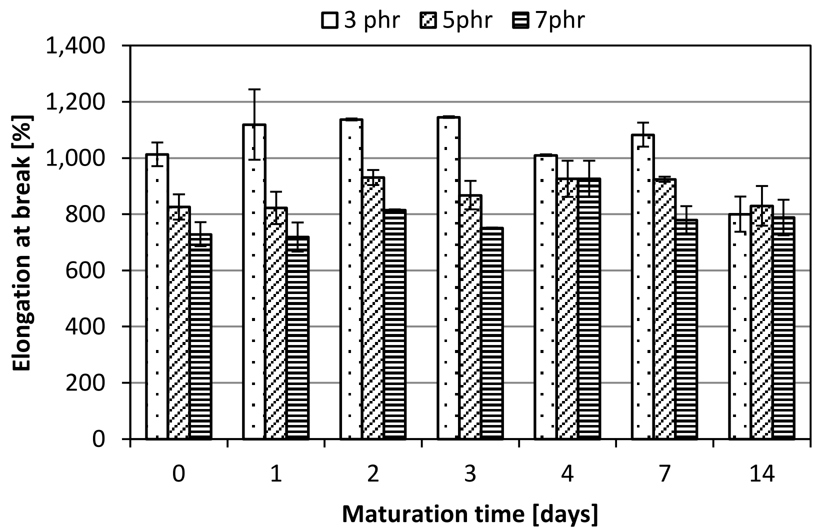


Figure 2: Elongation at break vs. maturation time for IR0401 films cured with Bostex™851 at three concentrations – 3phr, 5phr and 7phr.

It can be inferred from the above data that IR0401 latex compounded with Bostex851 cure package can be used to make products by the coagulant dipping process. Films obtained from a compound containing 5phr Bostex851 and cured at 130°C for 20 minutes exhibit mechanical properties that are specified by ASTM D3577 for surgical glove application.

However, the compound based on this cure package appears to have a short pot-life, approximately 7-14 days. Also, this cure package contains DPG, which is suspected of being a type IV skin sensitizer and a reproductive hazard. Some European countries have laws that require rubber-based businesses to use DPG-free cure systems, and other parts of the world may slowly move towards the same. To address the above issues, we conducted studies on IR0401 latex compounded with the DPG-free cure package Bostex862, and the results are described in Section 2.2.

2.2. Evaluation of cure package Bostex™862

It can be seen from the MSDS of Bostex862 that it contains the same ingredients as Bostex851 except for DPG. Based on the results on Bostex851 cure package described in section 2.1, and also as recommended by Akron Dispersions, 5phr Bostex862 was used to prepare IR0401 latex compound.

Several cure conditions were studied by varying the cure temperature and time. Figure 3 shows tensile strength of the films as a function of cure time at temperatures of 100°C, 110°C, 130°C and 140°C. It can be seen that at lowest temperature of 100°C, it takes about 40-50 minutes to attain the peak tensile strength (~27 MPa). A shorter cure time of 20 minutes is possible if the films are cured at 130-140°C. At the higher temperature of 140°C, the films are cured non-uniformly as can be seen from the high standard deviation in the data. Based on these results, we cured all films at 130°C for 20 minutes for further studies.

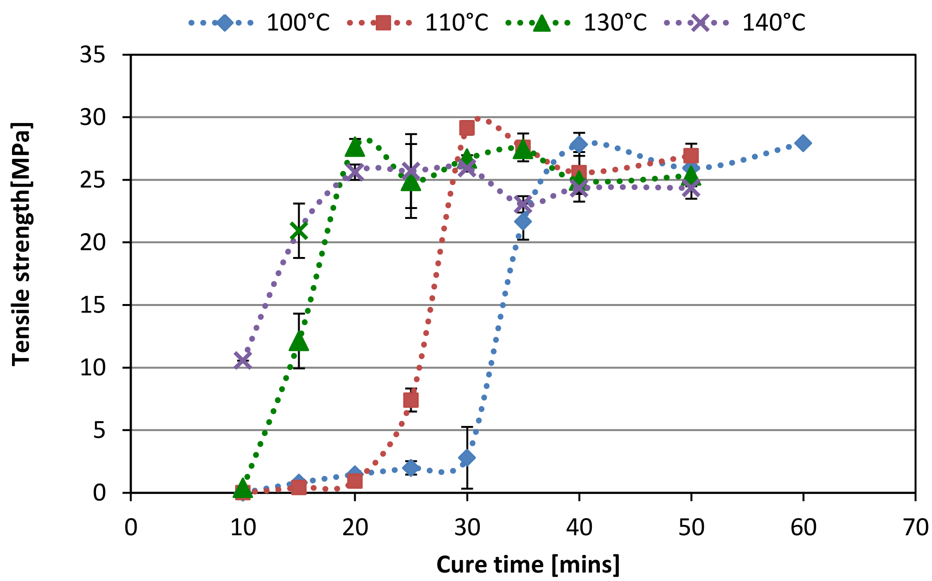


Figure 3: Tensile strength vs. cure time for films prepared from IR0401 latex compound with 5phr Bostex™862 and cured at different temperatures.

Figure 4 shows tensile strength, M100, M300 and M500 of IR0401 films prepared with 5phr Bostex862 compound as a function of maturation time. It can be seen that although tensile strength of the films drops slightly after 7 days, it remains above 20 MPa for the first 21 days. Beyond this time, it was found that although the tensile strength is in the range of 15-20 MPa, fluctuation in film properties as seen by measurement is large. Therefore, we conclude from this data that the pot-life of IR0401 latex compound with Bostex862 is at least 20 days when stored at temperature of ~23°C (ambient laboratory temperature) during maturation. For continuous coagulant dipping operations, this compound seems to allow for a very good pot-life. Modulus at 100% and 300% elongation remain almost constant for all maturation days. Although M500 increases with maturation time, it is well below 7 MPa, as specified in ASTM D3577 for surgical glove applications.

From this data we conclude that Cariflex® IR0401 latex can be used to make products with good mechanical properties with a cure package that is free of DPG, like Bostex862. The IR0401 latex compound with this cure package also seems to have an extended pot-life of 20 days. The disadvantages of Bostex862 are that it is a high temperature cure formulation and the end product is opaque white because of the presence of zinc oxide. In order to overcome these shortcomings, we worked with another cure formulation from Akron Dispersions, Bostex909. The results based on this compound are described in the next section.

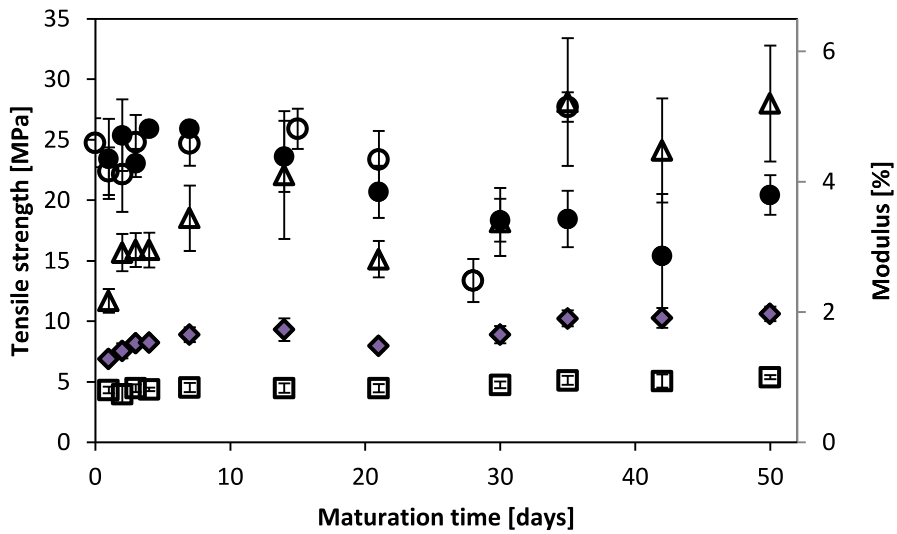


Figure 4: Mechanical properties of films prepared from IR0401 latex compound with 5phr Bostex™862 as a function of maturation time.

2.3. Evaluation of cure package Bostex™909

Bostex909 is a cure package that is free of DPG and zinc oxide. IR0401 compounds were made with 5phr of Bostex909 and also with 5 phr of Bostex862. Films were made from both compounds by coagulant dipping procedure and cured at either 115°C or 130°C for 15, 20 and 25 minutes. All films were prepared during 1-3 days of compound maturation.

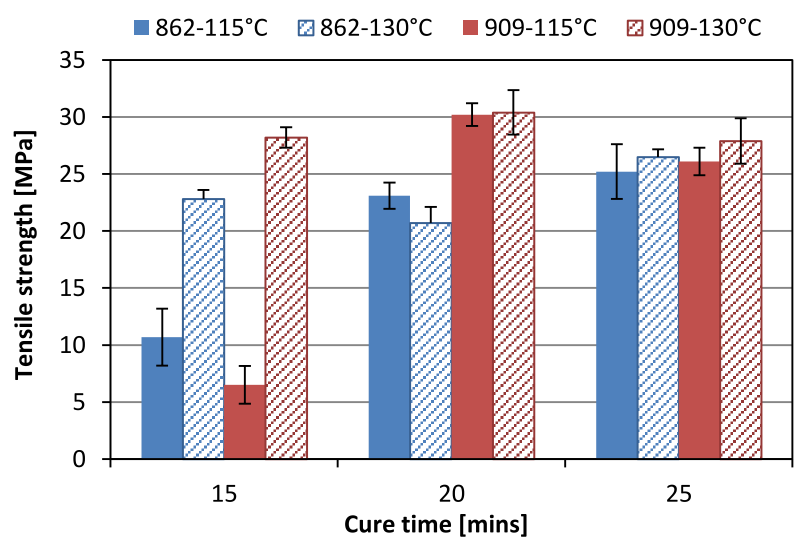


Figure 5: Tensile strength of films prepared using IR0401 latex compounded with Bostex™909 and Bostex862 and cured for 15, 20 and 25 minutes at two different cure temperatures – 115°C and 130°C.

Figure 5 shows the tensile strength of the films made from both compounds as a function of cure time. The modulus at 100% elongation as a function of cure time is shown in Figure 6 for films made from both compounds. The data is shown for films cured at temperatures of 115°C and 130°C. It can be seen from this figure that when cured at 115°C for 15 minutes, the tensile strength of films made from both compounds is very low (≤ 10 MPa). When cured at 130°C for the same time, the tensile strength is higher.

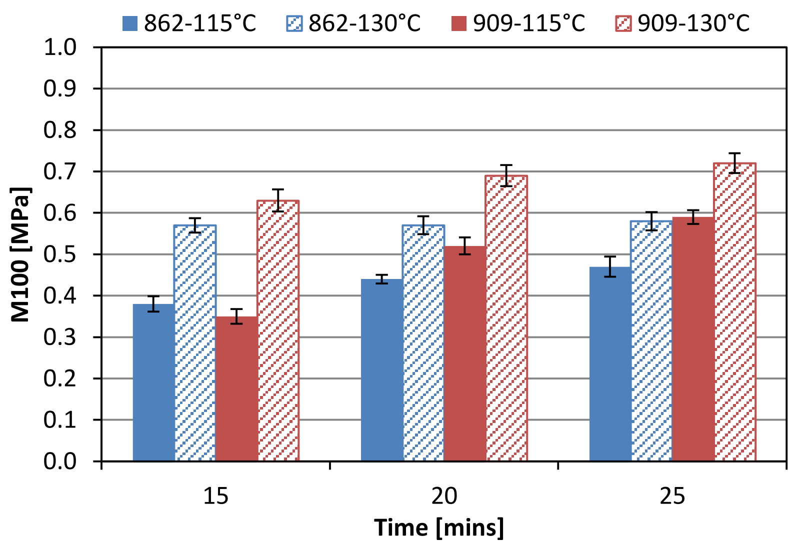


Figure 6: M100 of films prepared using IR0401 latex compounded with Bostex™909 and Bostex862 and cured for 15, 20 and 25 minutes at two different cure temperatures – 115°C and 130°C.

It can also be observed from the data in Figure 5 that at either 115°C or 130°C the films have to be cured for at least 20 minutes to attain tensile strengths of greater than 25 MPa. When cured for 20-25 minutes at either temperature the films made with Bostex909 cure formulation shows higher tensile strength as compared to those made from Bostex862 compound. An explanation for this may be, since Bostex909 does not contain zinc oxide as opposed to Bostex862, that the amount of sulfur and accelerators and the ratio of the two will be higher in Bostex909 than in Bostex862, leading to a higher degree of crosslinking and consequently higher tensile strength. This is also reflected in the data on M100 in Figure 6, where M100 for films made with Bostex909 compound is higher than films made with Bostex862 compound for cure temperatures of 115-130°C and cure time of 20-25 minutes.

Another advantage of this Cariflex® latex compound is that the films are much clearer (almost transparent) due to the absence of zinc oxide in the formulation. Figure 7 shows the transparency of films (measured with Byk Hazeguard) as a function of film thickness for films made using Bostex862 and Bostex909 compounds. It can be seen that the transparency for films made using Bostex909 is much higher than Bostex862. The difference in clarity of the films is also very well illustrated by the photograph shown in Figure 8 of films made from both compounds. Films made with Bostex909 are very clear, although yellowish, which is most probably due to the presence of unreacted excess sulfur.

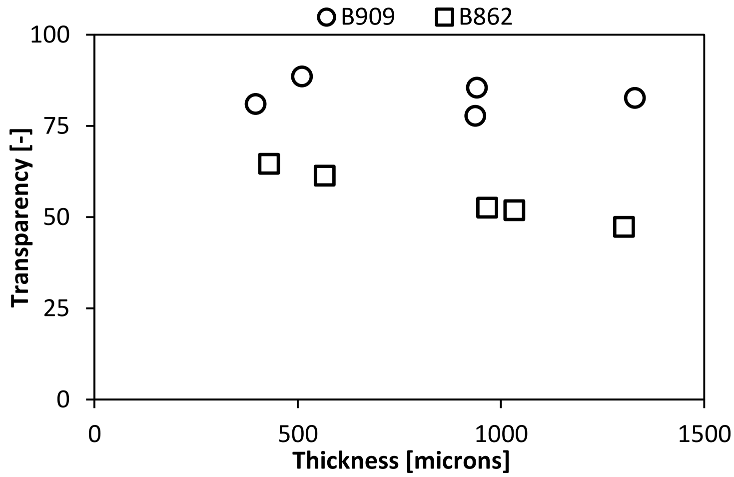


Figure 7: Transparency vs. film thickness for films made from Cariflex® IR0401 latex compounded with Bostex™862 and Bostex909

Figure 8: Cariflex® IR0401 films of varying thickness prepared with (a) Bostex™862 cure package – appearance of film is opaque (film on the left) and (b) Bostex909 cure package – film appears much clearer (film on the right).

The key information we get from these experiments is that IR0401 latex compounded with Bostex909 can be cured at lower temperatures (~115°C), for a time period of 20-25 minutes, and still obtain good mechanical properties, along with the additional advantage of excellent clarity and film transparency.

2.4. Potential of Cariflex® IR0401 with cure systems developed using individual dispersions

Based on the observations stated in the above sections, further experimentation was conducted with Cariflex® IR0401 latex to determine if a cure formulation without elemental sulfur can be used to prepare films having mechanical properties which meet the specifications required by ASTM D3577 for surgical glove application. For this purpose, cure formulations were prepared by combining individual water-based dispersions of accelerators and/or sulfur donors that are used in polyisoprene vulcanization. IR0401 compound was prepared using such a cure formulation free of elemental sulfur (labelled as ID-SF for "**I**ndividual **D**ispersion-**S**ulfur **F**ree). This cure system comprised of only two chemicals, a sulfur donor (DPTH) and an accelerator (ZDEC),where the total concentration of the curatives was in the range of 2-4phr (we have filed a patent application on this package). Films were prepared by coagulant dipping procedure using this compound. All films were cured at 130°C for 20 minutes.

Figure 9 shows the tensile strength vs. maturation time of films prepared from ID-SF. It can be seen from this figure that for all maturation times studied, tensile strength of films is almost a constant and above or equal to 17 MPa. This shows that this type of a compound can also be used for dipping after day 1 itself, and also is an indication of long pot-life, when compound is stored at ambient temperature of 23°C. The long pot-life was reinforced by conducting mechanical tests on a film prepared after 28 days of maturation, where the tensile strength measured was 21 MPa. It was found that the cure system should contain at least 1.25phr DPTH and at least 0.75phr ZDEC to obtain tensile strengths of more than 20 MPa.

Films were also prepared from a cure formulation that included a small amount of elemental sulfur (labelled ID-w/S for "**I**ndividual **D**ispersion-**w**ith **S**ulfur). Again, a total of 2-4phr of ID-w/S was added to IR0401 latex, where the amount of sulfur in the formulation was 0.5-1phr. The tensile strength of films dipped from this compound on different maturation days is also plotted in Figure 9. It can be seen from this figure that addition of a small amount of sulfur leads to an improvement in tensile strength of the films on all maturation days.

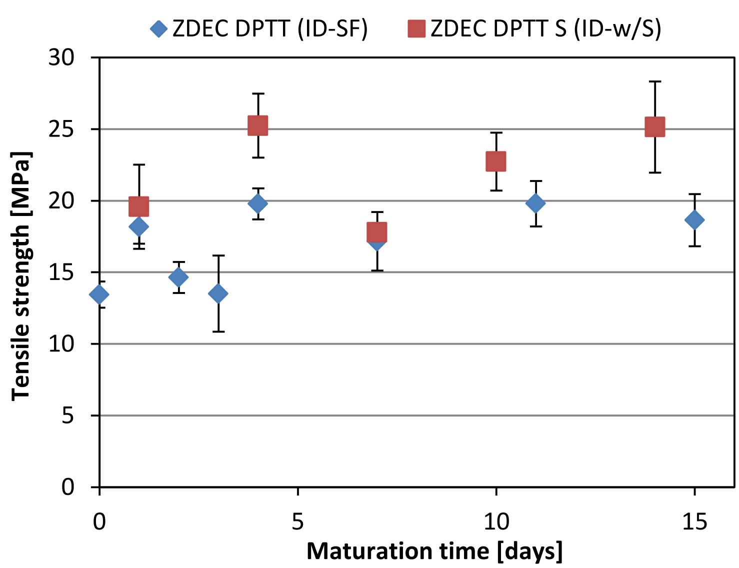


Figure 9: Tensile strength vs. maturation time of films prepared from Cariflex® IR0401 compounded with (i) cure formulation free of elemental sulfur (ID-SF) and (ii) cure formulation with additional elemental sulfur (ID-S).

As mentioned previously, the above results are based on latex compounds that were stored at ambient temperatures of 22-25°C. However, if these compounds are stored at ambient tropical conditions, where temperatures are in the range of 28-32°C, the pot-life is significantly reduced to be around 7 days. In order to overcome this, the same compound can be cooled down. However, cold storage reduces the rate of compound maturation greatly, leading to very long maturation times before dipped films can be made. Films made from compounds that are not sufficiently matured exhibit visual defects such as bulging or blistering during vulcanization and in some cases, higher glove width for a given glove mold size comparatively.

A way to address this issue is by keeping the level of ZDEC higher above 1phr or by addition of a small amount of a semi-ultra accelerator, for instance ZMBT to the latex compound, whilst–keeping the total amount of accelerators in the compound the same. Further, the latex compound should be matured at around 28-33°C for approximately 24 to 48hours prior to dipping. The higher ultra and semi-ultra accelerator addition coupled with the higher temperature speeds up rate of maturation of the compound. After maturation at higher temperature, the compound can be stored at a lower temperature of at least 23-25°C to obtain a pot-life of around 6-7 days. Good films with tensile strengths of 22-25 MPa can be obtained by dipping after 24 hours of maturation.

The accelerated compounds can also be cured at lower vulcanizing temperatures of 115°C. The tensile strength of films made from this type of compound and cured at 115°C and 125°C is shown in Figure 10. It can be seen that tensile strengths above 22 MPa can be obtained for films cured at a lower temperature of 115°C also, when cured for at least 20 minutes. It can also be seen from Figure 10 that these compounds have good ageing resistance. There was no blistering or bulging observed on gloves prepared from this type of an accelerated compound as shown in the photograph in Figure 11.

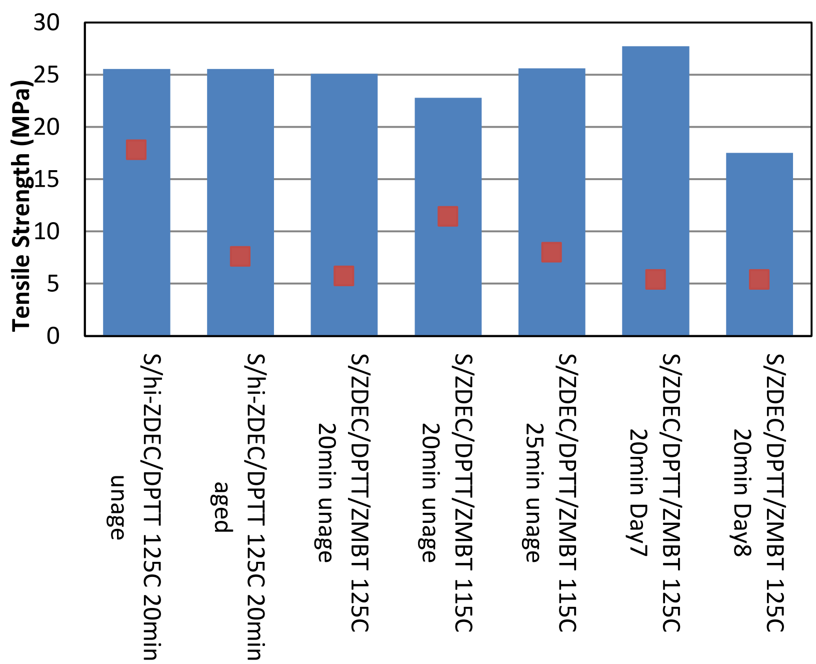


Figure 10: Tensile strength of films made from compounds containing an added semi-ultra accelerator. The compounds were allowed to mature at high temperature of 28-33°C for 24 hours and then stored at 23-25°C. "hi-ZDEC" represents formulations containing ZDEC above 1phr. The red squares represent the coefficient of variance in the experimental data.

Figure 11: Picture of cured film on glove former showing no blistering or bulging. IR0401 compound prepared with individual dispersions of cure chemicals, containing a semi-ultra accelerator was used for preparing the gloves. The compound was matured at a temperature of 28-33°C 24-48 hours prior to dipping.

The degree of maturation of the compound can be monitored by swell index of uncured films dipped on different maturation days, and correlated to tensile strength of cured films dipped on the same day to determine the pot-life of these accelerated compounds. The data of swell index (of uncured films) and tensile strength (of cured films) dipped on different days of compound maturation is shown in Figure 12.

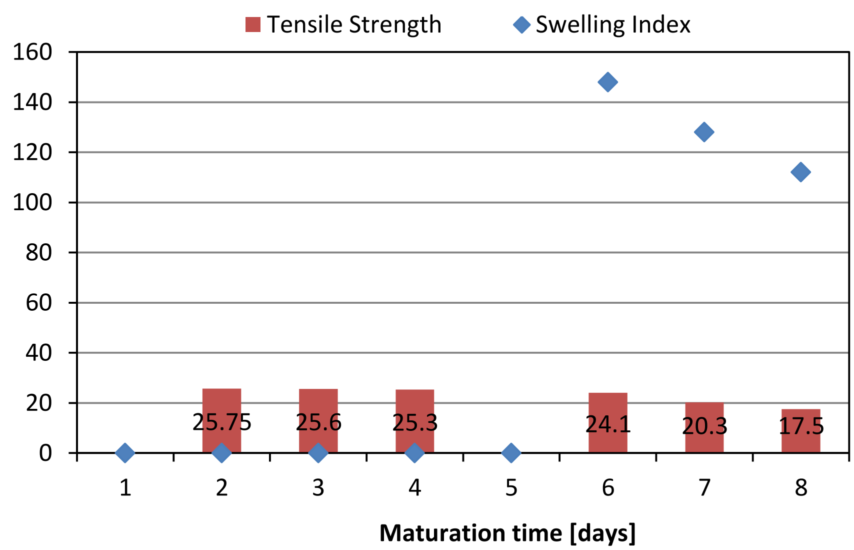


Figure 12: Relationship of swelling index to deterioration in tensile strength as a function of compound maturation. (Swell index of 0 indicates that the film dissolved in toluene due to low crosslink density in the latex phase).

A swell index of 0 is observed between days 1-5. Films dipped and cured during this period of maturation have high tensile strengths of around 25 MPa. From day 6, the uncured films start swelling in toluene instead of dissolving. The swell index decreases from day 6 to 8 indicating increase in crosslinking in the latex phase as maturation progresses. Deterioration in the tensile strength of cured films can be seen during the same period of maturation.

From the results discussed in the above sections, it can be seen that films can be made using compounds of Cariflex® IR0401 latex which are prepared with simpler cure formulations containing lesser number of cure chemicals. However, all the above formulations contain DPG and/or thiuram, both of which may cause type IV allergies in consumers. Surgical glove producers are actively moving towards DPG and thiuram free gloves. To this end of accelerator-free or very low amount of accelerator containing latex products, a new development in the Cariflex® latex line of products is “2GL”. The features and benefits of this developmental product are discussed in the next section.

2.5. Introducing Cariflex® 2GL

Cariflex 2GL is a synthetic latex of a styrene modified polyisoprene rubber, having low styrene content. This developmental product, again suitable for dipped goods, has been custom-designed to combine the “Pure, Strong and Soft” features of Cariflex IR0401 latex with a thermoplastic-like behavior. Depending on performance requirements of the final goods, it can be used free of cross-linking chemicals, or with low levels of them.

Thus, a potential advantage with Cariflex 2GL is that even without any cure chemicals, soft and flexible films can be dipped from the pure latex and they have high tensile strength of the order of 20 MPa. It can be used to make clean accelerator-free products. A weakness of such films lies in the fact that they dissolve rapidly in many low polarity solvents. Light vulcanization of Cariflex 2GL can enhance the film properties like improved solvent resistance, durability as well as tensile strength. An attractive attribute of 2GL is that films can be made using compounds containing very low levels of curatives (less than that required by Cariflex IR0401 latex) since Cariflex 2GL films require very low degree of chemical crosslinking to exhibit excellent mechanical and physical properties.

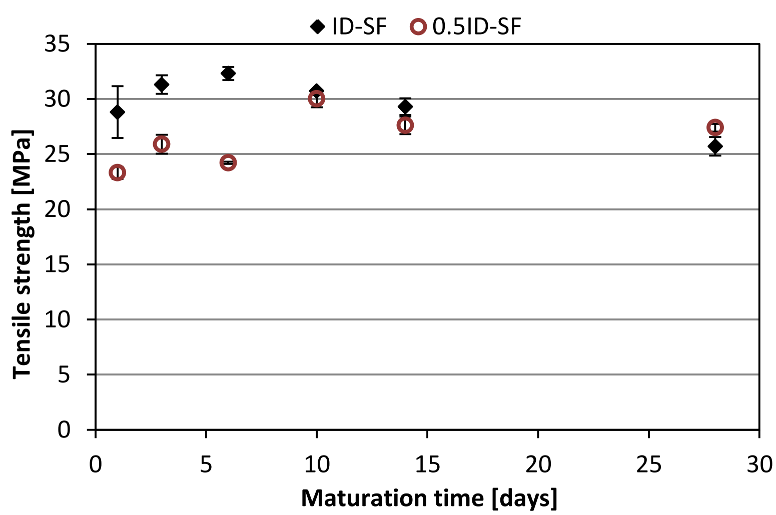


Figure 13: Tensile strength vs. maturation time of films prepared using Cariflex® 2GL compounded with (i) ID-SF and (ii) 0.5ID-SF.

Compounds of Cariflex 2GL were prepared using cure formulations ID-SF and 0.5ID-SF. 0.5ID-SF means that the cure ingredients in ID-SF were halved, so that 0.5ID-SF had 1-2 phr of total amount of curatives as compared to 2-4phr in ID-SF. Films were dipped from both compounds on several maturation days and cured at 120°C for 20 minutes. Figure 13**Error! Reference source not found.** shows the tensile strength of films as a function of maturation time. It can be seen from this figure that the tensile strength of films made with ID-SF compound has high tensile strength from day 1 itself. Also, the tensile strength is almost a constant with maturation time for at least 28 days (length of study). For the compound containing 0.5ID-SF, although the tensile strength starts increasing only after 10 days of maturation, it shows a tensile strength of 25-30 MPa in the time span of 10-28 days. By slight adjustments made to this formulation, the right balance between maturation and mechanical properties can be obtained and films can be dipped to have high tensile strengths starting from day 1 itself.

Cariflex 2GL was also compounded with a cure formulation provided by Akron Dispersions, Bostex™866, which is both DPG-and thiuram-free. Compounds were prepared with 2.5phr and 5phr of Bostex866. Films were dipped on maturation days 1, 4, and 7 and cured at 120°C for 20 minutes. The tensile strength vs. maturation time is shown in Figure 14 for both compounds. It can be seen that 2GL with Bostex™866 shows high tensile strength from maturation day 1, and remains constant for all maturation days. Also, it does not show a dependence on the amount of curative, indicating that this latex can be easily compounded with a lower amount of the cure package. The modulus at 500% elongation (M500) vs. maturation time for both compounds is shown in Figure 15, and is equivalent to that of IR0401 latex films. The combination of 2GL with this cure package seems to give mild crosslinking along with all the desired properties of high tensile strength, DPG- and thiuram-free films, short maturation time, and soft films. The lightly crosslinked 2GL films also swell in toluene instead of dissolving, thus having more chemical resistance than completely accelerator-free 2GL.

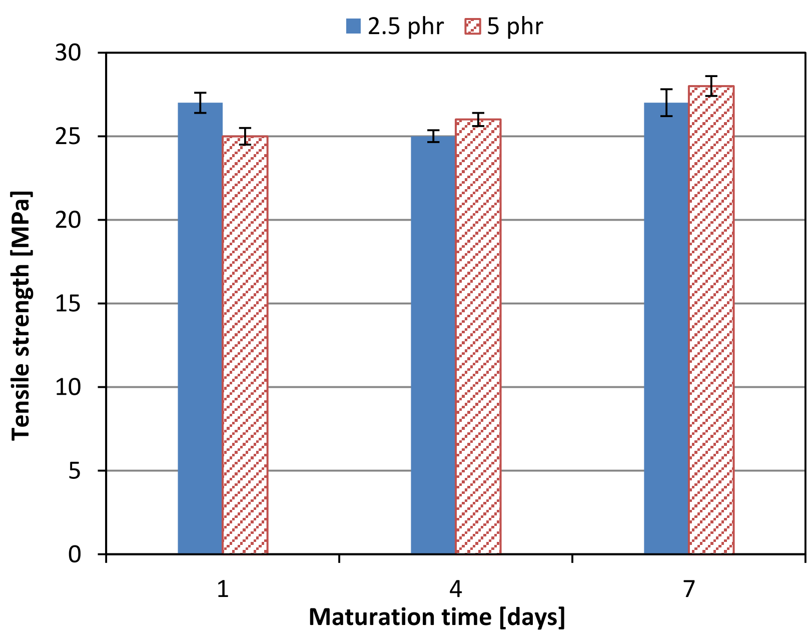


Figure 14: Tensile strength vs. maturation time of films prepared from Cariflex® 2GL compounded with Bostex™866 at two different concentrations (i) 2.5phr and (ii) 5phr.

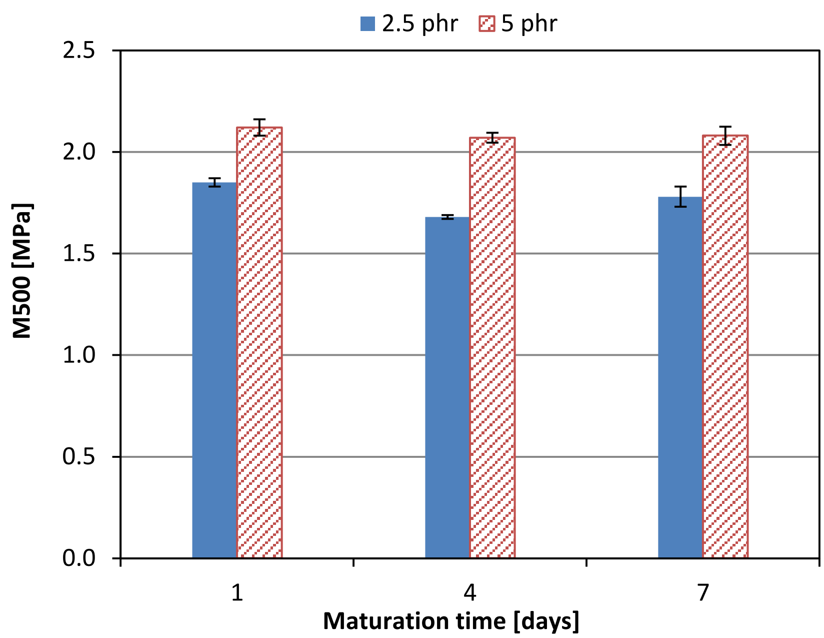


Figure 15: M500 vs. maturation time of films prepared from Cariflex® 2GL compounded with Bostex™866 at two different concentrations (i) 2.5phr and (ii) 5phr

3. Conclusions

For Cariflex® IR0401 latex, beside its well-known "Pure, Strong and Soft" features, we are now offering a toolkit of formulations that can be used, and further fine-tuned if necessary, by customers in order to extract further value from this raw material.

The toolkit includes options which potentially reduce risks associated to Type IV allergies, improve productivity, implement more forgiving processes, or produce more transparent films. More specifically, the toolkit counts the following compound types:

- a ZnO-free recipe that yields **more transparent films** potentially of interest for consumer goods applications,
- two **DPG-free formulations**,
  - one for curing at 130°C for 15-20 minutes, and
  - another one for curing at 115°C for 20 minutes, thus **working in low heat capacity ovens**
- basic **starting formulations (sulfur-free and with sulfur options)** using individual dispersions of cure chemicals
  - consists of just 3 ingredients (thiuram, carbamate and anti-oxidant)
  - starting formulation can be tweaked easily to meet demands of the application
  - transparent, and white films
  - **long pot-life** of compound

Cariflex® 2GL has been presented as a new developmental synthetic latex product, suitable for dipped goods, that has been custom-designed to combine the "Pure, Strong and Soft" features of Cariflex IR0401 latex **with a thermoplastic-like behavior**. Depending on performance requirements of the final goods, this new raw material can be used free of cross-linking chemicals, or with low levels of them.

Specifically, it can potentially:

- **work without curing chemicals**, subject to some compromises on end properties, such as resistance to non-polar solvents,
- yield good quality cross-linked films with a **DPG-free, thiuram-free compound recipe at only 2.5 phr level**,
- deliver **high strength films (~30 MPa)** based on a simple thiuram-based but DPG-free recipe.

While Cariflex 2GL has originally been designed for surgical glove applications, we can envision potential in other end uses, such as condoms, catheters, adhesives, films, foams etc.

Please contact Kraton Polymers[1] if you wish to discuss these opportunities.

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APPENDIX – Experimental Methods

Latex Formulation and Compounding

Cariflex® IR0401 latex was first filtered using an 80 mesh size filter cloth. Compounds of the polyisoprene latex were prepared with a number of different cure formulations. All compounds were diluted with deionized water to have a solids content of 30%. Due to dilution, it was necessary to add a surfactant to stabilize the compounds. The surfactant Manawet™ 172 (Manufacturer's Chemical) was used for this purpose in the amount of 0.75 phr. The pH of the compounds was adjusted to be approximately 11 by adding 10% potassium hydroxide (reagent grade, 90%, Sigma-Aldrich) solution. The compounds were stored at room temperature (not controlled) for maturation for at least 24 hours before making films. During this period they were either stirred continuously or kept in motion on a roller bench to ensure homogenization.

The cure packages Bostex™851, Bostex862, Bostex909 and Bostex866 were provided by Akron Dispersions. Individual water-based dispersions of sulfur, accelerators and anti-oxidants were obtained from Technical Industries and Aquaspersions.

Dipping and Curing

IR0401 latex films were prepared by coagulant dipping procedure. Rectangular stainless steel plates were heated to 100°C in an oven and then dipped in a coagulant solution at 50°C. The coagulant solution comprised of an aqueous mixture of calcium carbonate (>99%, sigma Aldrich) and calcium nitrate (>99%, Sigma Aldrich), where the calcium carbonate is the release agent, and calcium nitrate is used to coagulate the latex. 0.2 wt% of a wetting agent, Surfynol TG (Air Products) was added to ensure uniform coating of the coagulant on the steel plate. The formers were placed in an oven at 100°C until they were dried completely.

The plates were then dipped in the latex compound for 30 to 40 s to obtain a film with thickness of at least 0.2 mm. After dipping in latex, the films were dried at 130°C for about 1 minute and then leached in a 50°C water bath for 5 minutes. The films were then cured in an air-circulated oven. Several cure protocols were followed depending on the cure package used, and have been described in section 3. After curing the films were dusted with silica and then stripped off the formers. The films were stored in a refrigerator at 4°C to slow down possible post-curing.

Mechanical Testing

The degree of maturation of the latex compounds were determined using swell tests in some cases. For this test, a strip of polyester film was dipped in the coagulant solution and dried. Subsequently, it was dipped in the compounded latex for about 15s, and dried for at least 1 hr at ambient conditions. The film was then dusted with silica powder and a circular piece was cut out of the film. The latex film was taken off the polyester backing and immersed in toluene in a petri-dish for 1 hour. The initial diameter and diameter after swelling for an hour was measured and degree of swell was determined as %swell as shown in the equation below:

$$\%\boldsymbol{swell} = \frac{(\boldsymbol{diameter}_{\boldsymbol{swollen}} - \boldsymbol{diameter}_{\boldsymbol{unswollen}})}{\boldsymbol{diameter}_{\boldsymbol{unswollen}}} \times \mathbf{100}$$

Mechanical tests were conducted on the films according to ASTM D412 C. All tests were conducted on Instron 3365 tensile bench equipped with a 100 N load cell. A long-range travelling extensometer was used to measure extension. Mechanical properties obtained were tensile strength, elongation at break, modulus at 100%, 300% and 500% (M100, M300 and M500 respectively). Six specimens were tested for each sample to determine standard deviation in the data collected. Standard deviation is represented by error bars in the data reported.

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