PEF - The Green PET

PEF Strategy - Focus on high-value applications

The Interview

Interview by Barbara Appel and Dr. Otto Appel
with Tom van Aken, CEO, Avantium

When did Avantium start business?

Van Aken: The company was founded in 2000. This year we are celebrating our 20th birthday. I joined the company in 2002. I can tell you that it was a very different company from what it is today. At that time, the company was focused on providing high-throughput technology-based R&D services to companies in the chemical and pharmaceutical industries. We are now very much focused on renewable chemistry and renewable polymers. We still use our expertise in high-throughput R&D and catalytic process development, but we have definitely driven the company towards circular and renewable materials. And this is the topic that is becoming increasingly important. In recent years, it has not only been about renewability, but also about circularity. Anyone in the industry can confirm this.

What led to a change in direction?

Van Aken: In 2005, I became CEO. At that time, Avantium was a R&D service-oriented company for the chemical and pharmaceutical industry. This was when I was asked, "Can we transform this business into a technology company?" We identified green chemistry, where renewable feedstocks are used as the most promising area for the development of new catalytic processes. Our advantage? We are really good at catalysis. Everyone did catalysis based on petroleum, natural gas or coal. Then we said, "If you start from different feedstocks, you need different catalysts, you need different processes. And which molecules are we going to target?" Switching from petroleum to sugar or biomass as the raw material does not mean just a simple change of the raw material. This means a huge change in the industry. To be fair, bringing a new polymer to the market is not easy and took a lot longer than we thought (laughs). It was a phenomenally interesting challenge. Fifteen years ago there was still little attention for renewable materials or for issues like climate change. And now, of course, this is the most pressing issue in the global economy. And when you see how long it takes to develop new technologies and new polymers, you must solve many different challenges. It's not just chemistry. No, a lot of things must be solved in parallel and you have to develop and optimize. So, I'm happy that we started already in 2006. That is why we are here today and have a 5-10-year lead over potential competitors starting today.

The climate discussion is also taking its toll on the plastics and packaging industries. If you only started your business today, would the pressure be higher?

Van Aken: (laughs) I always felt the pressure - and still do. But yes, the expectations might be even higher. We first looked at the monomers that come into question. And we saw FDCA as the key building block for the production of bio-based products. This can be made much better from renewable raw materials than from fossil resources. Then it took us a couple of years to come up with the chemistry to make FDCA. And it worked. We solved the problem. We call it the natural version of terephthalic acid. In fact, we felt watched continuously. First, we were asked, "What are you doing with FDCA?" And we thought, "Hey, the whole polymer industry is waiting, right?" That is when we said, "Come on guys, why don't you get involved?" But we were critically eyed from the distance. The situation was so new, so unfamiliar. After all, we were in the process of launching a new polymer on the market, which does not happen so often.

So it wasn't easy to find partners?

Van Aken: The company NatureWorks got involved with us in 2009, together we started to produce different polyesters based on FDCA. So basically, we started combining FDCA with all sorts of diols to make different polyesters. Nature Works already knew that PLA was a difficult product. So, they wanted to investigate new polyesters next to PLA. Together with them we synthesized PEF for the first time, but also PBF and PPF and other variations of FDCA. Together we decided to focus on PEF, because of its exceptional barrier properties. The chemical and polymer industry remained skeptical. Then we started with the next phase: making bottles, making films, making fibers. A key moment for us when the brand owners started to show genuine interest. In 2009/2010

Coca-Cola started talking about the plant bottle, which was 30% bio-based because the MEG was bio-based. They said, "We would like to go 100% on plant materials." And we said in response, "Well, here we are!". This put Avantium on the map, suddenly everyone was talking about PEF bottles.

Am I right that it was about huge volumes?

Van Aken: Exactly. It was all about an extremely high volume of bottles. And it was not just about replacing PET, but also about glass and cans. The costs were really challenging and the volumes extremely high. And our new chemistry was still very young! We worked hard on the project at the time, and we made mistakes which is an inherent phenomenon of innovation. We had made the step from the laboratory scale to the pilot plant. And because of this the brand owners immediately demanded very high volumes saying, "You should go to the largest scale as possible immediately." And that didn't stop. "You should go even higher." We then involved BASF and started talking about a large-scale strategy.

BASF has withdrawn the cooperation. What was the reason?

Van Aken: It was very unfortunate this joint-venture fell apart. This was unrelated to the product or the market, nor the technologies we use to make it. We greatly benefited from our partnership with BASF, in optimizing and streamlining our technologies. We are thankful for their technological contribution. BASF and Avantium had quite different views on commercialization. BASF's commercialization strategies wanted to

Fig 1: Pilot plant YXY technology (Gelen)
Source: Avantium

rapidly proceed to high volume product coming out at a lower price point; but they struggled with the risks associated to this strategy. Avantium wanted to start with specialty higher value applications, establish the product and then build from there into larger scale market and subsequently build larger scale plants. Obviously the parties have different risk appetites; bringing a new polymer to the market is inherently risky, capital intensive and time-consuming. In my view it is important to balance risks and investments with opportunities and market potential. Looking at our progress over the past 12 months, I am glad this venture came to an end. We are much more innovative and faster because of the split. We have been acting much more agile and been able to enter into other partnerships which we would not necessarily be able to if the joint-venture was still in place.

You are talking about mistakes you made. What have you learned from that time and from your mistakes?

Van Aken: During this time, we found out a lot more about the polymer itself. That it has outstanding barrier properties and excellent additional properties such as mechanical strength and favorable thermal properties. This conclusion came almost automatically. We started off to position PEF as a green version of PET, resulting in immense pressure on price and volume. After all, the manufacturing process of PET has been improved year-on-year over a period of 50 years. I find it incredible how they have been able to squeeze all the costs out. And of course, the industry produces at massive scale, so for the right reason it is called a commodity. I conclude that it is impossible to launch a new polymer and compete directly with a commodity like PET. So we decided that - with our brand-new approach to position PEF as a performance polymer- we did not want to take on this 800-pound gorilla directly. For this reason, we now have a strategy that focuses much more on high-value applications. Then we can use our learning curve and watch the market to go into larger volumes at the appropriate time.

What are high quality applications in your definition?

Van Aken: In particular, we are looking for applications where we can compete on performance. We are interested in

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applications where barrier performance, mechanical properties, as well as the recyclability of the product are well leveraged. If there are low-cost, well-functioning material solutions in place for a specific packaging application, it doesn't make sense to introduce a new polymer like PEF, so we are focusing on unmet needs or applications that don't have a well-functioning technological solution. The renewable basis of PEF is a great qualifier, but not a differentiator – that is determined by performance.

Are there applications in the beverage sector?

Van Aken: It's about beverages, cosmetics, but also film applications in electronic and packaging applications. Multilayer applications currently make up a large proportion of the films, but the trend is towards mono-material applications, since multilayer applications cannot be recycled. Because of the barrier properties of PEF, we foresee that monolayer PEF solutions can be developed to replace multilayer films. That is why we work with several other companies to co-develop high-performance films. And we are working on specialty bottles. We don't focus now on regular (larger-volume) soft drink bottles, because it will take some time before we reach price points of regular bottles for PEF. But we believe that PEF will play in this area in the long run. In the meantime, we take care of specialty bottles and support brands looking for something different, new and innovative. So, for example beer bottles.

Now we're talking about the Carlsberg Paper Bottle?

Van Aken: Yes, in 2019 we joined the alliance of The Paper Bottle Company (Paboco®). This is a joint venture between paper packaging material developer BillerudKorsnäs and bottle manufacturing specialist ALPLA. Companies such as Carlsberg and Coca-Cola Europe also joined the alliance of the Paper Bottle Company. Carlsberg presented a prototype of the Carlsberg Paper Bottle last year. This paper bottle is fully plant-based and recyclable. The outside of the bottle takes care of the mechanical strength of the bottle. Our PEF, in the form of a thin liner on the inside of the bottle, provides the Paper Bottle with the high barrier properties. What I personally like about the Paper Bottle is that it makes sustainable packaging so visible, and visibility will be increasingly important for consumer marketing of sustainable packaging.

A not uncontroversial approach. It is criticized that it is a packaging alternative made of wood, that logging and thus forest destruction is necessary to create beverage packaging.

Van Aken: Let's first establish that we need a source of carbon to make plastic materials – you cannot make plastics without using carbon as the backbone. We can either use carbon originating from extracting fossil resources like petroleum or we can use renewable carbon from agricultural or forestry sources. The current mindset in the petrochemical industry is that there is an unlimited amount of petroleum available. The downside is that CO_2 emissions have increased to such a level that climate change is now the biggest threat to our way of living. The switch to renewable carbon is simply inevitable. This can be from agricultural resources, as long as you don't interfere with the food supply,

Fig 2: Paper bottle with PEF liner
Source: Avantium

or from forestry resources, as long this is done in a sustainable fashion, focused on responsible forest management and regeneration. Plants and trees help us to alleviate our CO_2 problems for free, they clean the air and store CO_2 naturally, thanks to photosynthesis. They grow every year, so when managed carefully it provides for a valuable resource for the production of chemicals and materials without destroying the planet. Only the forestry waste that we can't use for the production of valuable products should be used for the generation of energy. If you add recycling to the use of renewable carbon, you reduce the amount of virgin raw materials, and you come to a real circular economy!

Sounds logical. Do consumers see it that way?

Van Aken: Of course, I cannot predict how consumers will respond to this type of new packaging format. The funny thing is that there are analyses and studies that predict that in 20 years all beer will be packed in plastic. But nobody wanted to be the first, so let's see if Carlsberg is the first to switch to such a sustainable alternative.

Where do you see PEF in this context?

Van Aken: It is extremely interesting for us to see the market response once we introduce PEF into these applications. In any case, it will be very, very interesting to see what this industry will look like in the future and how it will adopt to the trend towards renewable carbon and circular packaging. The only way to assess the attainable market of PEF is to get it on the market. Once PEF is on the market, it will find its way into a wide variety of applications. In the hands of brand owners and consumers we can see how the market evolves and which applications are best suited. Then we can think about how further scaling can best be realized. The fact that other companies are also involved in FDCA shows that the industry has recognized that this is a very interesting product. I very much welcome the involvement of other companies because I think it takes multiple parties to grow the market rapidly. Take a look at the PLA markevan Aken: it was dominated for more than a decade by NatureWorks, and now a second supplier is on the market, Corbion, the market grows much faster. However, if you want to get samples of PEF now, you have to come to Avantium, in particular if you want to make quality bottles or films. With that in mind, I think we have a really good head start, and of course our goal is to make sure that we maintain this leading position.

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If I compare the development of PEF on the monomer structure with PET, then you have an advantage: You talk about recyclability right from the start. In the early days of PET, other aspects were in focus: low weight, high-performance. Yes, recycling has always been talked about for PET, but not with the same importance as today. I would say that if the PET industry had also considered recyclability and, above all, the circular economy from the start, we would not be in this situation today: PET is a material that can be recycled excellently, but consumers doubt it.

Van Aken: Of course, PET as polyester is one of the most suitable products for recycling: mechanical recycling, chemical recycling - everything is possible. It has considerable advantages over polystyrene, polyolefins etc. I agree that the recycling idea really came to life rather late, after about 30 years of using PET in the bottle industry. Nevertheless PET has the highest percentage of recycling of al polymers. I expect that legislation will be much stricter in the future, just look at the EU plastics directive, it is a sign of what it coming at us. With the recyclability profile of PEF we are ready for these changes.

When Avantium announced its first FDCA flagship plan in January, I thought briefly: What will the future bring? Maybe the end of PET appears on the horizon, or will it just lose market share? Will PEF follow in PET's footsteps? What is your vision?

Van Aken: For the next 10 years, I see PEF more in the use of high-value solutions than in the mass market. I think it's more likely to compete with aluminum, multilayers, films. Specifically, multilayer bottles and films are among the products we want to compete with. It really comes down to scaling. To reach the volumes and price points of PET, we have to reach a much higher production scale. You know, as a small company, we simply won't be able to achieve the volume that is necessary to compete with PET on a price per kilogram basis. For this reason, we plan to license it. We will build our first FDCA and PEF supply chain by ourselves and with partners. After that, we will license the production process to ensure the technology is deployed around the globe. This will make it possible to get to a larger scale much faster than if we were to do it ourselves.

Fig 3: PEF Bottles
Source: Avantium

Would this ensure the survival of the raw material producers?

Van Aken: The interesting thing is that PET manufacturers can use their existing assets and their production lines to produce PEF. The investments will be made more on the side of the monomer production. If I were a PET manufacturer, I would follow this very closely and pay attention to the right moment to change my product mix or add PEF. It will be interesting in the chemical industry when FDCA is available in quantities that have a real impact on terephthalic acid. Of course, you not only need FDCA, but also MEG, and we favor Bio-MEG, a technology that we are also working on. In my view, there are two major factors. First, the industry itself is not driving change. For the past 10 years I have always been disappointed with the petrochemical industry. They talk a lot about the transition, they talk a lot about sustainability, but what happens? Not much! They continue with what they are already doing. Secondly, it is the consumer who plays a very big role. When consumer behavior changes, brand owners, retailers and the entire supply chain react. The government can decide to accelerate the change by legislation, but I am convinced it is the consumer who will drive the change.

Is the concentration of material manufacturers helpful for Avantium? You currently only have to negotiate with a few large ones. Or would your position be better if there were still more material producing companies in different sizes?

Van Aken: Good question. The main difficulty is that this part of the value chain is mainly interested in one thing: the lowest cost, lowest cost, lowest cost. Therefore, there is unfortunately often little room for innovation and that makes it difficult to switch to new monomers and new polymers. On the other hand, the major manufacturers primarily listen to what their end customers want. In turn, we interpret the trends as an indication that there is great interest in plant-based products. It doesn't have to be 100% of the market directly, but if 20% of the market demands more sustainable products, then these parts in the supply chain increase. We also have the advantage that our technology runs on existing infrastructure and resources. To your question, the most logical thing is that it would be easier if there were more because a certain pressure could be created. A few large companies can protect their market more easily. But I'm not sure if it will actually work that way. I see that some of the big players are also very interested in developing more sustainable and plant-based solutions. The nice thing is, of course, that the market is growing, and PET is still growing. It's not that the market is declining and we're coming up with something new. I don't think PEF is seen as a threat to PET either. We are seen as a kind of 'next version'. We also like to talk to the manufacturers and ask them questions such as, "as a PET producer, it would be a very logical next step to include PEF in your portfolio. Why don't you join now?" and "can you help us to open up markets, products and applications in which we are interested?"

Let's talk about the cost. Assuming PEF would be available in the same quantities as PET: How much more expensive would it be?

Van Aken: It is hard to make a fair comparison: PET has gone through decades of learning; with PEF we are just at the beginning. My current assessment it that on the same scale, PEF would be between 25 and 50 percent more expensive than PET on a ton by ton basis, provided you understand disclaimers about raw material prices. At small scale it is three to five times more expensive. But I don't really want to be compared to PET. My current goal is not, for example, to provide a 1L bottle for soft drinks. Instead, I'm interested in the film industry. A supplier of a multi-layer film, a beautiful construct made of different materials, faces the problem that the film is not recyclable. They could

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switch to a PEF monolayer and retain the high-quality barrier, while gaining recyclability. These are the discussions we are currently having. For bottles, PEF is in play again when it comes to volumes below 500ml. For specific applications, PET has insufficient CO_2 barrier in small container bottles. This market is increasing due to popularity of small packages. PEF can compete with cans and glass bottles or multi-layer bottles for these small volume packaging formats.

The PEF bottle is more expensive than a standard bottle. The difference is the price that has to be paid for the more sustainable solution.

Van Aken: This is a topic that comes back often: are consumers prepared to pay a "green premium"? We have been discussing this for years. It really drives me crazy that many people in the PET industry claim that consumers don't want to pay a cent extra. There are many examples that show that people are willing to pay more for sustainability. Again, it's not about the entire market. Even if 20% of the market wants to pay a premium, things will get moving. We have recently sponsored a study from the University of Amsterdam that evaluated whether consumers worldwide are willing to pay more for sustainable products. The result is not very surprising for us, but probably surprising for many industry experts…Yes, consumers are willing to pay extra. Some want to pay 10% extra; some want to pay up to 50% extra. Provided they really feel confident that they are not being cheated and that it has an impact. Look at organic meat. For example, the price range for chicken fillets is immense between discounter and farm products. Keep in mind that with our strategy for high value products, we aim for customers to pay for performance, the "green premium" is more like a cherry on the cake.

If it is always a matter of passing on costs, what does that do to our society?

Van Aken: I very much agree with you that this should go hand in hand and that we should find solutions that help everyone. We do not want to be dependent on legislation because, as you know, governments can sometimes be a barrier to innovation. However, if you look for example at legislation proposed by the European Commission for single-use plastic packaging, you will see massive changes that will affect us all, for the better.

Let's stay with the consumers for a moment: do they have a chance to understand the difference between a water bottle made of PET or PEF? Can you communicate the pros and cons? Or is it still 20 years away?

Van Aken: Good point. It really depends on how you communicate about it. However, we are a technology company and will probably never win this communication battle. But, let's take a look. Firstly, Avantium pursues products in applications for which we believe there is an unmet need. Many performance benefits are easy to communicate. A longer shelf life of a lighter package are straightforward benefits to communicate. It can also be about recycling. Example: a brand owner switches from a multilayer packaging that cannot be recycled to a monolayer PEF package that is fully recyclable. I can see how brands would communicate this to the consumer. It

becomes more challenging when it is not about performance and only about sustainability. Communicating about the carbon footprint or the feedstock may not be the most straight forward marketing, but this can change rapidly when consumers would no longer tolerate the use of petroleum as a feedstock in the manufacturing of their packaging. We have seen examples of this and with the increasing concerns over climate change, one can foresee this becoming a major factor. Education is still needed, and I am sure that plant-based packaging will find acceptance more easily than petroleum-based packaging. So, these things must be solved. Alternatives have to be available and more economical, and consumer education has to be more effective.

Education is and remains a hot topic. There is still debate about whether PET or glass is more sustainable. Isn't that unfortunate when you look at the PET industry to make bottles lighter, use less energy, save more CO_2?

Van Aken: Let me tell you honestly that I'm not sorry for the industry. The industry was more focused on short term profits than long term sustainability. For example, the litter issue. The industry has been saying for too long that this is the problem of consumers and not their problem. In my opinion, the industry underestimated the problem and didn't take responsibility. Recently I see that this is shifting. I see many industries that have really changed their philosophy about recycling, and this is their most important challenge right now. It's a bit late, but it's good that they have come to this conclusion.

How high do you estimate the advantage of the degradability of PEF over PET?

Van Aken: That is clearly the advantage. PEF is very similar to PET, but it is also a little different. It's similar because we really position it as a fully recyclable polymer, and I think recycling is the best solution. In this sense, the empty bottle is a perfect raw material to produce the next bottle. I firmly believe in recycling and I think that is what we should always communicate and push for. Now, let's look at the difference between PET and PEF. The degradation of PET is predicted to take hundreds of years, and to be truthful no one really knows yet. This is one of the biggest differences to PEF. PEF is broken down much faster, we expect in a matter of years, this is something we are testing right now. This is also a sign of the times: before you bring a polymer to the market, you need to understand it end of life faith in nature. I wish our industry had done this for all the polymers that are on the market today! Unfortunately there is a significant misunderstanding about the terminology of biodegradability, which makes it hard to get the communication to the end markets right. A topic we have to work on as a polymer industry.

One of the advantages of PEF over PET is supposed to be compostability. In what periods is PEF mined - on an industrial scale and in nature?

Van Aken: We have first looked at industrial composting of PEF and have collected data that shows that PEF degrades much faster than PET under composting conditions. Right now, we are undertaking tests to determine how quickly PEF degrades in natural conditions. We started with it a year and a half ago and are already seeing how nature deals with PEF compared to PET. It is already clear that bacteria like PEF much better than PET. That being said, we believe that recycling is a much better solution than composting or degrading.

Do consumers recognize recycling as a lifeline?

Van Aken:If you ask consumers, they would likely say that degradability is the solution. Well, if we all start throwing our garbage into nature and counting on it being biodegraded, the world will be an even bigger mess. In my view, recycling is a much better way. We should never give up a bottle lost. We must be able to convince consumers and put an end to the confusion. Which brings us back to the education.

What is your vision of sustainable packaging?

Van Aken: In my view, we carry sustainable packaging in a real cycle: we produce, we collect, we recycle, and then we produce again. This will not be an eternal loop, as we will always need new raw materials to manufacture packaging. When this happens, we will use renewable, sustainable and regenerative virgin materials instead of relying on fossil raw materials. However then of course you have to look at the entire production and use of these materials. What is the ecological footprint based on in order to manufacture, process and recycle it? All of this shapes the sustainability profile of a product.

What is your vision for Avantium?

We want to bring new, innovative polyester technologies to the markevan Aken: plant-based, circular and with a range of functional properties. Better for packaging, better for electronics, better for cars. I still don't think the polymer industry is as creative as it could be, since not many new polymers have come onto the market in the past few decades. Let's change that. The drive for sustainability is an excellent reason for more radical innovation!

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Poly(ethylene 2,5-furandicarboxylate) (PEF) has a barrier that is reported to be up to 19x better on CO_2[1] and up to 10x better on O_2[2] than that of PET. Therefore, PEF can applied as an alternative for incumbent barrier solutions. Besides the fact PEF is from renewable feedstock, PEF has favorable properties for recycling.

Recycling of barrier materials in the PET stream

The trend of moving towards packaging solutions that fit the circular model has become so apparent during the last years, it hardly needs any introduction. At the same time, there has been a strong increase in the demand for barrier packaging solutions. Barrier layers and -additives can be very effective in improving CO_2 or O_2 barrier for rigid or flexible PET packaging. As such, these developments can result in dramatic weight reduction; the foremost important driver in a sustainable circular approach. However, the barrier materials that are currently commercially available can encumber or even obstruct recycling of such packages and us such true circularity.

Poly(ethylene 2,5-furandicarboxylate) (PEF) is a bio-based polyester with a known good barrier performance[1,2]. As such it can compete with commercially available (passive) barrier materials such as MXD6 and EVOH. One of the drawbacks of using these existing barrier materials is that they typically have poor compatibility with PET, resulting in poorer performance of resulting resin blends. Therefore, there is a need to have proper separation of the barrier layer from the recycled PET stream, for example by flaking (with the aim to delaminate the barrier layer) and subsequent sorting. When applying a passive thin barrier layer the latter case, converters need to balance between easy delamination of the barrier layer from the PET and the performance of the multilayer article during its use. Data published on bottles made of blends with PET and PEF[3], suggests that PEF would not necessarily need to be separated from the PET stream as it hardly influences the processing behavior of recycled PET and its performance in bottles. Additional studies have led to an interim approval by EPBP of PEF to enter the European PET bottle recycling stream at up to 2% of the total volume of that recycling stream[4].

A recent article on the miscibility of PET and PEF[5] indicates however that PET and PEF blends are not intrinsically miscible. It is important to mention that the blends for this study were prepared by first dissolving both polymers in a solvent and subsequently mixing these solutions (solvent mixing). This method prevents any transesterification to occur. Only during DSC measurements, the resulting blends were shortly brought in melt, then quenched and subsequently a heating ramp was applied to determine the glass transition(s) in the enthalpic data. The resulting DSC traces show that for these PET/PEF blends the time in melt (without the presence of shear) was not sufficient to allow for transesterification, leading to a blend with phase separation between PET and PEF. Apparently, the transesterification of PET and PEF requires more time, and possibly shear, to fully take place, leading to a PET/PEF co-polyester with only one glass transition as observed in the previously mentioned study on bottles made from PET/PEF blends[3]. In the latter study, the PET and PEF are dry blended and subsequently injection molded into preforms. Obviously, this latter procedure allows for more transesterification, as the residence time in melt is longer. An actual bottle-to-bottle mechanical recycling route will allow for even more transesterification as this procedure does not only include an extrusion step, but also a solid state polymerization in addition to the injection molding step. Therefore, only an injection molding step is a worst case estimate of the amount of transesterification that can take place. Here, some additional PET/PEF blend data as produced by dry blending and injection molding will be presented, supporting the statement that PEF is a bio-based barrier solution that can enhance the recyclability of (multilayer) barrier containers.

Injection molding of blends

The mixture of PET and PEF was fed pre-dried and dry blended into a Boy 50M injection molding machine at 170°C. The resin was molded into 76x76 mm² plaques with a nominal thickness of 1 mm and a shot weight of about 13 g. The molding parameters were kept constant, with a melt temperature of 280°C, injection time of around 0.6 s and total cycle time of 24 s. The resulting total residence time of the polymer melt in the barrel is estimated to be 5-9 minutes, while the mold was kept at 20°C. Other than the injection pressures, no significant differences were observed during molding the plaques from the different blends. In addition to the PET and PEF blends, a PET and MXD6 blend (at a ratio of 95/5 wt%) was molded. Visually, there is a clear difference between the different blends as seen in Figure 1 (top), showing in transparency the logo and caption through 4 plaques of 1 mm thickness stacked. A relatively high haze value for the 100 wt% PET control was found, which is probably due to the texture on the mold surface (R_a value is 0.4 µm). This roughness is the same for all the samples and therefore, only the differences in haze between the blends and the pure PET plaques are reported in Figure 1 (bottom). The results clearly show that PEF has a much lower b* and haze buildup than the MXD6 blend. It is worth noting however that blends of PET with MXD6 had much lower haze than plaques made from PET with only 1 wt% of PLA. For these plaques the Δhaze was found to be 44%; historically one of the reasons why the introduction of PLA in the bottle market was not successful.

The mechanical properties of the plaques made from the different blends were measured with a TA instruments Discovery 850 DMTA at an oscillating strain of 0.1%, a frequency of 1 Hz and a temperature ramp of 1°C/min. The resulting storage moduli as a function of the temperature are shown in Figure 4. From the trace it is clear that the plaque made from the PET/PEF blend has only one phase, resulting in only one glass transition with a value in between that of PET and PEF. The 5 wt% PEF blend only has a marginally small difference in mechanical behavior in the blow molding temperature window, supporting the observation that the blowing conditions of PET/PEF preforms do not differ much from pure PET preforms[3].

Bottles made of blends

The influence of blending a barrier material into PET on bottle performance was assessed by producing a small (12 oz/355 mL) generic CSD shaped bottle containing 5 wt% PEF or polyamide (PA). The most obvious difference in bottle properties is the appearance as is visible in the photograph in Figure 4 (top): whereas the PET+PEF blend bottle remains virtually haze free, the PET+PA blend has a clearly visible haze. The difference in compatibility also becomes apparent in other bottle performance as listed in the table below Figure 4. The PET+PEF blend bottle performs on par with PET and actually has a bit better CO_2 shelf life performance (in line with the previously cited study[3]).

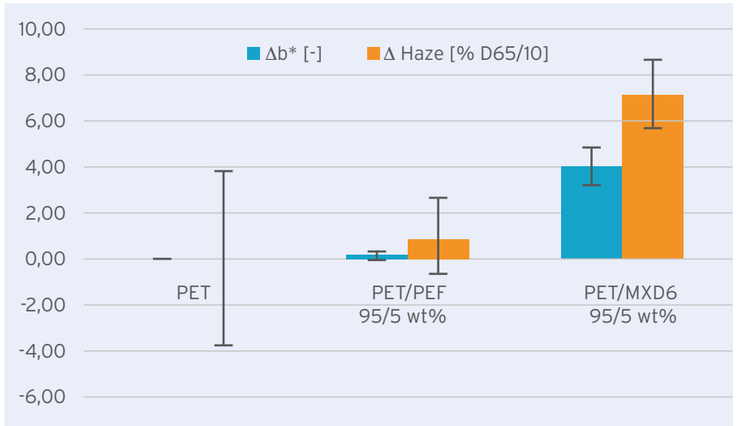

Fig 1: Visual appearance of 4 stacked 1 mm thick plaques of different compositions on top of printed paper (top) and average and standard deviation (error bars) of Δb* and Δhaze from direct color measurements on 5 plaques (bottom). Each composition was compared with the average value of 100 wt% PET.

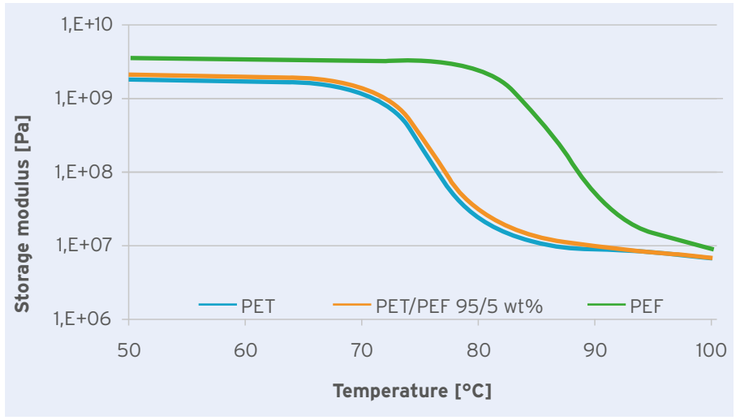

Fig 2: Storage modulus versus temperature as determined from DMTA measurements at an oscillating strain of 0.1%, frequency of 1 Hz and temperature ramp of 1 °C/min for PET, PET/PEF 95/5 wt% and PEF..

	PET	PET/PEF 95/5 wt%	PET/PA 95/5 wt%
Burst test	passed	passed	passed
Drop test (1.8 m)	passed	passed	passed
CO_2 shelf life (4.2 GV)	6.6 weeks	7.6 weeks	burst

Fig 3: Bottles blown from preforms containing different blends with PET as base material. From left to right: PET, PET+5 wt% PEF and PET+5 wt% PA. The table below the picture contains performance data of the bottles made from the different dry blends.

However, the bottle containing 5 wt% of PA does not pass the CO_2 barrier test as the bottles burst during the shelf life tests when pressurized at a 4.2 CO_2 gas volume.

Conclusion

When PEF enters the PET recycling stream in larger quantities (in the percents range), it hardly has any effect on the color and haze of the products made from the polymer coming from a mechanical recycling loop. This is a unique value proposition of PEF when compared to incumbent barrier materials and as such makes it a very interesting material to support the development of sustainable (multilayer) barrier packaging.

Acknowledgements

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