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# Developments in absorptive glass mat separators for cycling applications and 36 V lead−acid batteries

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## Abstract

The major markets for valve-regulated lead−acid (VRLA) batteries are undergoing a radical upheaval. In particular, the telecommunications industry requires more reliable power supplies, and the familiar 12 V electrical system in cars will probably be soon replaced by a 36/42 V system, or by other electrical systems if part of the automotive market is taken over by hybrid electrical vehicles (HEVs). In order to meet these new challenges and enable VRLA batteries to provide a satisfactory life in float and cycling applications in the telecommunication field, or in the high-rate-partial-state-of-charge service required by both 36/42 V automobiles and HEVs, the lead−acid battery industry has to improve substantially the quality of present VRLA batteries based on absorptive glass mat (AGM) technology. Therefore, manufacturing steps and cell components have to be optimized, especially AGM separators as these are key components for better production yields and battery performance.

This paper shows how the optimal segregation of the coarse and fine fibres in an AGM separator structure can improve greatly the properties of the material. The superior capillarity, springiness and mechanical properties of the 100% glass Amerglass multilayer separator compared with commercial monolayer counterparts with the same specific surface-area is highlighted.
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*Keywords:* Absorptive glass mat (AGM) separator; Capillarity; Mechanical strength; Specific surface-area; Springiness; Standard monolayer; Valve-regulated lead−acid battery

## 1. Introduction

Lead–acid batteries are commonly used in many different motive-power applications, e.g., automobiles, golf carts, forklift trucks and wheel chairs, as well as in the uninterruptible power supply (UPS) and telecommunications sectors. Accordingly, different levels of performance are required from the batteries. Following the ongoing progress achieved in these technical fields, a need for even more powerful and reliable power sources is emerging (i.e., for the telecommunication industry), as well as new demands such as high-rate-partial-state-of-charge (HRPSoC) operation for the new generation of electrical systems for cars (36/42 V or hybrid electrical vehicle). These developments are forcing lead–acid battery manufacturers to develop improved batteries, via optimized production processes and cell components, in order to challenge the alternative chemistries of nickel−metal-hydride and lithium-ion.

Over the past few years, valve-regulated lead–acid (VRLA) batteries have been greatly improved due to the use of new expanders and additives for the negative plate [1], new alloys for the positive grid [2,3], more accurate cell design and charging algorithms [4], and computer-based battery management systems for better efficiency [5]. The characteristics of the absorptive glass mat (AGM) separator have also become an important issue as its function is no longer simply confined to electrically insulating electrodes of opposite polarity and to allowing ion migration. Nowadays, it is considered to be a highly technical component, which can be instrumental in improving the electrical performance of cells.

More than in any other electrochemical cell, the performance of the separator in VRLA systems based on AGM technology is the key to successful battery operation [9]. Besides the basic insulation properties required from any separator system, an AGM separator, made of a mixture of coarse and fine glass micro-fibres, has the following additional functions.

(i) It is the immobilizing agent for the electrolyte and the only acid reservoir between the plates. Therefore, pore

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volume and acid absorbency are important characteristics and the fibrous structure has to be optimized to face problems like acid stratification or drainage.

(ii) As oxygen recombination is the basic function of a VRLA battery, the oxygen generated at the positive plate during charging does not escape, but has to transfer to the negative plate, where it is reduced to form water. This limits water loss and maintenance needs. Therefore, oxygen gas has to find passages between the two electrodes through the fibrous structure of the partially-saturated separator. The efficiency of oxygen transfer has to be optimized in order to avoid water loss, but its rate needs to be controlled so that the complete recharge of the negative plate can occur before oxygen reduction takes place.

(iii) The retention of plate-group compression is also critical for AGM, as most glass micro-fibre separators do not have adequate springiness and might lose contact with the plate, which leads to capacity decay and accelerated end of battery life. To maintain electrical contact and support adequately the active material, the separator must be sufficiently resistant to compression, but most importantly have a good resilience.

(iv) In addition to performance issues, battery manufacturers strive for lower production costs and higher production yields. The mechanical properties of AGM separators can also have a large influence on the manufacturing efficiency. Separators with higher tensile strength can enhance battery assembly by increasing the speed of the wrapping machines. Furthermore, a separator with higher puncture resistance can reduce scrap due to short-circuits during assembly, as well as increase the durability of the battery by avoiding early failure due to dendrite growth.

The following will demonstrate how greatly the above-mentioned properties have been improved in the new 100% glass Amerglass multilayer separator, without increasing the specific surface area compared with a standard commercial product, and without any addition of synthetic fibres. The improvement is simply obtained by optimum segregation of the fine and coarse fibres in two different layers.

## 2. Specific surface-area of AGM separators—a critical parameter

Since the AGM separator in VRLA batteries is nowadays considered to be a highly technical component, its choice has to be made with care and will depend on the battery end-use. In one of the applications mentioned above, the battery has to stand simply at full charge, until a sudden need for power arises, when it has to be able to quickly discharge and deliver the right amount of energy. Such applications are known as 'float', 'standby' or 'stationary' service. In another type of application, the battery has to deliver power

periodically, by successive discharges and recharges, so-called 'cycle service'. In addition to these two industrial end-uses, another application called 'SLI' is found in automobiles, where high-rate discharges and demands for starting, lighting and ignition of the vehicle occur. Besides the conventional 12 V flooded system, both the new 36/42 V electrical system in cars and the emerging hybrid electrical vehicles require high-rate partial-state-of-charge operation.

Because the separator is so critical to battery performance [10], the same material should not be used in all the above-mentioned VRLA products, and different AGM materials, specially adapted to each type of operation mode (various rates of discharge, depth-of-discharge, float, or cycling) are recommended. The major issue is electrolyte management.

Acid absorption and saturation level, as well as fluid distribution and movement, all are mostly related to the separator capillarity, which is a function of the diameter and proportion of the different micro-fibres used in the mat. This property is linked to the separator specific surface-area (SSA, expressed in $m^2 g^{-1}$ and measured by the conventional nitrogen adsorption BET method). Considering that two different fibre types (one of coarse fibres, the other of fine fibres) are commonly used to produce the mat, the SSA of the resulting AGM will be proportional to the amount of fine fibres. For most currently used fibres, the approximate range of SSA that can be achieved is from $0.6-0.8$ to $2.0-2.5 \, m^2 g^{-1}$. In the following discussion, the AGM separator called 'low-SSA' is typically $0.8 \, m^2 g^{-1}$, while 'high-SSA' reaches $2.1 \, m^2 g^{-1}$.

### 2.1. Low-SSA separators: advantages and disadvantages

While the separator choice is critical and should be mainly driven by performance considerations, battery manufacturers mainly take cost issues into account. As a consequence, the same type of low-cost material is very often used for any type of VRLA battery assembled on the same production site. Most of the time, low-SSA products with low density are attractive, due to their lower cost.

AGM sample S2 described in Table 1 is a good representative of this type of material and contains mainly coarse fibres. The resulting SSA is $0.8 \, m^2 g^{-1}$ and the mean pore diameter, measured by the standard Coulter porosimeter technique, is around $11.0 \, \mu m$, with a broad distribution from $4.5 \, \mu m$ minimum to more than $25.0 \, \mu m$ maximum.

While the main benefit of this type of material is its lower cost, due to the very low level of fine fibres (which are more expensive than the coarser ones, due to a different manufacturing process), a second advantage is related to the wicking speed that is achievable due to the open structure. Culpin [6] has demonstrated the usefulness of the Washburn equation for evaluating wicking behaviour. The impact of the separator fibre composition on its wicking characteristics, mainly wicking speed, was examined. The study pointed out that an AGM with smaller pores will wick electrolyte to a

Table 1
Physical properties of AGM samples with various SSA

|  |  | S2 | S1 | Monolayer | Amerglass |
|---|---|---|---|---|---|
| SSA ($m^2\,g^{-1}$) |  | 0.8 | 2.1 | 1.1 | 1.1 |
| Pore size ($\mu m$) | Min | 4.5 | 1.2 | 5.0 | 2.0 |
|  | Mean | 11.5 | 2.1 | 9.0 | 3.5 |
|  | Max | 26.0 | 5.3 | 21.0 | 7.0 |
| Tensile strength ($kN\,m^{-1}\,mm^{-1}$) |  | 0.105 | 0.540 | 0.260 | 0.500 |
| Puncture resistance ($N\,mm^{-1}$) |  | 2.0 | 4.5 | 3.0 | 4.0 |

higher maximal height, but much slower than an open mat with large pores.

The Washburn plot for sample S2 is shown in Fig. 1. The lower slope indicates that the kinetics of capillary rise are faster for this kind of low-SSA (i.e., large pores) material. This is helpful in production as it reduces the time necessary to fill the battery. Unfortunately, besides the advantages in cost and filling speed, sample type S2 has many drawbacks, as will be described below.

First of all, data from the wicking tests, carried out at the three compression levels of 20, 40 and 60 kPa according to the standard BCI procedure, show a significant and early drop in saturation values. This indicates that the retention of electrolyte is incomplete for all compression levels at all heights, even at the bottom of the sample between 5 and 10 cm (Fig. 2). In addition, sample S2 demonstrates an inability to wick any electrolyte above a height of 40–45 cm. The region up to ~15 cm is critical, as any drop in saturation level would suggest that cells made from this type of separator material would suffer from electrolyte drainage (and most probably a high level of stratification later in life). This would create a condition where the separator in the bottom of the cell is saturated, leading to very poor oxygen transfer

and recombination, while the upper part of the separator would have an abnormally high percentage of void space, leading to an intensive internal oxygen cycle. Using higher compression has been demonstrated to be helpful in reducing the tendency towards drainage, but even at an unrealistic manufacturing level of 60 kPa, there is still a noticeable drop in saturation from 5 to 20 cm.

The impact of poor saturation and low capillary forces on oxygen transfer through sample S2 has been studied by means of a new oxygen transfer test. The system, described in Fig. 3, is radically different from that previously used by Culpin and Hayman [9] and aims to determine the processes taking place in the cell. Oxygen gas is emitted from a bottle and passes through flow-meters, which control the flow-rate from 2.5 to 590 ml h$^{-1}$ very precisely. For this series of experiments, only one oxygen emission source has been used with a flow rate of 37.5 ml h$^{-1}$, and oxygen gas is allowed to reach the AGM sample which is compressed at 25 kPa between two Plexiglas plates (same principle as the wicking rig), after acid saturation by vertical wicking. The amount of oxygen passing through the partially-saturated sample is collected at the opposite side and measured by oxygen sensor cells (OSCs) that are distributed regularly (each 5 cm) over
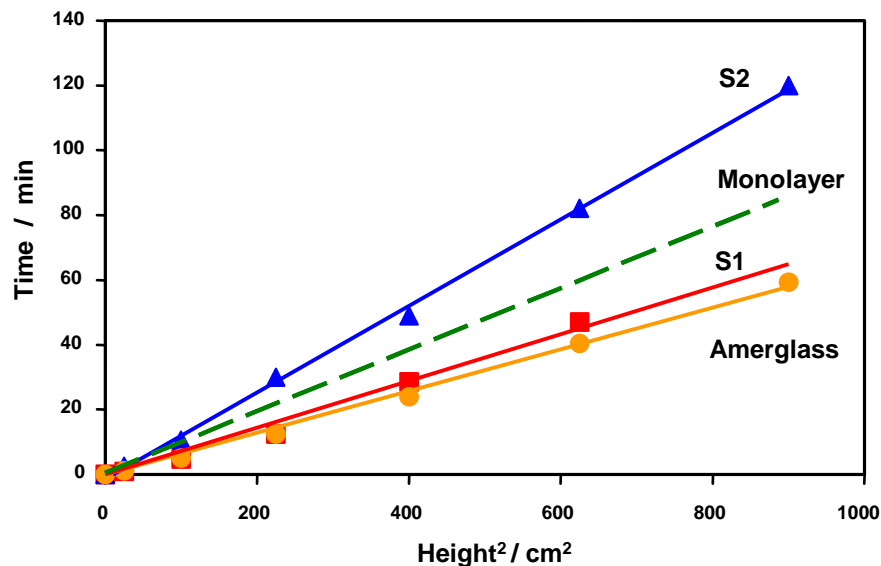


Fig. 1. Washburn plots for AGM samples: sample S2 with low SSA (0.8 $m^2\,g^{-1}$); sample S1 with high SSA (2.1 $m^2\,g^{-1}$); standard monolayer with intermediate SSA (1.1 $m^2\,g^{-1}$); Amerglass multilayer separator with 1.1 $m^2\,g^{-1}$.
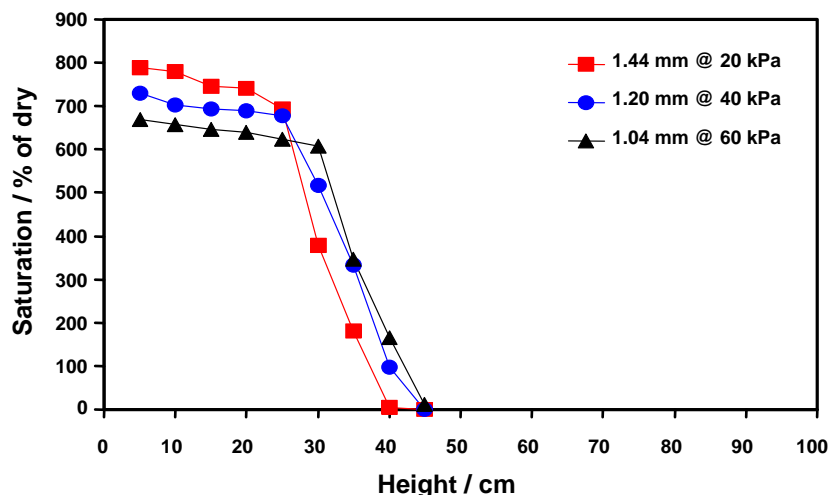
Fig. 2. Saturation wicking curve for sample S2 (AGM with low SSA) at different compression levels (20, 40, 60 kPa), according to BCI procedure.

the entire height of the sample. According to the type of sensor, 1 mA of current emitted by each OSC corresponds to $0.224\,ml\,h^{-1}$ of oxygen consumed by that OSC. At the end of the oxygen-transfer test, the separator is recovered in sections of 2 cm height. These are then weighed to evaluate the acid saturation at the different OSC locations.

A typical graph representing oxygen transfer through sample S2 is shown in Fig. 4 (zero time corresponds to the start of oxygen emission), together with a schematic representation of the sample saturation level as a function of separator height.

The data show that the detection of oxygen is very fast after the start of the emission. This means that no delay is observed between the oxygen emission and the time when oxygen crosses the partially-saturated separator. Even at high saturation levels (90.6% at the first OSC), oxygen has no difficulty in transferring through the AGM. This is due to the low capillary pressure exerted by the large pores. As the acid

is not so tightly maintained inside the pores, oxygen gas has no difficulty in displacing it and passing through the fibrous structure in order to reach the OSCs (i.e., the negative plate). High oxygen-transfer rates are therefore expected with this type of material, which lead to very efficient recombination. Therefore, incomplete recharge of the negative plates occurs.

Plots of thickness as a function of compression from 10 to 100 kPa and back (according to the BCI compression test procedure) exhibit large hysteresis both in the dry and the wet states (Fig. 5). The thickness loss of the material reaches 13.1% at 20 kPa and 29.2% at 40 kPa, which indicates that considerable initial compression is achievable with this type of very compressible separator. Additionally, the thickness recovery is only 81.3% at 40 kPa and 76.6% at 20 kPa (Fig. 5 and Table 2). This result means that a low-SSA micro-glass fibre separator like sample S2 has poor 'spring-back' quality and will be irreversibly compressed and lose thickness once exposed to the expansion of the
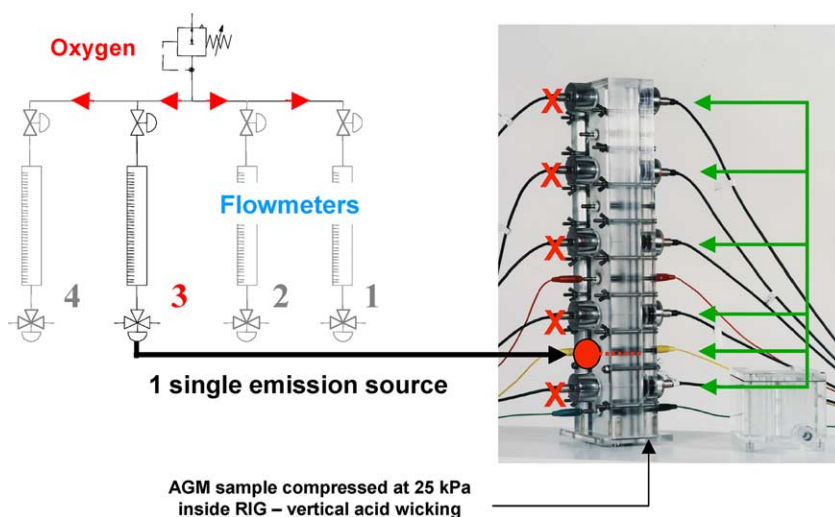


Fig. 3. Vertical rig with oxygen emission and detection for oxygen-transfer measurements through partially-saturated AGM separators.
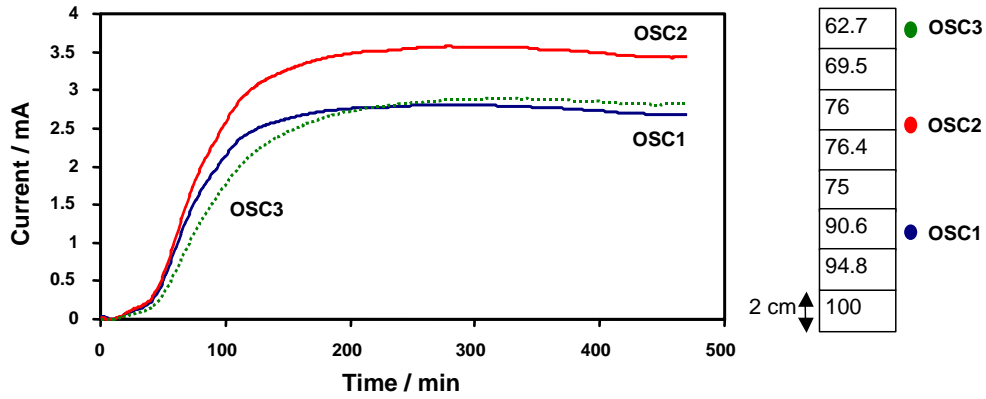
Fig. 4. Oxygen transfer through AGM sample S2 (low SSA) compressed at 25 kPa, after acid vertical wicking. The variation of saturation (expressed in %) as a function of separator height is given for each 2 cm portion beside the graph. The position of each oxygen sensor cell (OSC1, OSC2, OSC3) is also indicated.
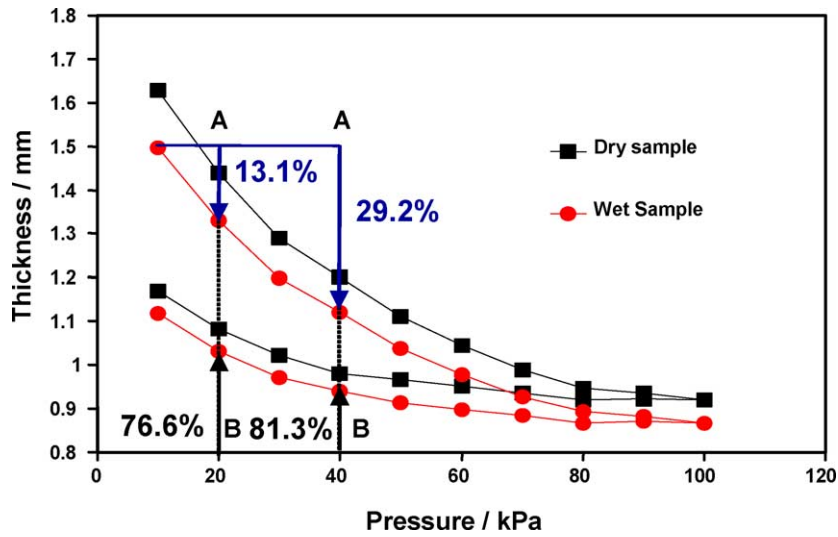


Fig. 5. Compression curves for dry and wet sample S2 (AGM with low SSA), according to BCI procedure. Arrows A indicate the thickness loss from 10 to 20 kPa (respectively, 40 kPa). Arrows B indicate the thickness recovery at 20 kPa (respectively, at 40 kPa) after a pressure load from 20 kPa (respectively, 40 kPa) to 100 kPa.

active masses during life. Therefore, the required compression inside the battery cannot be maintained during cycle-life. This will lead to irretrievable premature capacity loss due to poor plate–separator contact (PCL2). It will also have a major impact on the oxygen transfer. This is because the contact will be destroyed between the plates and the separator, and oxygen emitted at the positive plate will most probably be unable to cross the separator (due to the lack of compression) and will escape to the overhead space.

Besides these performance considerations, sample S2 has many mechanical weaknesses, which are directly related to the fact that low-SSA means less contact points among the fibres, where hydrogen bonds can promote mechanical strength. As shown in Table 1, the tensile strength is low

Table 2

Thickness loss (%) from 10 to 20, 40 and 60 kPa and thickness recovery at 20, 40 and 60 kPa after pressure load at 100 kPa of wet AGM sample S1 (high SSA), sample S2 (low SSA), standard monolayer, and Amerglass multilayer

| | Thickness loss wet (%) | | | Thickness recovery wet (%) | | |
|---|---|---|---|---|---|---|
| | @ 20 kPa | @ 40 kPa | @ 60 kPa | @ 20 kPa | @ 40 kPa | @ 60 kPa |
| S1 (2.1 m² g⁻¹) | 6.5 | 17.5 | 23.4 | 81.4 | 86.0 | 89.7 |
| Monolayer (1.1 m² g⁻¹) | 16.5 | 30.0 | 39.0 | 78.4 | 84.6 | 88.5 |
| Amerglass (1.1 m² g⁻¹) | 10.4 | 23.1 | 31.1 | 82.7 | 86.3 | 91.4 |
| S2 (0.8 m² g⁻¹) | 13.1 | 29.2 | 42.0 | 76.6 | 81.3 | 88.0 |

(only 0.105 kN m$^{-1}$ mm$^{-1}$) which not only causes difficulties in handling, but also reduces the speed achievable in the wrapping machines. Another direct consequence of the lack of fine fibres is the low puncture resistance of the product (only 2–2.5 N mm$^{-1}$). The resulting problems are higher scrap during battery production due to a higher amount of short-circuits arising at the assembly step, as well as reduced battery performance due to a lower resistance to dendrite growth through the separator.

Considering the above findings, it is obvious that this type of separator can only result in poor quality batteries and cannot be recommended for the high-performance batteries that are required nowadays by both the telecommunications and the automotive industries.

### 2.2. High-SSA separators: advantages and disadvantages

On the other side of the product range, the AGM sample S1 with high-SSA (2.1 m$^2$ g$^{-1}$) will also be described with its advantages and drawbacks. As indicated in Table 1, this separator, mainly composed of fine fibres, has a mean pore diameter of 2.1 μm and a narrow pore-size distribution between 1.2 and 5.2 μm.

As expected, the finer pore structure created by the high ratio of fine fibres allows much better retention of acid than in separator S2. The saturation of S1 as a function of wicking height for three compression levels (20, 40 and 60 kPa), according to the BCI wicking test procedure, is shown in Fig. 6. As expected on theoretical grounds [7–9], higher compression levels depress slightly the saturation, but significant drainage is not anticipated with this type of separator, and it is noteworthy that the plateau between 500 and 700% saturation lasts until 70 cm height at all compression levels. Therefore, the separator will promote homogeneous acid supply to the plates, at any height, with reduced risk of stratification.

A direct consequence of the high capillary forces exhibited by the small pore size, and the resulting tight retention of electrolyte inside the pores is illustrated by the typical oxygen transfer curve in Fig. 7. As shown by the graph, no oxygen is detected by the OSCs, even 16 h after the oxygen emission starts, at none of the saturation levels between 89 and 94% measured after the test. This means that the oxygen pressure exerted is not sufficiently high to displace the electrolyte from the small pores of this AGM material, which results in very low oxygen recombination at the beginning of battery life and higher water loss. Only when sufficient enough dry-out has occurred, can it be anticipated that some free paths will be created and oxygen transfer and recombination can be initiated. Despite the initial higher water loss, however, the main advantage of this material, which has very small pores and high inner capillary pressure, is that the negative plate can be fully recharged and not be disturbed by a too early oxygen reduction.

Moreover, unlike sample S2, the harmful impact of compression loss on oxygen transfer is not anticipated with sample S1. Pressure–thickness curves for S2 in the wet and dry states are given in Fig. 8. The curves show a closed hysteresis in going from 10 to 100 kPa and back. The thickness loss of the material is only of 6.5% at 20 kPa and 17.5% at 40 kPa, which indicates that the material is not easily compressible and will lead to higher initial compression in the cell after assembly. The thickness recovery is very good and reaches 86% at 40 kPa and 81.4% at 20 kPa (Fig. 8 and Table 2). The former results indicate that the material has a better springiness and will be able to maintain a good contact between the plates and the electrolyte reservoir during life, while the active masses are 'breathing'.

The other mechanical properties are also very much improved, due to the high amount of fine fibres. In particular, the tensile strength is very high on account of the hydrogen bonds developed among the fibres at the very numerous
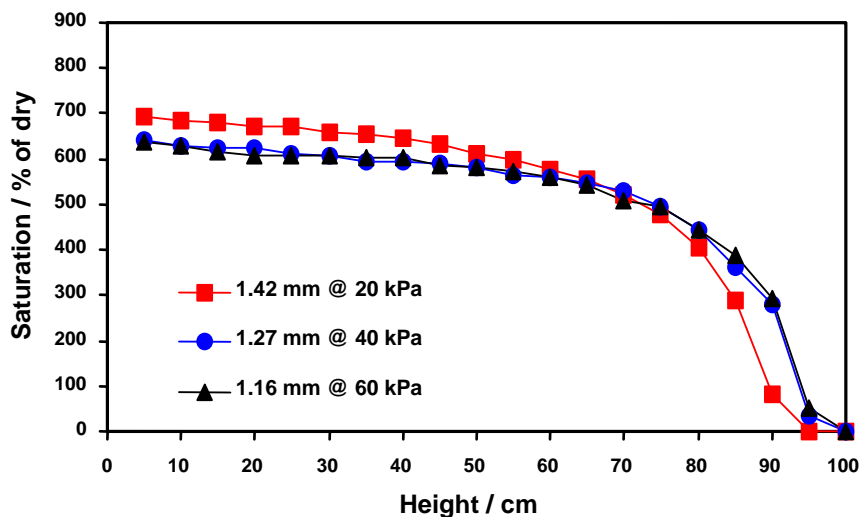


Fig. 6. Saturation wicking curve for sample S1 (AGM with high SSA) at different compression levels (20, 40, 60 kPa), according to BCI procedure.
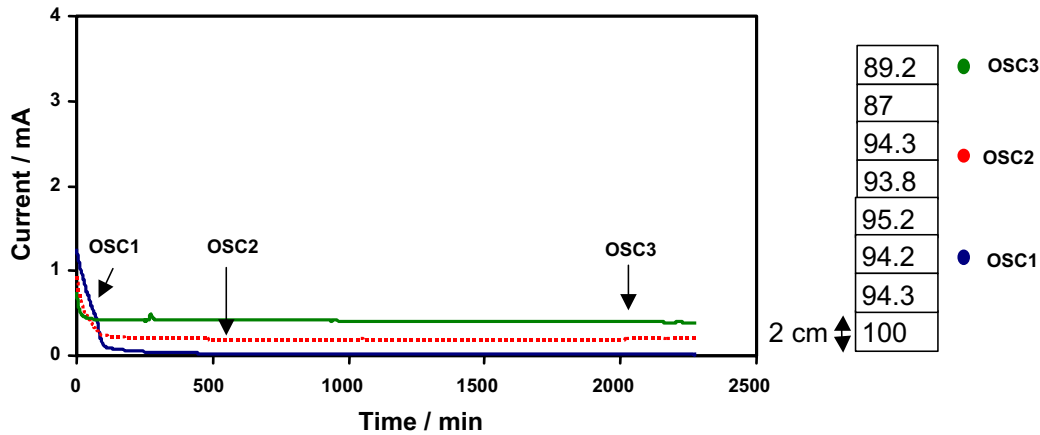
Fig. 7. Oxygen transfer through AGM sample S1 (high SSA) compressed at 25 kPa, after acid vertical wicking. The variation of saturation (expressed in %) as a function of separator height is given for each 2 cm portion beside the graph. The position of each oxygen sensor cell (OSC1, OSC2, OSC3) is also indicated.
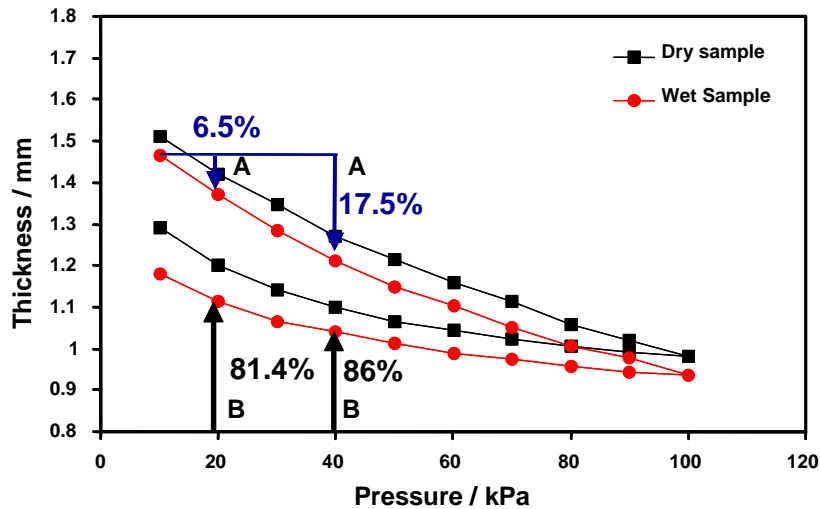


Fig. 8. Compression curves for dry and wet sample S1 (AGM with high SSA), according to BCI procedure. Arrows A indicate the thickness loss from 10 to 20 kPa (respectively, 40 kPa). Arrows B indicate the thickness recovery at 20 kPa (respectively, at 40 kPa) after a pressure load from 20 kPa (respectively, 40 kPa) to 100 kPa.

contact points ($0.540\,\mathrm{kN\,m^{-1}\,mm^{-1}}$ as indicated in Table 1, compared with $0.105\,\mathrm{kN\,m^{-1}\,mm^{-1}}$ for sample S2). This will result in better handling in production, higher production yields and better productivity due to higher speed being reached on the wrapping machines. The puncture resistance has also been increased from $2-2.5\,\mathrm{N\,mm^{-1}}$ for the low-SSA sample S2 to $4.5\,\mathrm{N\,mm^{-1}}$ for sample S1. The direct consequences are a lower scrap at the assembly step due to less short-circuits, as well as better battery durability as dendrite growth will be impeded.

Unfortunately, besides the positive characteristics mentioned up to this point, AGM materials with high-SSA and a high amount of fine fibres have two main drawbacks. The first is related to the manufacturing process, and especially the filling operation. As shown in Fig. 1, the slope of the Washburn plot for sample S1 with $2.1\,\mathrm{m^2\,g^{-1}}$ SSA is quite strong, which shows will take a long time to fill the battery and thus will reduce productivity significantly. The main drawback is the cost of such a material which is prohibitive, as fine fibres are appreciably more expensive than coarse fibres. As a result, most battery manufacturers cannot afford to use this type of separator, as the cost pressure exerted by the telecommunications and automotive industries grows stronger every day.

## 3. Optimum segregation of fine and coarse fibres in fibre mixes as key aspect for higher performance

### 3.1. Advantages of new Amerglass multilayer AGM compared with standard commercial monolayer materials

In order to counter the drawbacks and combine the advantages of both high-SSA and low-SSA products in a

single, optimized, glass micro-fibre material, Amer-Sil has developed an oriented multilayer AGM called 'Amerglass' (Table 1). This is composed of one open layer, which has large pores of around $10\,\mu m$, laminated on to a second layer, which contains mainly fine fibres and has very small pores (around $2\,\mu m$ mean pore diameter).

The properties of this new multilayer separator have been compared with standard monolayer materials from the market with the same SSA of $1.1\,m^2\,g^{-1}$. The major difference between both kinds of product is that the coarse and fine fibres are homogeneously mixed and deposited in one single layer in the case of the standard conventional AGM, but the fine and coarse fibres are optimally segregated into two different layers in the case of Amerglass. As will be described below, the resulting physical properties are radically different.

As demonstrated in Fig. 1, the slope of the Washburn plot for the Amerglass multilayer separator is surprisingly similar (and even slightly lower) to that for the low-SSA S2 sample, while the curve measured for the conventional $1.1\,m^2\,g^{-1}$ monolayer lies between the low-SSA and high-SSA samples S1 and S2, as expected. This means that the wicking speed of the multilayered material is mainly driven by its coarse layer, which results in faster and easier filling than any standard monolayer with the same SSA, which is a major manufacturing advantage especially for tall plates with a tight spacing.

On the other hand, the wicking test profile shows a very flat plateau up to 55 cm height (Fig. 9), contrary to the monolayer material, which exhibits a very slight drop in saturation from 0 to 40 cm, after which the saturation starts to drop more drastically. These experimental results show the beneficial impact of the fine fibres layer in the Amerglass material, namely, in maintaining acid to a higher plate height, compared with conventional commercial AGM. As acid appears to be more closely bound in the fine structure of the

Amerglass fine fibres layer, less drainage and stratification problems are encountered than in conventional monolayer separators.

The segregation of the fine and coarse fibres in two different layers, having a more or less open structure, also has a beneficial influence on the oxygen transfer. If the coarser layer with larger pores and lower capillary pressure is placed against the positive plate, the acid will be easily displaced by the emitted oxygen, thus enabling the gas transfer to be initiated. As a result, less oxygen will move along the positive plate and be vented. Then, the oxygen will face the fine layer, with much smaller pores, where the electrolyte is more tightly maintained inside the pores. Consequently, oxygen gas will have more difficulty to displace acid from the fine layer fibrous structure and continue its way to the negative plate. This will reduce the transfer rate (without decreasing the final recombination efficiency), and, thereby, will allow the full recharge of the negative plate to occur before oxygen recombination takes place.

Finally, the oxygen transfer will be optimized, as no excess of water loss will occur, as oxygen will enter the separator as soon as is emitted. This gives good recombination efficiency, but the transfer rate will be reduced to such an extent that no early change in the potential of the negative plate can occur.

Additionally, the compression properties of the double layer in the dry and wet states are much better than for the standard monolayer, as indicated by the data from Table 2. The thickness loss from 10 to 20 and 40 kPa is only of 10.4 and 23.1%, respectively, while it reaches 16.5 and 30.0% for the monolayer. This means that the initial compression achievable with the same production process with the Amerglass material will be higher than with a conventional single-layer product. More importantly, the thickness recovery of the Amerglass after a pressure load at 100 kPa reaches 88.2% at 40 kPa and 84.0% at 20 kPa, compared
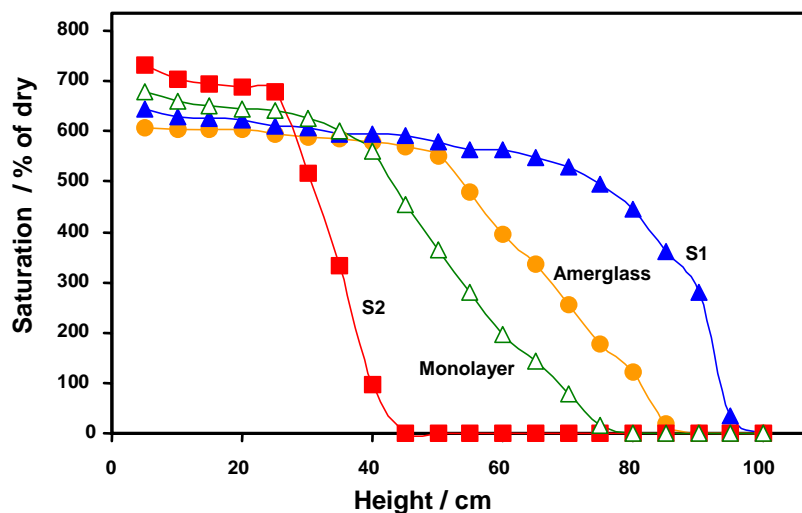


Fig. 9. Saturation wicking curves according to BCI procedure for sample S1 (AGM with $2.1\,m^2\,g^{-1}$ SSA), sample S2 (AGM with $0.8\,m^2\,g^{-1}$ SSA), Amerglass multilayer (double-layer AGM with $1.1\,m^2\,g^{-1}$ SSA) and standard AGM (monolayer with $1.1\,m^2\,g^{-1}$ SSA), compressed at 20 kPa.
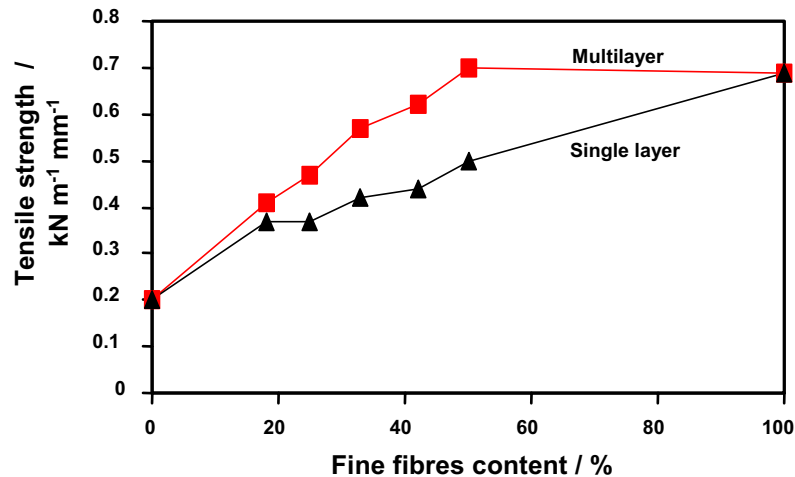
Fig. 10. Tensile strength of single layer (=monolayer) and multilayer AGM samples with same content of fine fibres content (i.e., same overall SSA).

with 84.6% at 40 kPa and 78.4% at 20 kPa for a commercial AGM with $1.1 m^2 g^{-1}$ SSA. Thus, the thickness recovery after a pressure load is better for the multilayer AGM separator than for a monolayer made with the same amount of fine fibres if homogeneously mixed into the coarse fibres. The resulting improved springiness of the separator can further compensate for the successive expansion and retraction of active masses during battery cycle-life, and will improve the plate-separator contact and avoid early failure.

Concerning the mechanical properties, the advantages of the fibre segregation in the Amerglass separator have also been demonstrated. The tensile strength obtained with increasing amounts of fine fibres is shown in Fig. 10 for single-layer material, in which the fine fibres are homogeneously mixed with the coarser ones, and for multilayer material in which most of the fine fibres are concentrated in a fine layer (as described previously for the Amerglass multilayer AGM). It is very clear that higher tensile strength is reached with the multilayer material, at all levels of fine fibres.

The results mentioned in Table 1 for the typical $1.1 m^2 g^{-1}$ materials confirm the results of the above test: $0.500 kN m^{-1} mm^{-1}$ has been measured on the Amerglass, while the monolayer has only $0.260 kN m^{-1} mm^{-1}$ tensile strength. Also, the puncture resistance of the multilayer AGM is higher than that for the conventional single-layer material ($4.0 N mm^{-1}$ typical value, compared with $3.0 N mm^{-1}$). These mechanical advantages will lead to better manufacturing yields and reduced production costs with the Amerglass than with other commercial monolayer products, due to higher wrapping speed and less scrap arising from short-circuits during assembly.

### 3.2. AGM density

In most of the published studies, SSA is mentioned as being the only key factor for electrolyte management in

AGM separators. The only parameter that influences the SSA of mats made of non-porous glass fibres is the dimension, mainly the diameter, of the micro-fibres deposited. It corresponds to the overall geometrical surface developed by all the fibres present in the mat. Contrary to belief, there is no direct relationship between SSA and AGM density, as the same fibres can be deposited either in a very dense mat or in a loose structure, depending on the process parameters. The resulting sheets will then have the same SSA, but different density. The pore structure will also be different, especially in the $z$ direction perpendicular to the $(x, y)$ sheet plane.

In order to examine the influence of density on separator properties, three AGM samples have been produced with the same SSA of $1.1 m^2 g^{-1}$ and different densities, namely, 156, 175 and $195 g^{-2} mm^{-1}$. The thickness loss was measured for each material from 10 to 20, 40 and 60 kPa. The thickness recovery was measured at each 20, 40 and 60 kPa compression level after a pressure load to 100 kPa. The data in Table 3 demonstrate that the thickness loss of the AGM separators at any compression is inversely proportional to their density. While the less-dense product loses 17.8, 29.1 and 41% thickness after applying pressures of 20, 40 and 60 kPa, respectively. The denser AGM loses only 9.1, 16.1 and 26% of its thickness at the same compression level. Moreover, the thickness recovery measured at different pressures after a load to 100 kPa showed that denser products have a better thickness recovery than the mat of lower density. The AGM with $156 g m^{-2} mm^{-1}$ density (measured at 20 kPa) recovers only 81.2% of its initial thickness when taken back to 40 kPa after a pressure load at 100 kPa, while the recovery of the AGM with $195 g m^{-2} mm^{-1}$ density (measured at 20 kPa) reaches 88.4%. Therefore, the springiness of an AGM with a given SSA increases with increasing density.

The puncture resistance of AGM samples with the same SSA of $1.1 m^2 g^{-1}$ is proportional to the density (measured at 20 kPa in the figure), as shown in Fig. 11. For the same amount of fine fibres, materials with higher densities have

Table 3
Thickness loss (%) from 10 to 20, 40 and 60 kPa and thickness recovery at 20, 40 and 60 kPa after pressure load at 100 kPa of wet AGM monolayers having the same SSA of 1.1 m$^2$ g$^{-1}$, but different densities (expressed at 20 kPa)

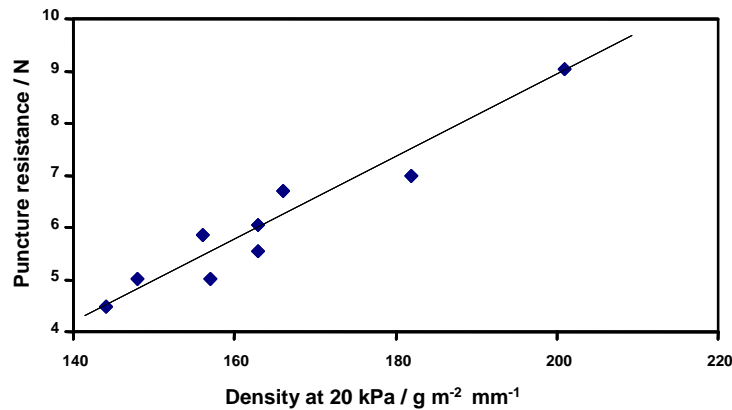| Density (g m$^{-2}$ mm$^{-1}$) at 20 kPa | Thickness loss wet (%) | | | Thickness recovery wet (%) | | |
|---|---|---|---|---|---|---|
| | @ 20 kPa | @ 40 kPa | @ 60 kPa | @ 20 kPa | @ 40 kPa | @ 60 kPa |
| 156 | 17.8 | 29.1 | 41.0 | 72.2 | 81.2 | 86.1 |
| 175 | 11.3 | 19.8 | 30.8 | 84.6 | 86.6 | 89.0 |
| 195 | 9.1 | 16.1 | 26.0 | 87.7 | 88.4 | 90.1 |



Fig. 11. Puncture resistance as a function of AGM density (measured at 20 kPa).

better resistance to perforation than AGMs with lower densities.

Therefore, SSA is not the only critical parameter. Rather, the SSA−density couple plays a major role in determining the physical properties of an AGM separator, and therefore in the fluid management inside the cell.

Taking into consideration that an optimum segregation of fibres in multilayer materials brings real advantages (as described above for the 1.1 m$^2$ g$^{-1}$ Amerglass compared with a more conventional 1.1 m$^2$ g$^{-1}$ monolayer), it is therefore highly recommended to use a denser multilayer Amerglass separator in order to increase the performance of any AGM design of VRLA battery.

## 4. Conclusions

It has been shown that the fibrous structure of an AGM separator can greatly influence its mechanical and capillary properties and, thereby, result in more or less handling efficiency during the manufacturing process, as well as more or less electrical performance of the battery.

Therefore, various parameters, beside cost, have to be taken into account, in choosing the best-suited AGM separator depending on the battery end-use. The fine-coarse fibre ratio, directly related to the SSA of the product, is one of the main properties to be considered. In addition, having the correct material density is important.

Surprisingly, it appears that an optimum segregation of the fibre mix, especially in a double-layered structure of the type developed for the Amerglass multilayer AGM, has a synergetic effect and leads to highly improved capillary and mechanical properties compared with the same fibre mix deposited in a homogeneous single layer. With this type of 100% glass multilayer separator, the use of high-cost AGM with an increased amount of fine fibres is not necessary, neither is the incorporation of hydrophobic synthetic fibres or any organic additive, which would lead to increased drainage, stratification and lower cranking performance.

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