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Journal of Power Sources 133 (2004) 67–78
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

'Density/solidity' of recombinant battery separator material—its influence on both separator and battery performance in valve-regulated lead–acid systems

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Received 8 August 2003; received in revised form 15 December 2003; accepted 15 December 2003

Abstract

The relationship between the porosity of recombinant battery separator material (RBSM) and separator/battery performance is examined. The porosity is inversely related to the sheet solidity and bulk density of the separator. The connection between high porosity and high acid absorption in the separator is well understood. The ability of RBSM to provide a very high porosity is a major reason why this material functions well in valve-regulated lead–acid (VRLA) batteries. Investigations have shown that the separator, besides providing space for the acid, must also provide a force on the plate active-material to eliminate the effects of premature capacity loss. This study examines the effect of changes in separator porosity/density on the ability to retain the wet force between the plates. It is found that retention of the force in the plate group is enhanced by an increase in the bulk density of the separator.

Keywords: Density/solidity; Lead–acid battery; Micro-glass; porosity; Recombinant battery separator mat; Valve-regulated

1. Introduction

The application of recombinant battery separator mat (recombinant battery separator material (RBSM); also known as absorptive glass mat, AGM) was instrumental in the development of valve-regulated lead–acid (VRLA) technology by Devitt [1]. The high porosity (>95%) of 100% micro-glass separators enables a suitable quantity of acid to be absorbed within the battery. Early separator designs focused primarily on obtaining the highest porosity possible from a given fibre composition. This resulted in low solidities, i.e., very low bulk density (bulk density is defined as the sheet weight divided by the thickness). In some cases, the high targetted porosity resulted in separators that had very steep compression curves, i.e., there was a large change in the force that the separator exerted in a dry as opposed to a wet condition. This was not viewed as a problem during the infancy of VRLA technology since most early compression work was performed with fully-saturated separators which had compression properties that were different to those of a partially-saturated separators [2,3].

Another issue in the early days was the lack of standardisation of important separator properties such as the thickness. This was highlighted in 1987 by Fujita [4] who reviewed all the different methods of thickness measurement that were being used for separators. Although the industry has subsequently improved its practice, many different thickness methods remain in use and therefore standardisation is still required. This is especially important when separator density is being considered.

Thickness is used to determine the bulk density, i.e., the grammage ($g\,m^{-2}$) divided by the measured thickness (mm). The density of Dexter's grade X8983 was given by Fujita [4] as $0.14\,g\,m^{-3}$. This was obtained with a 0.7 psi thickness gauge with a 2 in. diameter anvil. In terms of the standard set for thickness by the Battery Council International (BCI), which is measured at 10.3 kPa, the density would be closer to $0.15\,g\,m^{-3}$. It is interesting that in reviewing the properties, there is little difference from present-day separators. Even the quoted glass surface area of $1.2\,m^2\,g^{-1}$ is very similar to that of previous years.

In general, modern separators are vastly improved in overall quality. This indicates that many of the design inputs that the separator manufacturers must provide to their customers have changed little over the years. The separator bulk density is one of those design targets that has stayed

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doi:10.1016/j.jpowsour.2003.12.024

relatively constant. Although this situation is starting to change given the movement towards improved compressive force, i.e., higher bulk density. The use of separators with higher density has helped battery manufacturers to safeguard against failure problems associated with premature capacity loss type 2 (PCL2), namely, expansion and degradation of the positive active-material. Nevertheless, in some regions, manufacturers still aim to use separators with the lowest density possible. Whereas this may reduce cost, there can be an accompanying adverse effect on battery performance.

Separator density is based on the type of cell construction. One major problem associated with the prismatic construction is the relationship between RBSM and the dry/wet force that the separator exerts towards the plates and the walls of the battery case. Compared with a spiral construction, the prismatic alternative has less ability to hold the high compression values that can be imposed by a resilient RBSM separator. Most prismatic cases cannot resist the high force required for proper wet compression in the cell without some form of deformation of the rectangular case. Even though the case may rebound from its deformation, the plastic remembers this deformity. Under high temperatures, the plastic can resort back to this deformity and this results in a loss of separator compressive force, or worse, a loss of plate contact. In many cases, the compression design is decided by the ability of the prismatic case to restrain the inserted group. This is even more noticeable with prismatic inter-partition cell walls [5]. By contrast, a spiral cell provides a more beneficial method to compress the resilient RBSM separator in a uniform manner and to higher pressures. As a cell is wound, the winding tension of the coil can be computer-controlled to provide uniform tension across the total diameter of the cell. In addition, the force in the cell is not easily transmitted to neighbouring cells. Since the construction is a spiral, the force will be directed radially inward towards the centre. The original Gates cell (a spiral cell) was reported to use a dry compression force of over 100 kPa during winding.

The problem with prismatic case strength is one reason why the separator bulk density must be increased to accommodate the change from dry to wet force-loads within the cell. During the early 1990s, a flurry of patent activity [6,7] focused on fully pre-compressed RBSM. The various pre-compressed patents claimed different ways in which separators were held in a compressed form until assembly into the battery case. In some cases, organic binders were employed that were soluble and, once wetted, released compressed fibres. Brecht [8] used magnesium sulfate and silica as the binding agents.

In the Zguris patent [6], the fluid surface tension of a small amount of liquid was discovered to be adequate to hold the glass separator in a compressed mode until the plates are wrapped and then additional acid was added in the filling operation. One issue with this patent is the fact that the plates are exposed to a moist separator during the wrapping process. This gives rise to a concern over the pickling of plates. Recent work by Pavlov [9] has reported beneficial effects of a hydrating layer on plate surfaces. This may mean that the pickling issue in pre-compressing a separator with a small amount of fluid to hold the separator's fibres together may, in fact, prove beneficial in terms of battery performance. This would be in addition to the benefits of providing a pre-compressed separator that expands, once wetted, with acid. Simplifying the total operation of wrapping, cast-on-strap welding and stuffing of groups into the battery jars should help to speed up the manufacturing process of VRLA batteries. It should be noted that as the automotive market moves towards the use of VRLA batteries, manufacturing efficiency will become more critical.

The requirement for greater separator wet force inside the cell once filled with acid, together with the problems with the dry force required to obtain a suitable wet compression force on the weak prismatic case walls, has led to developments in which higher bulk densities have appeared. These separator types are referred to as semi-pre-compressed separators [5]. The average bulk density has moved from 130 to 140 $g\,m^{-2}\,mm^{-1}$ of thickness, to 150–180 $g\,m^{-2}\,mm^{-1}$ of thickness ($gsm\,mm^{-1}$). This has allowed battery manufacturers to design VRLA batteries with improved performance. The amount of separator, i.e., grammage, between the plates is the critical parameter. Higher bulk densities allow the manufacturer to assemble batteries with higher inter-plate separator density, i.e., lower inter-plate porosity, but with greater retained wet force.

With separators moving to higher bulk density, the impact of such a change on battery performance must be understood. This is the purpose of the present study.

2. Experimental

Several experimental separator materials were made either by means of a laboratory handsheet method or by using a prototype paper machine. The investigations examined the effect of separator density on properties such as compression decay, pore structure, and tensile strength.

In order to obtain a better determination of the compression decay of separators, a Chatillon compression decay fixture (Fig. 1) was use to plot changes in the force−time curve of RBSM material, and to determine the change between the dry and the wet force of different separators. The fixture has a force gauge, and mounted to the platen is a digital micrometer that determines the spacing between the manual moveable bottom platen and the top pressure foot which is mounted on the force gauge. The pressure foot has a diameter of 70 mm. It has been demonstrated that this equipment is very sensitive for determining changes in separator compression with time or when acid addition is made. Depending on the alignment (parallelism) of the platen with the bottom platform, large differences in force can be recorded with different gauges. Therefore, the experimental results should not be taken as absolute numbers. Another issue with this protocol may be the fringe effects of the pressure foot.

Fig. 1. Chatillon compression decay fixture.

In one experiment, where beam deflection was being determined for a steel rod, a cycle variation in the force was recorded. This was traced to the heating and air-conditioning system being turning on and off. A further experiment showed that a small application of heated air with a heat gun had a major impact on the force indicated by the gauge (Fig. 2). Such observations provide a clear demonstration of the sensitivity of the equipment.

3. Results

3.1. Impact of fillers on density

Laboratory handsheets were made to explore the impact of fillers (particulate/silica) on the bulk density of a RBSM separator. The laboratory handsheet mould is shown in Fig. 3. To assure that the density of the filler did not have an impact on the overall bulk density, a specially-prepared silica was made with the same relative density as that of the micro-glass fibre. Studies show that the overall bulk density increases with increasing filler content (Fig. 4). The last data point in the graph reflects the density obtained in the handsheets as the relative density of the filler is modified by the use of a different type of silica. This lowers the overall bulk density of the particulate matter and, as expected, a decrease in the overall bulk density of the material is observed. The tensile strength decreases as greater levels of filler are added to the blend, although a small increase is seen with small additions of a specially-made filler (see Fig. 7, later).

3.2. Impact of processing the fibre on density

A 0.8 μm micro-glass fibre was manufactured into laboratory handsheets. These were used to examine simple changes

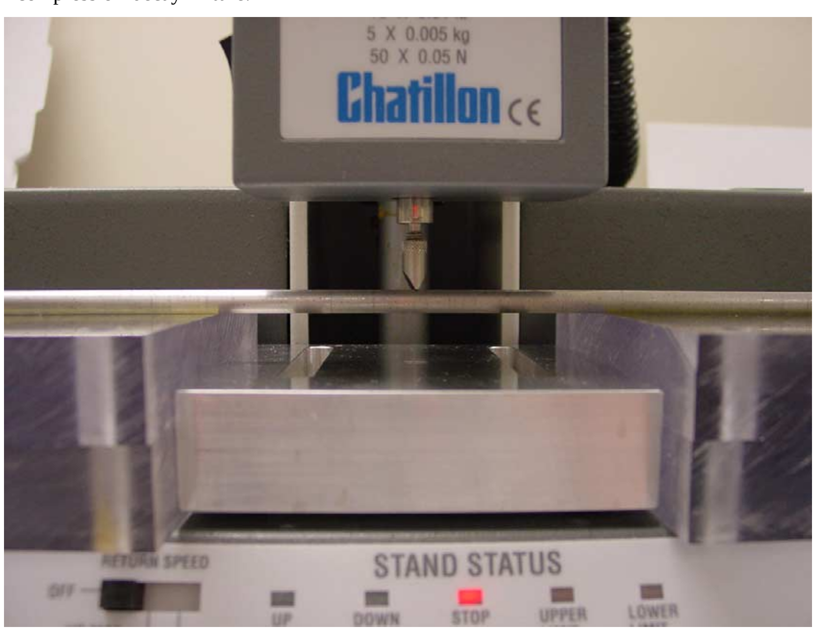

Fig. 2. Beam deflection experiment—steel rod.

Fig. 3. Handsheet mould, allows prototype laboratory development.

in the processing conditions of the fibre during mixing and forming. Three different processing modifications (A, B and C) were made to reflect three different levels of density in the finished sheet, while not destroying the micro-glass fibres. The change in density gives rise to an increase in separator density (Fig. 5). The tensile strength also increases with the bulk density of the handsheet (Fig. 6). A regression analysis shows a 0.9935 linear correlation between density and tensile strength for the three conditions. The data demonstrate that frictional forces amongst the micro-glass fibres exert a major influence on the total tensile strength. As the bulk density increases, there is greater likelihood of fibre-to-fibre frictional contact and, therefore, a linear enhancement of tensile strength. This also supports the fact that, once inside a battery, a separator with low density and low tensile strength may not be inferior to one with high-density and high-tensile strength. Rather, the critical factor for a RBSM separator is the minimum strength required for battery assembly.

Glass fibres with different diameters will give different values of tensile strength based on the area of frictional contact between the fibres, as well as other factors such as the skill of the manufacturer. An estimate of the number of individual fibres in 2 g of fine fibres is 5.6 billion fibres, while a coarse (3 μm) fibre will only have 28 million fibres to interact with each other. Other factors such as the method by which the glass fibres have been manufactured or the chemistry of the selected glass can give different absolute values of the tensile strength and the density of the separator. Actual battery performance is not linked directly to the tensile strength of the as-received separator. As stated above, the key criterion is that the separator should meet the minimum strength required for the battery-assembly purposes, otherwise tears or cuts may give rise to internal-shorts in the battery. The use of high-density separators helps to eliminate such a problem. For a fibrous sheet, the tensile strength increases with the density, as shown in Fig. 6. By contrast, increased density based on adding a filler typically leads to lower tensile strength and a less robust separator, assuming the filler is not bonded to the glass. This relationship is shown in Fig. 7.

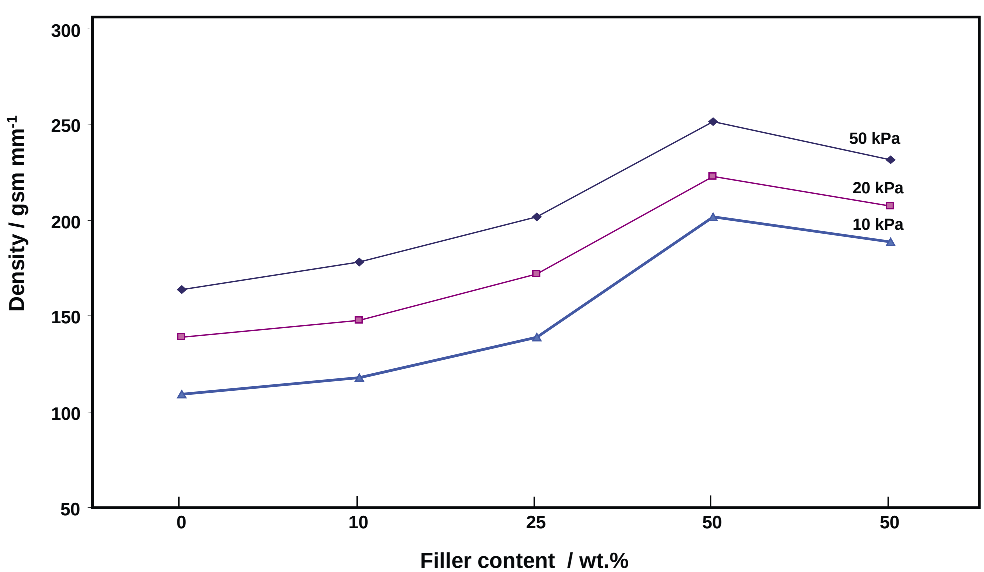

Fig. 4. Change in bulk density with addition of filler (silica particles) in handsheets.

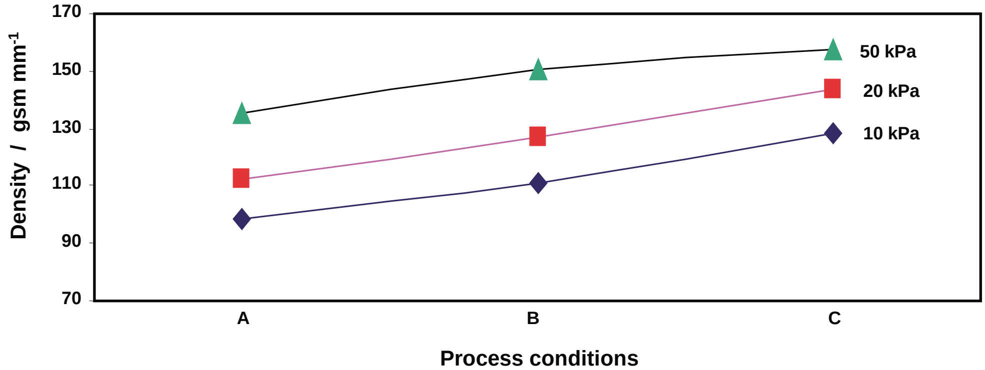

Fig. 5. Impact of process changes on density of 100% micro-glass separator using 0.8 μm glass fibres (handsheet study).

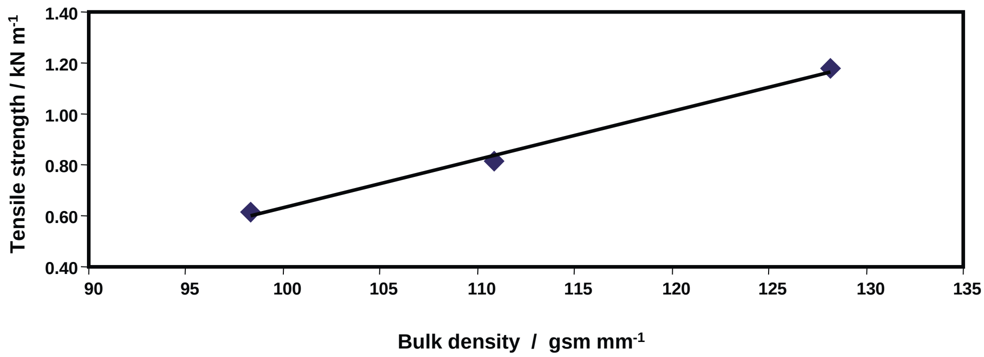

Fig. 6. Relationship of tensile strength with sheet bulk density (handsheets of 0.8 μm glass fibre).

3.3. *Influence of densification on pore structure*

A study was undertaken to examine the influence on the pore structure of all-glass separators that were a blend of fine and coarse glass with a surface area of 1.1 $m^2 g^{-1}$. Handsheets were made and divided into two. In each case, one of the halves was then compressed. The levels of compression were 10, 20, 30 and 40%. The pore structure was tested to determine the influence of densification on this separator property (Table 1).

The separator pore structure is important since the electrolyte distribution is controlled by the pore distribution. The rate of filling of the battery and electrolyte stratification are controlled by the pore structure. Larger pores will wick fluid faster and transfer fluid to smaller pores. After a certain period of time, the influence of gravity influences the upward wick rate, whereas the smaller pore rate of wicking overtakes the larger pores [10]. This study shows that by increasing the solidity, the pore structure is mainly modified by a decrease in the largest pores, while the mean and minimum pore sizes do not show a decrease (see Table 2). The correlation of maximum-pore size with density for all the materials tested is shown in Fig. 8. This behaviour was also displayed by a high-density RBSM which was made

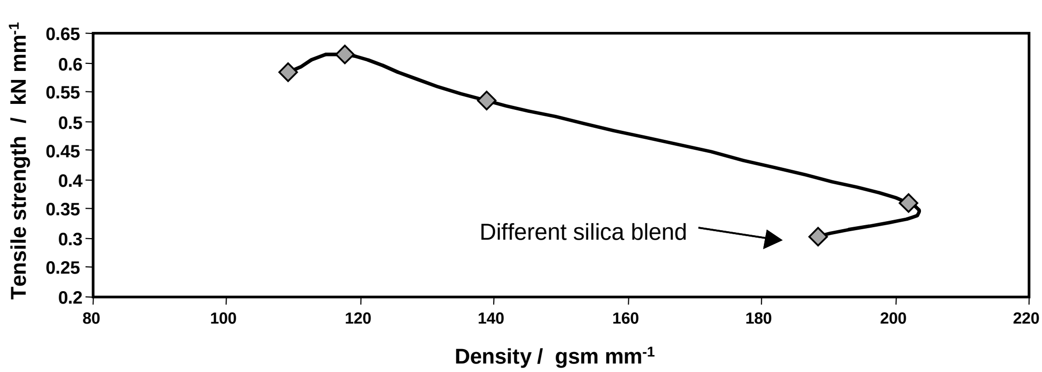

Fig. 7. Plot showing that increase in density by use of filler technology lowers the tensile strength with increased bulk density. Data from laboratory handsheets. Last point shows that a different silica will influence tensile strength.

Table 1
Impact of different processing of fine micro-glass

	Tests A	B	C
Handsheet test properties			
Grammage ($g\,m^{-2}$)	169	168	166
Thickness (mm)			
At 10 kPa	1.72	1.52	1.29
At 20 kPa	1.50	1.33	1.16
At 50 kPa	1.25	1.12	1.05
Density ($gsm\,mm^{-1}$)			
At 10 kPa	98	111	128
At 20 kPa	112	127	144
At 50 kPa	135	151	157
Total tensile strength ($kN\,m^{-1}$)	0.62	0.81	1.177
Pore size (μm)			
Minimum	1.38	1.29	1.18
Maximum	11.4	10.0	9.2
Mean	2.4	2.5	2.4
Visual water wicking (time to 10 cm) (s)	191	185	220
Visual 1.286 sp.gr. acid (time to wicking to 10 cm) (s)	508	481	587

on a pilot paper machine. The density from one side of the machine to the other was adjusted to investigate changes of density with properties such as pore structure and compression decay. The RBSM material was mainly all fine glass and was run to a high density of 200 $gsm\,mm^{-1}$, as discussed in Section 3.4.

3.4. Influence of extreme density during battery manufacture

To answer the question: 'are there limits to the denseness of RBSM separators?', a study was made to examine the impact of very high density in an all-glass separator. The experimental material was made on a pilot paper machine similar to those used to make commercial RBSM material. A blend of 90% fine glass and 10% chopped glass fibre was used as the fibre matrix. The density was modified while the material was being run on the paper machine. The material was densified from one side to the other, which thus created a gradient in density, from the front to the back of the paper machine. The density ranged from the targeted 200 $gsm\,mm^{-1}$ to a very high 250 $gsm\,mm^{-1}$.

The thickness gradient did not allow rolls to be cut. Therefore, samples were cut by hand to investigate the impact of these high densities. Again, it was observed that with increased density, the maximum pore decreased while the mean pore remained unchanged, and the minimum pore actually increased. Compression decay was investigated to determine whether such very high densities offer any benefit with regards to the retention of compressive force in an assembled battery. The data in Table 3 show that the highest

Table 2
Properties of handsheet study that examines compression (increased bulk density) vs. change in pore structure

Property	A		B		C		D	
	Uncomp.	Comp.	Uncomp.	Comp.	Uncomp.	Comp.	Unoomp.	Comp.
Handsheet study								
Thickness (mm)	1.56	1.49	1.68	1.38	1.57	1.2	1.55	1.07
Thickness change (%)	na	4	na	17	na	24	na	31
Density of sample ($gsm\,mm^{-1}$)	124	128	116	140	122	163	123	182
Pore size (μm)								
Minimum	3.7	3.33	3.6	3.7	3.5	3.8	3.5	3.7
Mean	6.2	6.2	6.8	6.6	6.8	6.4	6.3	6.3
Maximum	19.9	20	23.3	20.2	19.1	16.8	20	18.2

Notes: Uncomp.: uncompressed; Com.: compressed. Handsheets are made from an all-glass AGM (surface area = 1.1 $m^2\,g^{-1}$). The sample is cut in halve, with one halve compressed while vet. Sample A is 10%, B is 20%, C is 30% and D is 40% compression. Thickness at 10 kPa. Pore size is determined with a Coulter porometer.

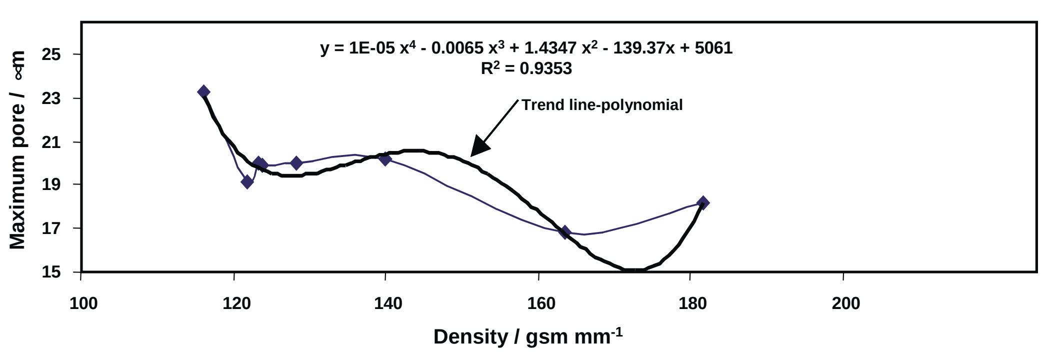

Fig. 8. Combined plot of all maximum pore values vs. compression (increased bulk density).

Table 3
Pilot machine high-density all-glass separator, showing that increased density above a certain limit can decrease the force exerted by a given separator composition

Uncompressed density (gsm m^{-1})	248	206	198	255
Compressed density (gsm m^{-1})	300	288	299	370
Change (%)	21	40	51	53
Separator compressed thickness (mm)	0.97	0.97	0.97	0.78
Force exerted by separator (kPa)				
Dry				
0 min	39.3	61.7	86.1	86.1
1 min	37.5	59.9	82.8	83.2
5 min	37.3	59.6	82.1	82.9
30 min	36.6	58.1	80.5	81.5
Wet (7X dry weight with water)				
1 min	27.8	50.4	70.2	69.3
2 min	27.7	50.2	69.1	69.1
5 min	27.7	50.2	67.7	68.3
30 min	26.1	47.9	65.2	66.5
1 h	25.4	47.0	63.7	65.4

Separator composition: 90% 0.8 μm glass and 10% chopped glass fibre.

density material does not offer any advantage. Materials with densities of 248 and 255 gsm mm^{-1} display greater compression decay than the other two materials with lighter densities. The overall decrease in the retention of force at an equivalent spacing can be seen in Fig. 9, and the change in force whilst under compression with time is presented in Fig. 10. These data demonstrate that whereas there are limits to the denseness of a separator, there is increased inter-plate retention of force.

This study supports the assertion that higher density materials must be used with caution since there are upper limits to the density. Increased compression/density of the incoming separator may not achieve a gain in plate retention of force. It should be noted that other ways to increase density have not been investigated. In the paper-making process, there are multiple ways to densify the web of fibres. Each method will have a different impact on the fibre structure and the inherent structural soundness of the glass fibre, which is a remarkable material in that it is very durable, inexpensive, and has good acid durability. On the other hand, glass is hard and brittle. Glass fibres can be destroyed if not treated properly. As an example, if a plate-wrapping machine uses a role to feed the glass separator, and if the nip-roll does not have a suitable gap, then excess damage can occur to the glass fibres. Other factors that must be considered are the length of the glass fibres, the retention of the fibre, and the manufacturing method. A fibre process similar to the traditional flame-blown method produces a very flat, straight fibre [11], while the patented controlled attenuation process by Evanite Fibre Corporation [12] produces a curly fibre that gives substantially more loft and compression force for a given fibre [13]. Due to very high elongation, this material will exhibit a lower tensile strength than sheets made with other fibre technology. When RBSM separator is used, there are different types of decay based on the level of compression. This has been discussed in some detail by Ball et al. [14]. In other studies, Pendry [15] has reported that RBSM separator will not be destroyed at forces of 100 kPa, which is well above the ability of most manufacturers to assemble cells.

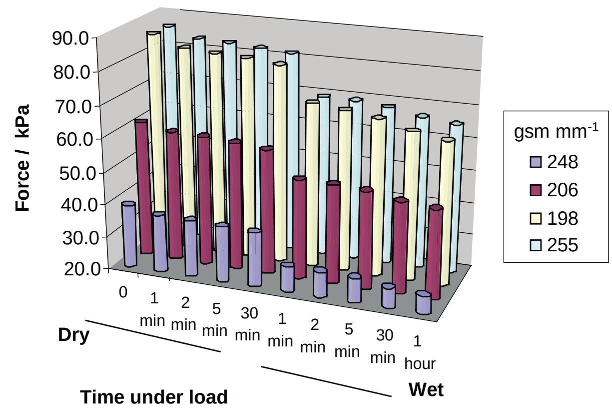

Fig. 10. Retention of force vs. high-density RBSM. Pilot machine study showing excess density can adversely impact compressive force. Bar graph represents the change in force whilst under compression with time.

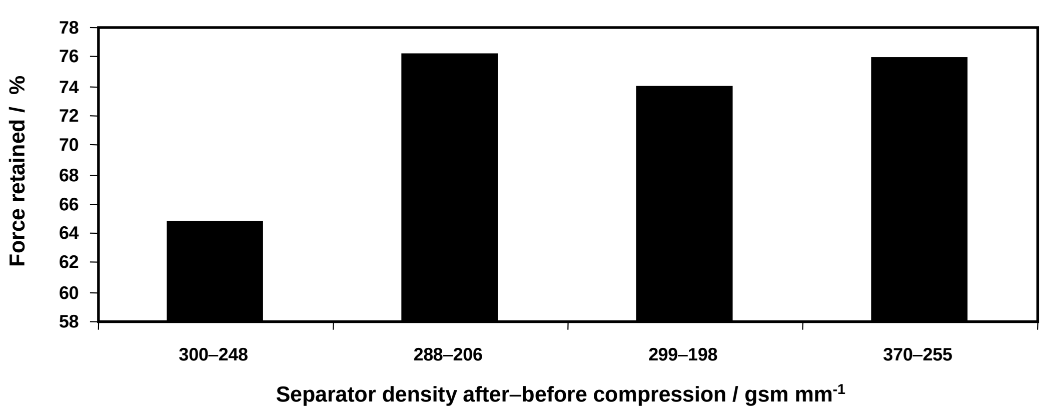

Fig. 9. Retention of dry force after 1 h of being wetted. The material with the 248 gsm mm^{-1} shows a greater compression decay than the other two lighter densities. An overall decrease in the retention of force at an equivalent spacing can be seen.

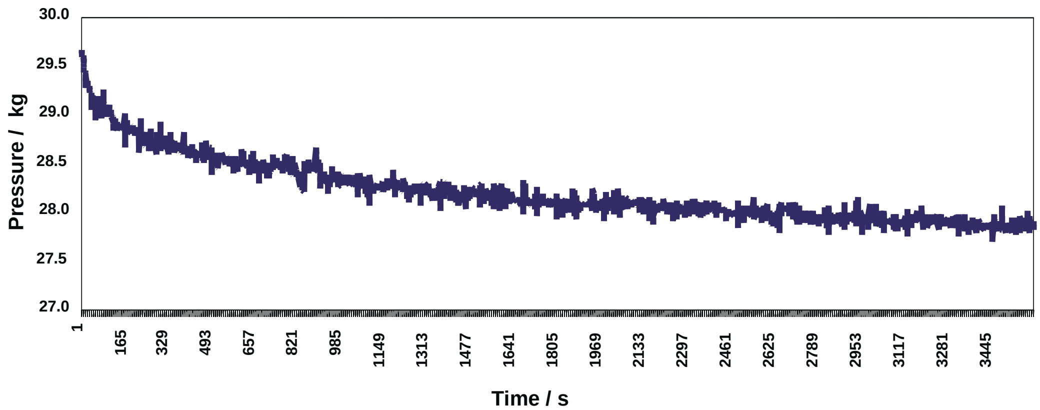

Fig. 11. Chatillon compression decay curve for a melt-blown, composite, alkaline separator. Two layers, compressed to starting compressive force and decay time of 1 h.

With very lofty (low density) separators, the surface fibres are brought up like a tent or pyramid. This type of fibre structure is quickly disturbed and only a small pressure is required to flatten the material. Also, separators manufactured with such a surface structure can exhibit much higher electrical resistance inside the battery.

As more force is applied to the separator, examination by scanning electron microscopy reveals that the fibres do not break but are actually moved and spread apart. In some cases, there are fibre bundles, which make an overall thicker fibre structure. This may be one reason why the maximum pore structure is modified at higher density, since bundles of the larger fibre structures are dis-entangled. After a certain point, fibre damage starts to occur. The amount of force a separator will withstand will be dependent upon the glass fibres used and the diameters of the fibres. In general, finer fibres provide greater crush resistance to external forces.

It should be noted that compression decay is not unique to glass fibre structures—it is also observed in organic webs. The compression decay of a melt-blown non-woven separator and a dry-laid non-woven separator is shown in Figs. 11 and 12, respectively. These separators are used in alkaline batteries. The same shape of decay for an all-glass sheet is presented in Fig. 13, while Fig. 14 shows how a small decrease (0.02 mm) in inter-plate spacing can cause a large increase in the force that the separator exerts on the plates in a battery. These curves demonstrate that the Chatillon compression decay fixture is a good tool for examining changes in the force/pressure inside a battery during service. As the positive plate grows and expands, it can be seen that additional separator pressure will be obtained on the plate, but

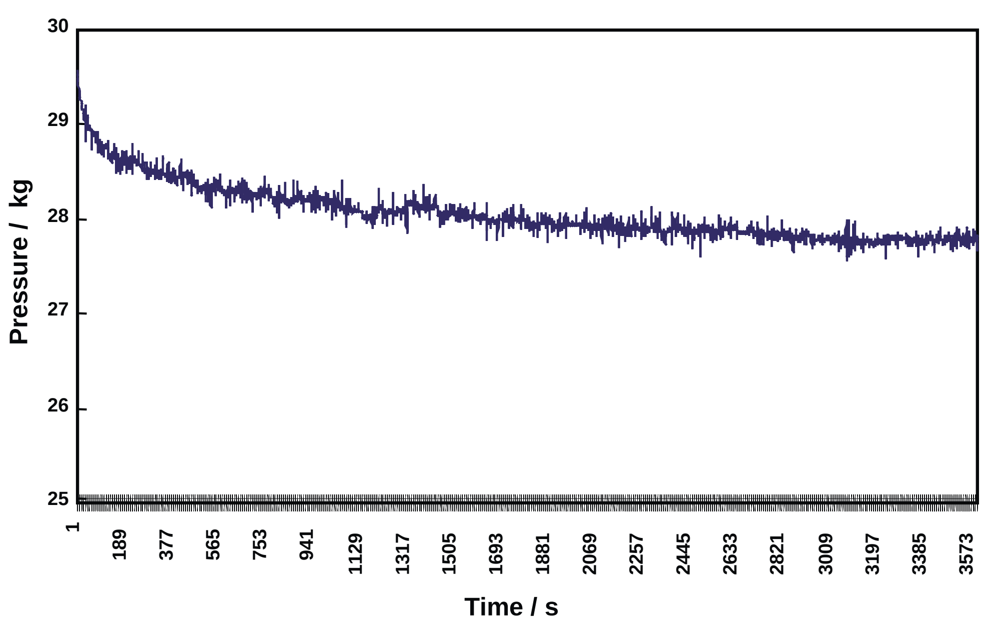

Fig. 12. Compression decay of a dry-laid, non-woven, alkaline battery separator. Test uses 2-layers and shows the decay after 1 h. Note that, compression decay is not unique to glass fibre structures as the same type of decay is observed with bonded organic webs.

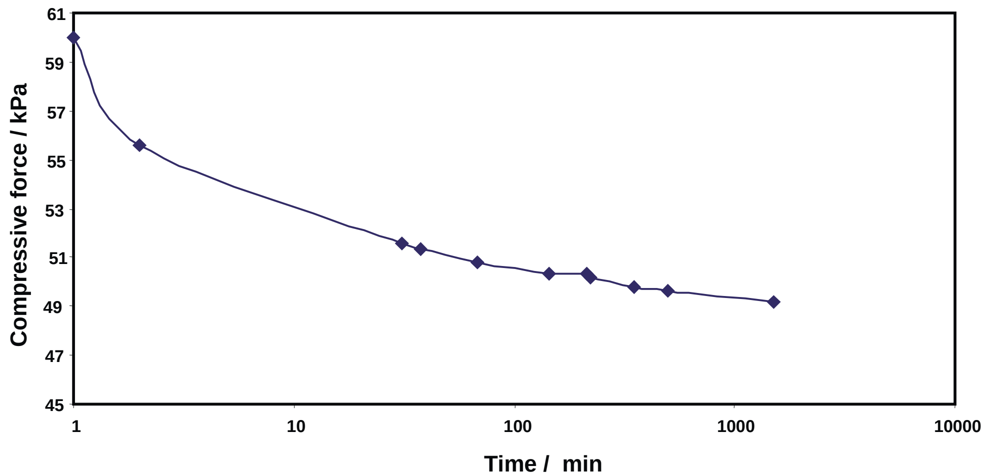

Fig. 13. Chatillon force decay curve of a 440 g m^{-2} all-glass RBSM. All-glass shows same type of decay curve as the melt-blown and dry-laid. Data verify that the spring decay is common to fibrous mats.

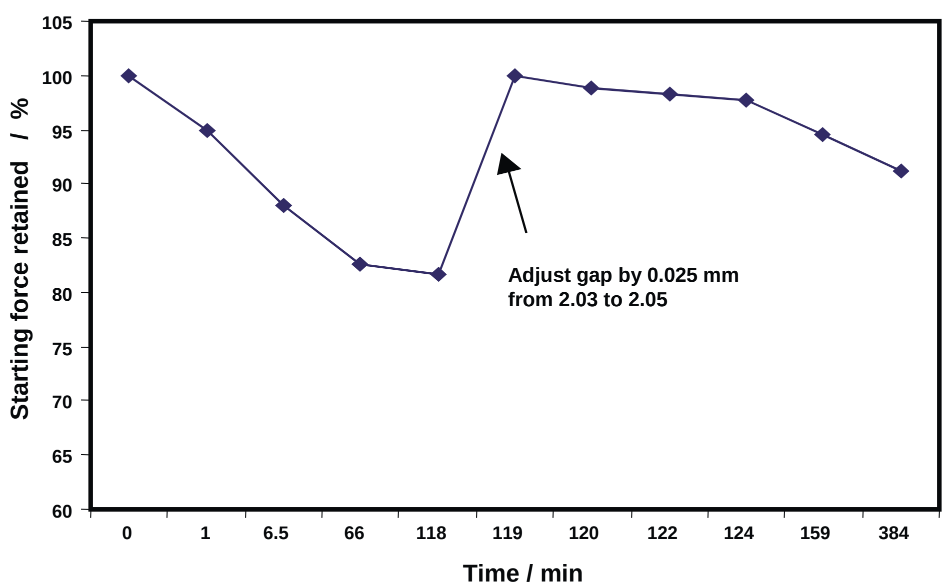

Fig. 14. Compression decay impact of gap swell shows that a small decrease (0.02 mm) in inter-plate spacing can have a large increase in the force that the separator would exert on plates in the battery. The data demonstrate that the Chatillon compression decay fixture is a good tool for understanding potential changes in force/pressure inside the battery case during service-life. As the positive plate grows and expands, it can be seen that additional separator pressure on the plate will be obtained.

the question remains: is controlled plate growth a benefit for VRLA technology?

4. Discussion

The results from the above experiments show that selection of an RBSM separator is a complex task. Today's separator has grown in complexity. All separators are not the same, even from the same manufacturer. In the early days of VRLA technology, it was very simple to specify a separator. A few criteria, such as the thickness or surface area, were sufficient. This was due to the very limited variety of RBSM separators that were available. There were fewer manufacturers, and fewer proven and accepted raw materials available for use. It was considered that only fine micro-glass of 100% purity would function within the battery. Considerable development and testing of alternatives in the early history of this technology have been reported. Two patents [16,17] proposed the use of separators with low surface area for improved battery performance, especially for high-rate applications. Glass fibres of large diameter dispersed in the matrix of the separator besides offering improved battery performance also helped to control the cost of the separator. The beneficial effects of using a more leachable glass fibre were also discussed [16].

Until the latter part of the 1980s [18], organic-glass hybrid separators were not considered an option. Nowadays, hybrid separators offer a viable alternative to all-glass types and provide improved performance opportunities for VRLA batteries [5,19].

Separator thickness was a useful parameter in the early days of RBSM technology, since, for a given fibre blend, it was best practice to manufacture at the highest bulk density possible. This was based on the principle that the largest porosity would give the most available acid volume. The practice also created larger variations in grammage in the separator to accommodate high porosity (thickness).

The fact that, once partially wetted with acid, the separator must supply a consistent force against the positive plate, or the impact of the separator's solidity on this parameter were not, however, fully appreciated. Inter-plate solidity can be reached in many ways. A higher bulk density can be obtained from the manufacturer in what, as mentioned above, has been referred to as a 'semi-pre-compressed condition', or the manufacturer can use a higher compression factor when designing a high-porosity separator. The impact of an increasing level of initial density or increasing compression on inter-plate separator density is shown in Table 4.

Table 4
Impact of density on separators at various compression levels

Original separator density (gsm mm^{-1})[a]	Separator compression (%)				
	20	25	30	35	40
130	163	173	186	200	217
140	175	187	200	215	233
145	181	193	207	223	242
150	188	200	214	231	250
160	200	213	229	246	267
170	213	227	243	262	283
180	225	240	257	277	300
190	238	253	271	292	317
200	250	267	286	308	333
220	275	293	314	338	367

Porosity is dependant on separator composition.
[a] Values are densities once compressed between the plates.

It must be remembered that at 95% porosity, there is only 5% solidity of the material. If the separator is compressed by 20%, the solidity becomes only 6%. If the retention of force or other compression force is related to the interaction of the glass fibres, it is not easy to understand the importance of solidity of the separator inside the cell. The interaction highlights and supports the need for greater emphasis on understanding the bulk density of the separator and its importance to overall performance. Nevertheless, the bulk density is not the only parameter that affects battery performance. The raw materials and equipment used to make the separator, the packaging and handling after the separator has been manufactured, and abuse of the separator during the assembly process will all influence separator performance.

In summary, thickness alone can no longer be fully descriptive of present separators, or their performance. Sophisticated products are now available with a range of densities and solidities. Separators with the same density that are obtained from different sources may have been produced by different manufacturing methods. This, in turn, may impart different attributes to the separator. At the same bulk density, varying porosities may be the result of comparing a highly loaded organic-synthetic separator and an all-glass separator. A change in separator porosity will give a change in acid volume, which will affect low-rate capacities. As discussed earlier, certain process modifications will have a linear influence on the tensile strength of the separator. This could be important when increasing the plate-wrapping speed. The tensile strength of RBSM changes with time and can only be used as a reference.

The tensile strength and compression properties of hybrid separators will display different behaviour depending on the hybrid technology. If the hybrid is based on bonding a skeleton structure of organic fibres, the separator will have permanent strength properties, even after being wetted with acid. An electron micrograph of this type of hybrid is given in Fig. 15. Another hybrid type, known as a 'membrane within a separator' [5,19], is shown in Fig. 16. These

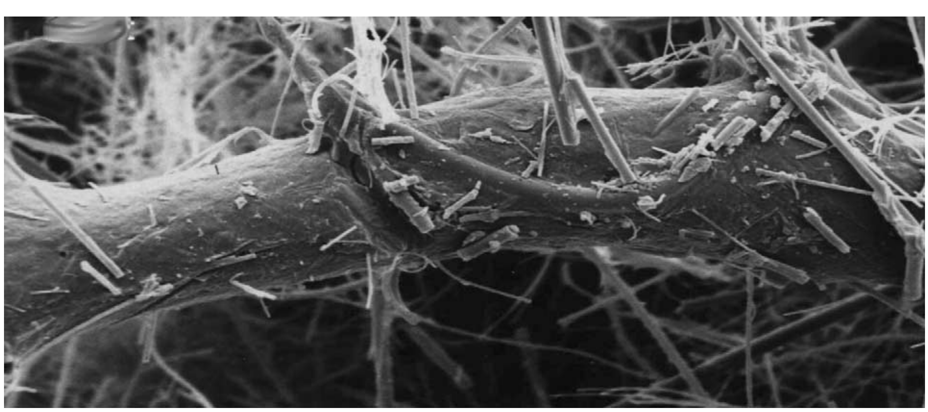

Fig. 15. Electron micrograph of a bonded hybrid separator (EnergyGuard® separator, formally known as II-15.) It is seen that glass fibres are bonded into the larger organic fibre. This gives permanent wet strength and modifies the hydrophobic nature of the synthetic fibre.

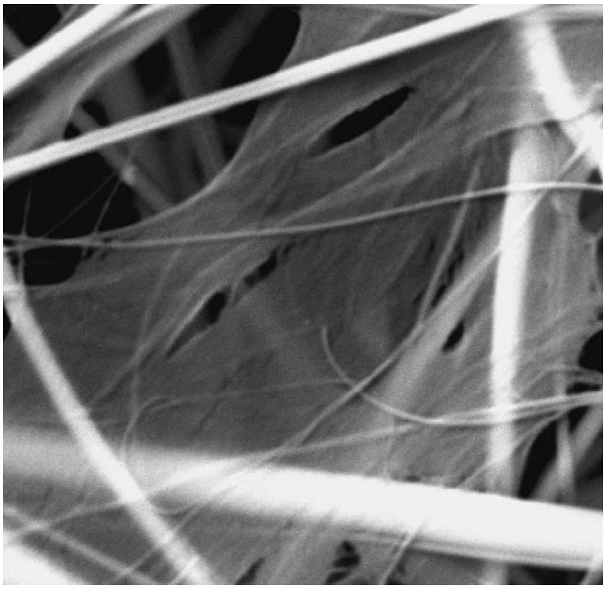

Fig. 16. Electron micrograph of a membrane within a separator technology (TufGuard® separator).

different hybrids will give different bulk densities, as well as different porosity and strength characteristics. The two hybrid technologies reflect the greater complexity of present separator technology. Therefore, it is even more important that the separator must be considered as part of the battery system as early in the battery design phase as possible. The recent work of the Advanced Lead–Acid Battery Consortium (ALABC) has reconfirmed the critical need for proper RBSM selection, as dictated by the intended application of the battery. Studies have demonstrated the importance of high compression and high surface area for good battery cycling performance, i.e., more force against the plates. For example, research conducted by CSIRO in Australia has identified the need for a high plate-group pressure of around 40 kPa, and has confirmed the benefit to be gained by increasing RBSM density, irrespective of whether separator is a hybrid or an all-glass design (Fig. 17) [20].

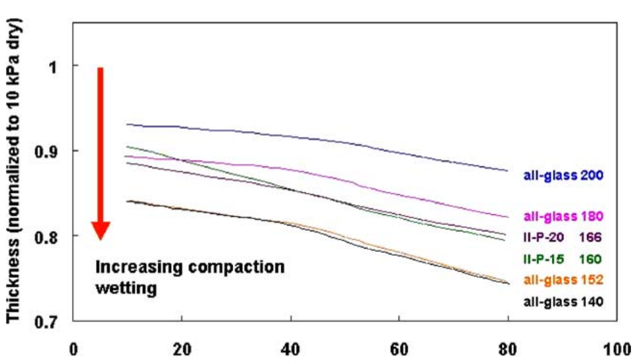

Fig. 17. Thickness–pressure behaviour of glass-inorgnaic (II-P-15; II-P-20) and all-glass separator materials when saturated with acid. Each line represents steady-state behaviour [20].

5. Conclusions

There is now a greater awareness of the benefits of the individual component properties in a VRLA batteries. In particular, the density and solidity of the separator has gained in importance. The initial density of the separator will impact battery life in a manner similar to changes in the density of the battery's active-materials. It should be noted, however, that careful testing should be performed to determine whether the system is at optimum force.

Selection of the components of VRLA batteries must be considered with a systems approach. A higher separator density will decrease problems in manufacturing such as

- case distortion after group insertion;
- improved cover-to-case sealing as result of decreased case distortion;
- diminished thermal plastic case/jar memory distortion;
- separator scuffing (peel) during wrapping and stacking operations;
- easier group insertion.

A higher density separator, as a rule, will enhance battery cycle-life. Too high a density will, however, result in performance loss. Lower inter-plate separator porosity will occupy additional volume between the plates and must be considered, especially in battery designs that are very acid limited, since capacity could be impacted.

The selection of RBSM density must be based on the individual composition since different fibres may have different relative densities. Since the density of hybrid separators will have different porosity/solidities than 100% micro-glass separators, designs must take this into account when determining the available acid volume within the separator. Additionally, more hybrid separators are being based on the technology of the Badger patent [21] that incorporates hydrophobic sites in the separator. In this case, a proper acid volume and filling system is a critical consideration when a battery is designed.

The density of RBSM plays a major role when determining the key attributes that a good separator must exhibit, such as the wet force placed on the active-materials and the grid. This attribute is estimated by the use of properties such as the compression from a given dry thickness. Most RBSM separators will exhibit a decrease in force from dry to wet conditions. Increasing the separator density will reduce this effect. Fundamentally, the goal is to reach a density at which the change in force between dry and wet conditions still maintains an optimum wet force amongst the plate groups and enhances battery life, while providing sufficient acid for the rated battery capacity.

Acknowledgements

The author is grateful to Hollingsworth & Vose Company for permission to publish this work.

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