Abstract:
The acoustical tiles Akoustolith and Rumford, developed by Rafael Guastavino Jr. and Wallace Clement Sabine, were used extensively in the early twentieth century to control reverberation, maximize speech intelligibility and limit the noise levels in large public spaces.
Their unprecedented sound control capabilities and the stone-like appearance made them a very attractive option for architects that were building monumental spaces during this period throughout North America.
Since the mid twentieth century, some spaces have decided to seal the original acoustical tiles to increase the reverberation and provide a more supportive environment for their music and organ programs. However, the acoustics of a space doesn’t depend exclusively on the reverberation time, but more importantly on the geometry and the size of the hall itself. Sealing the tiles is a non-reversible approach that has to be carefully evaluated because sometimes it could be the answer, but sometimes it is not.
Acoustical measurements performed in different spaces finished with Akoustolith and Rumford tiles are presented and compared with spaces of similar size in Europe, finished in stone instead of masonry acoustical tile.
Finally, the final outcome in spaces where the tiles were sealed is analyzed and a modern alternative is presented.

Historical background:
Rumford and Akoustolith tiles, patented by Rafael Guastavino Expósito (Guastavino Jr.) and Wallace Clement Sabine in 1914 and 1916 respectively, mark the start of the development of modern acoustical products using a modern and scientific approach.
Wallace Clement Sabine’s involvement in acoustics started in 1895, when President Eliot from the Corporation of Harvard University asked him:

“… to propose changes for remedying the acoustical difficulties in the lecture-room of the Fogg Art Museum, a building that had just been completed.”(3)

Sabine, a young physics professor without any particular background in acoustics, undertook this project and figured out how to improve the deplorable acoustics of this Lecture Hall. But not only that: starting from scratch, he was able to develop the first formula to calculate the reverberation time of a room based on the volume and amount of acoustical absorption present in the room.(3)

\[ T = 0.162 \times \frac{V}{A} \]

where
- \( T \) is the reverberation time in seconds
- \( V \) is the volume of the room in \( m^3 \)
- \( A \) is the absorption of the room in \( m^2 \), and calculated using the formula
\[ A = \sum_i S_i \alpha_i \]

where

- \( S_i \) is the surface area of every material present in the room in \( m^2 \)
- \( \alpha_i \) is the absorption coefficient (with values between 0 and 1) of a material

Because of his pioneering work and scientific approach in this field, he is considered the father of modern architectural acoustics. Sabine used this formula to help many architects solve new acoustical challenges, including McKim, Mead and White during the design and construction of Boston Symphony Hall in 1900.

At the time that Sabine was developing his formula and estimating the absorption coefficients of the most common building materials, Rafael Guastavino Jr. was very active at the Guastavino Company, leading important projects and beginning to take over the operations of the family business. At that moment, he was already showing an interest in acoustics that was probably motivated by some embarrassments with the acoustics of a few of the buildings being built by the company at that time.

Sabine and Guastavino Jr. crossed paths in 1911 when Architects Cram, Goodhue and Ferguson requested Sabine to determine the absorption coefficient of a Guastavino company’s installation at the chapel of the US military Academy at West Point. During that study, Sabine found that the absorption coefficient of Guastavino’s standard tile was, in average, \( \alpha = 0.033 \). Based on these results, Guastavino Jr. modified the standard tile and created a new one, which was used at the First Baptist Church in Pittsburgh (1911) by the same architects. Sabine found that this new tile, still with a low \( \alpha \) of 0.068, doubled the absorption coefficient of the previous one.

In 1912, Rafael Guastavino Jr. and W.C. Sabine started working together developing an acoustical absorptive masonry tile. Two years later, in 1914, the first product was patented: the kiln-fired Rumford tile. As stated in the patent:

“This invention is the result of a request from architects for structural walls and ceilings, which shall be at the same time finished in appearance and acoustically corrective.”

“… the air spaces may be connecting and must constitute channels traversing the rigid structure of the porous layer, and reaching to and penetrating the interior surface. It is desirable that these channels be irregular in form, expanding and contracting in cross section, so that their action will be like the muffling action of a muffler on an engine exhaust.”

“Clay, flux, such as feldspar, and a vegetable bearing earth, in a slightly moist condition, are pulverized and thoroughly mixed… In this powdered and lightly moist condition the material is the screened with a screen about sixteen meshes to an inch. The powdered material is then placed in molds of suitable form and subjected to sufficient pressure to cause the particles to cohere. The blanks are then dried, after which they are placed in a suitable kiln, the temperature of which is slowly raised until the vegetable matter in the blanks is consumed.”

Two years later, in 1916, the Rumford tile was superseded by the cheaper, more absorptive and more durable Portland-cement-based Akoustolith tile. As they explained in the new patent:

“In our Patent #1,119,543, issued December 1, 1914, we disclosed primarily a ceramic masonry material suitable for this purpose. Ceramic materials are, however, expensive and difficult to manufacture, as the porous blocks described in said patent have the tendency to warp when subjected to the heat necessary to fuse the flux, which when cooled, gives the strength and solidarity to the finished material or tile, and the object of the
present invention is to provide a material suitable for the purpose described, which will be easily and cheaply manufactured. '(2)

“A given quantity of sand, crushed stone, brick, or similar material, consisting of fine particles of suitable size, are mingled with a sufficient quantity of binding material, as for instance, Portland cement, to secure the particles firmly to each other at the points of contact; we have found that three parts of sand which will just pass through a sieve, about twelve meshes to the inch, and one part of Portland cement produce satisfactory results. If Portland cement is used, the requisite quantity of water must also be supplied to render the cement active. After these materials have been thoroughly mixed, they are placed in a suitable mold and the cement is allowed to set, thereby securing the particles to each other with irregular intercommunicating pores of variant dimensions between the particles, which only penetrate the exposed finished face of the material. '(2)

“The power of our product to absorb sounds of different pitches is dependent to a very large extent upon the dimensions of the pores between the particles of which it is composed, and the dimensions of the pores are largely dependent upon the dimensions of the particles; in other words, material composed of comparatively coarse particles is better adapted for the absorption of sounds of low pitch, whereas material composed of finer particles is better adapted for the absorption of sounds of higher pitch. We have determined by carefully conducted scientific tests that a graded porosity, with the larger pores in the front and the smaller pores in the rear increases the range in pitch over which our product is acoustically absorbed, and also increases its total absorbing power. '(2)

Good acoustics at the beginning of the XXth century:
The patent of Rumford gives a hint of the acoustical challenges encountered by architects at the beginning of the last century:

“The object of our invention is to provide walls and ceilings in auditoriums and the like which shall correct certain types of acoustical difficulties by the prevention, when properly used, of excessive reverberation and echo, and injurious focusing of sound.” (1)

“Walls to be effective in the correction of acoustical difficulties in auditoriums must be more highly absorbent especially for sounds having a pitch in the three octaves above middle C. Although the fundamental pitch of the male speaking voice is below middle C, the characteristic sounds which distinguish articulate speech lie mainly within this range.” (1)

Excessive reverberation was a common problem in large spaces, and especially at a time when speakers, preachers and cantors had to address their audiences without the aid of loudspeakers or microphones. As noted in the patent, good acoustics meant, in most cases, providing articulate speech or, in other words, good speech intelligibility.

The absorption coefficients of Rumford and Akoustolith, compared to the typical stone or plastered masonry structures are shown in the table below.

<table>
<thead>
<tr>
<th></th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone/plastered masonry</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>1” thick Rumford</td>
<td>0.07</td>
<td>0.12</td>
<td>0.19</td>
<td>0.25</td>
<td>0.26</td>
<td>0.22</td>
</tr>
<tr>
<td>1” thick Akoustolith A</td>
<td>0.06</td>
<td>0.13</td>
<td>0.38</td>
<td>0.52</td>
<td>0.52</td>
<td>0.36</td>
</tr>
</tbody>
</table>

As shown, Rumford and Akoustolith were extraordinary products capable of absorbing, at the “critical” frequencies (524 to 2096 Hz, i.e. the three octaves above middle C range), between 7 and 14 times more sound than their contemporary masonry products.

Speech Intelligibility:
The Articulation Loss of consonants (ALCONS) is one of the most commonly used parameters to evaluate speech intelligibility in an auditorium. ALCONS evaluates the number of consonants (in %) that is wrongly understood by a listener in a venue. (6)
summary, the higher the $AL_{CONS}$ (more consonants not understood) the lower the intelligibility:

<table>
<thead>
<tr>
<th>$AL_{CONS}$</th>
<th>Intelligibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%–1.4%</td>
<td>Excellent</td>
</tr>
<tr>
<td>1.6%–4.8%</td>
<td>Good</td>
</tr>
<tr>
<td>5.3%–11.4%</td>
<td>Acceptable</td>
</tr>
<tr>
<td>12%–24.2%</td>
<td>Poor</td>
</tr>
<tr>
<td>27%–46.5%</td>
<td>Bad</td>
</tr>
</tbody>
</table>

$AL_{CONS}$ degrades when increasing the distance between talker and listener. However, beyond a certain point, $AL_{CONS}$ remains constant:\(^{(6)}\)

\[
AL_{CONS} = \frac{200 d^2 T^2}{V + a} \% \quad \text{for } d < 3.16 \, d_{crit}
\]

\[
AL_{CONS} = 9 \,(T + a) \% \quad \text{for } d > 3.16 \, d_{crit}
\]

where

- $T$ is the reverberation time in seconds
- $V$ is the volume of the room in m$^3$
- $d$ is the distance talker-listener in meters
- $a$ is a zero correction-constant; for a good listener, approximately 1.5\%
- $d_{crit}$ critical distance $d_{crit} = 0.141 \sqrt{Q \, A}$; where $A$ is the absorption of the room in m$^2$ and $Q$ is the source directivity

**Acoustics of an European Gothic Church and a church finished with Akoustolith:**

What would be the intelligibility levels in a Gothic Church in Europe?

Assuming:

- $V = 28,000$ m$^3$
- Wall finishes: stained windows and stone
- Ceiling finishes: stone
- Floor finishes: stone + wooden pews
- $N = 1500$ (audience size)
- $a = 1.5\%$
- $T = 5.2$ sec at 2 kHz (empty)
- $T = 3.2$ sec at 2 kHz (occupied)

For a trained speaker and a good listener, in a fully occupied room, $AL_{CONS}$ would be poor at 13 m from the speaker (approximately at pew # 11); bad beyond 19m (pew # 17), reaching a loss of consonants of 30.3\% for listeners at distances greater than 21 m (pew # 19). For an empty room, $AL_{CONS}$ would be poor at 8 m from the speaker (approximately at pew # 6); bad beyond 12m (pew # 10), reaching a loss of consonants of 48.3\% for listeners at distances greater than 16 m (pew # 14).

Let’s assume that this same church was finished mostly with Akoustolith instead of stone (50% of wall and ceiling surfaces approx.). The estimated reverberation time would decrease to 2.0 seconds when empty and 1.55 sec with a full audience.
In this room, in fully occupied conditions, AL\text{CONS} would be poor at 27 m from the speaker (approximately at pew # 25); reaching a loss of consonants of 15.45% for listeners at distances greater than 31 m (pew # 30). For an empty room, AL\text{CONS} would be poor at 21 m from the speaker (approximately at pew # 19); reaching a loss of consonants of 19.5% for listeners at distances greater than 27 m (pew # 25).

**Reverberation of spaces finished with Akoustolith & Rumford tiles:**
The following table shows the measured reverberation time in different spaces finished with Akoustolith (Duke University Chapel before its 1971-1973 renovation when the tile was sealed\(^{(7)}\) and Rumford tile (Saint Bartholomew’s Episcopal Church and Saint Vincent Ferrer Church, both in New York City).\(^{(8)}\)

<table>
<thead>
<tr>
<th></th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000Hz</th>
<th>2000Hz</th>
<th>4000Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duke University Chapel (1970)</td>
<td>-</td>
<td>4.0</td>
<td>3.0</td>
<td>2.3</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>Saint Bart’s (2010)</td>
<td>2.5</td>
<td>2.2</td>
<td>2.1</td>
<td>2.0</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Saint Vincent Ferrer (2012)</td>
<td>3.5</td>
<td>3.5</td>
<td>3.0</td>
<td>2.9</td>
<td>2.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Most of these spaces were deemed a success when completed, mainly due to the impressive level of intelligibility compared to other contemporary spaces.

**Reverberation of spaces with sealed Akoustolith & Rumford tiles:**
Despite the huge improvement in speech intelligibility, there were some complaints documented as early as 1920, when the organist and choir of Hennepin Avenue Church in Minneapolis, complained to the architect G.H. Hewitt of Hewitt and Brown of too much sound absorption.\(^{(5)}\)

Simultaneously, in the 1920s and 1930s, the technology for public address systems (loudspeakers, microphones, amplifiers) was being developed. The *Jazz Singer* was released as a feature-length movie in 1927 and it was the first movie that included dialogue and music on the filmstrip itself. On April 27, 1933 Bell Labs succeeded in the first wire transmission of symphonic music from Philadelphia Academy of Music to the Constitution Hall in Washington DC.\(^{(9)}\) Later on, with the development of column speakers, it became possible to deliver adequate levels of speech intelligibility in very reverberant environments.\(^{(10)}\)

Starting in the 1950s, some spaces started to treat the Rumford and Akoustolith tiles to address the concerns of musicians. The approach followed consisted on painting the tiles to seal the porosity and, thus, reduce the absorption coefficients values. Sabine and Guastavino Jr. already stated in their first patent:

> “The body of material, is sponge-like in structure…It is essential to this invention that the sound penetrate the material.”\(^{(1)}\)

The following table shows the measured reverberation time in different spaces with sealed Akoustolith (Duke University Chapel after its 1971-1973 renovation\(^{(7)}\) and Church of the Heavenly Rest in New York City\(^{(8)}\)) and Rumford tile (Saint Thomas Church in New York City\(^{(8)}\)).

<table>
<thead>
<tr>
<th></th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000Hz</th>
<th>2000Hz</th>
<th>4000Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duke University Chapel (1971)</td>
<td>-</td>
<td>4.0</td>
<td>3.8</td>
<td>3.2</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td>Duke University Chapel (1973)</td>
<td>-</td>
<td>7.0</td>
<td>6.75</td>
<td>6.0</td>
<td>5.2</td>
<td>-</td>
</tr>
</tbody>
</table>
The two rounds of measurements (1971 and 1973) at Duke University Chapel show the extreme difficulty to seal these tiles. The measurement in 1971 was taken after applying two coats of sealant (this was the minimum requirement to seal the tile according to the lab measurements performed back then) and the one in 1973 was taken after applying two additional coats of sealant (to achieve the intended results).

**Sealing of the tile or Enhancement System:**
There are advantages and disadvantages of this type of treatment (sealing of the tile). One of the advantages is that, if the shape of the room is correct and the volume adequate, the musicians can play using the natural acoustics of the space. There are several disadvantages though: a) the treatment is irreversible. Once sealed (after applying 3 or 4 coats of sealant), there is no way to go back to the original absorptive product; b) changes of color and glossy finishes have been observed (especially with the first sealants used); c) the tiles are very porous and extremely difficult and expensive to properly seal; d) a better, more directional sound system is needed in order to overcome the extended reverberation.

Regarding the acoustical issues, it is interesting to note that many of the Gothic Cathedrals in Europe (due to their large volumes and lack of absorption) have extremely long reverberation times that make them good spaces for the organ repertoire and for plain-chant, but can render them unusable for most of the chamber, symphonic music and choral repertoire. In these large spaces it is very easy to go from too little to too much reverberation. Note that, generally, 1.2-1.5 seconds is a recommended reverberation time range for unamplified speech; 1.3-1.7 s for chamber music; 1.8-2.2 s for symphonic music; and 2.0-3.0 s for organ and choral music.

Additionally, acoustics is not just about reverberation. The shape and size of the space are as important as reverberation (if not even more). The shape of most of the spaces finished with Akoustolith and Rumford (cruciform-shaped churches with a transept between performers and audience, high ceilings and absence of side tiers/balconies) are usually not conducive to good acoustics because they tend to compromise the clarity and acoustical impact of sound, making the fast passages of classical music and choral repertoire disappear into the reverberant sound field and making them inaudible to the audience. Careful review of the shape and volume of the space and program for the space by an acoustical expert is required to fully understand the implications and compromises of sealing most or part of the tiles.

There is currently another option that can be considered for these spaces: an Electronic Enhancement System. These systems use microphones and speakers concealed in the space to electronically recreate (using very sophisticated signal processing techniques) the acoustics of a concert hall, cathedral or theater. Usually, a few microphones capture the sound coming from the performers and after processing it, different signals are sent to a set of speakers installed close to the audience -that provide the early reflections for clarity and impact- and to another set of speakers installed in the upper volume of the church -to create a longer reverberation tail-.

There are advantages and disadvantages of this type approach as well. The advantages are: a) it is less expensive and easier to install than sealing the tiles; b) it doesn’t change

<table>
<thead>
<tr>
<th>Saint Thomas (2012)</th>
<th>4.1</th>
<th>3.5</th>
<th>3.7</th>
<th>3.7</th>
<th>3.4</th>
<th>2.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Church Heavenly Rest (2012)</td>
<td>3.8</td>
<td>3.2</td>
<td>2.6</td>
<td>2.1</td>
<td>2.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>
the appearance nor the natural acoustical properties of these historical spaces and
masonry products; c) this technology allows to have several acoustics and change them
by the click of a button. The main disadvantages are: a) despite the recent advances
with this technology, musicians prefer to play using the natural acoustics of the space
instead of using electronics; b) the visual impact of the required speakers and
microphones.

Notes:
(1) U.S. Patent no. 1,119,543: “Wall and ceiling of auditoriums and the like”, December 1,
1914.
(2) U.S. Patent no. 1,197,956: “Sound-absorbing material for walls and ceilings”,
September 12, 1916.
(3) Wallace C. Sabine, Collected Papers on Acoustics, (Peninsula Publishing – reprint of
Harvard University Press, 1922),103-104.
(4) John Ochsendorf, Guastavino Vaulting – The Art of Structural Tile, (Princeton
Architectural Press 2010), 114-115.
(5) Richard Pounds, Daniel Raichel, and Martin Weaver, “The Unseen World of
(6) Victor Peutz, Speech Reception and Information, (Don Davis and Carolyn Davis,
(7) William J. Cavanaugh and Joseph A. Wilkes, Architectural Acoustics, principles and
practice, (W.J.Cavanaugh&J.A.Wilkes Editors, 1999), Case Study: Duke University
Chapel: A lesson on acoustical materials, 95-99 (based on a paper titled “Gothic
Sound for the Neo-Gothic Chapel of Duke University” by R.B.Newman and
J.G.Ferguson at the 98th meeting of the ASA, Nov. 1979).
(8) Data collected for Akustiks, LLC by Jaume Soler (2010-2012).
(9) Symposium on Auditory Perspective (1934); reprint of most important papers (1964);
9-32.