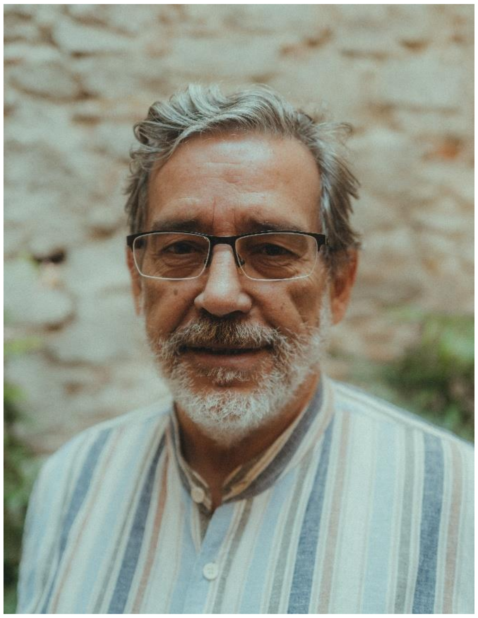
ISSN: 2582 – 8304



Francesc Aragall

aragall@designforall.org

Expert in Design for All / Universal Design, with 30 years of experience as an international consultant in the areas of urban planning, mobility, tourism and services, ICT, industrial design and building.

Learning from natural rock: sustainable urban paving

Francesc Aragall

Abstract

Current urban pavements for pedestrian use are the source of numerous safety, hygiene, accessibility, maintenance, ecological and economic problems. Based on a systematic analysis of these problems, the design team of the project, coordinated by the author, studied different types of materials and various manufacturing techniques to try to select a type of pavement and a street design that would solve the problems observed. The analysis of physicochemical characteristics concluded that none solved all the problems, however some types of minerals presented very interesting characteristics, although heterogeneous. This led the team to test the coalescence of mineral particles to create rocks with improved characteristics. From achieving a viable manufacturing method, its application as a sustainable urban pavement was studied.

Key words:

Urban design; pavements; sustainability; stone coalescence; accessibility.

Description of the problem

Access Safety is a company specialized in the development and marketing of technical flooring that was created in 2014. Its main

motivation since then has been to offer flooring that provides accessibility and safety in built environments.

Starting in 2017, the company undertook an in-depth research project on the necessary requirements in urban pavement.

This motivated it to undertake a systematic analysis of urban pavements for pedestrian use based on direct observation and interviews with citizens, urban planners; traffic and security; and construction companies, which allowed the preparation of the following table of problems:

Table 1. Problems in pedestrian pavements and their causes

Problem	**Possible causes**
Pedestrian, cyclist and motorcyclist falls.	**Uneven sidewalks, slippery and excessively sloping pavements are the cause of many pedestrian falls. Paint on crosswalks, especially when wet or poorly maintained, also causes accidents for pedestrians, motorcyclists and cyclists.**
Lack of accessibility in urban space. **In recent years, it has been observed that people who only used public spaces occasionally have now become regular users. The elderly, blind people,**	**The lack of tactile foot signage, poorly executed curb cuts and obstacles on pavements make it difficult for everyone to exercise the right to mobility.**

children, and people with intellectual disabilities or reduced mobility are some of these users.	
Noise pollution.	**Uneven pavements with deep engravings cause both vehicles and people carrying suitcases to generate noise. In addition, these types of flooring cause great discomfort to wheelchair users by causing vibrations.**
Dirty pavements.	**Oil stains, stuck chewing gum and animal droppings are the visible elements of dirt in public spaces, but even without seeing them, the urban space is home to countless bacteria that transmit diseases.**
Lack of adaptation to new modes of mobility. **Pedestrians, bicycles, wheelchairs and personal mobility vehicles of all kinds share the urban space with motorised vehicles for public and private transport, as well as for urban logistics.**	**The lack of compartmentalisation and signage of spaces entails a high risk for all people.**
Degradation of public space.	**Especially in old towns, the original materials degrade, worsening their appearance**

	every day, peeling off and breaking, affecting accessibility, comfort and aesthetics. All this leads to an increasing number of falls, greater noise pollution and less attraction for citizens and visitors.
Heat absorption.	**Dark and thick pavements tend to absorb solar radiation and therefore increase the temperature of the city in hot seasons.**
Excess water in pedestrian areas in case of torrential rains.	**Insufficient drains and slopes and an incorrect proportion between permeable and impermeable pavement, generate an excessive sheet of water in pedestrian areas.In the event of torrential rain, it contributes to street flooding.**
Aesthetic dissonance between the pavement and the environment.	**Use of low-quality or aesthetically unsuitable materials in historic settings and landscaping.**
Breakage of pavement pieces in shared spaces.	**The occasional or frequent passage of heavy vehicles in pedestrian areas causes the breakage of parts.**
Separation and progressive movement of the pavement	**Subbases that are too soft or that suffer from water**

pieces.	**infiltration, as well as the placement of parts without suitable adhesives generates these movements.**
High ecological, economic and labour impact.	**Although it is very different from each type of flooring depending on the origin of the materials and the type of extraction in their original environment, they all have in common a high environmental impact and a high weight, which involves significant efforts in their placement, and a relatively low useful life.**

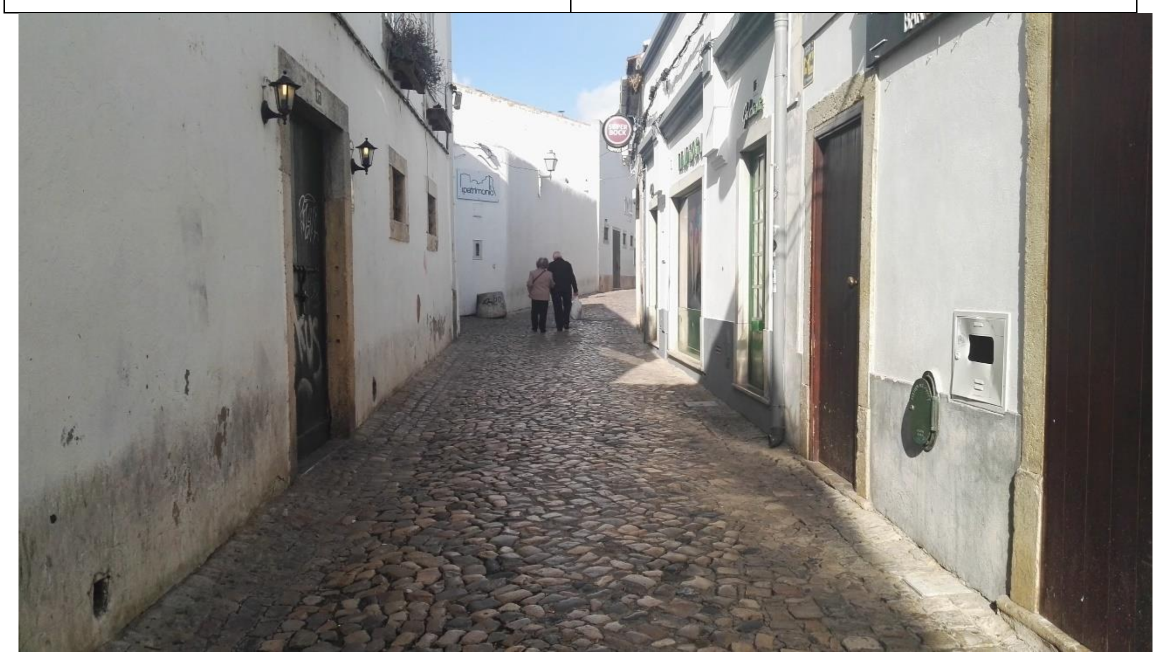


Image 1. Uneven pavement in pedestrian area
Source: Author's elaboration 2019.

Image 2. Uneven paving stones
Source: Author's elaboration. 2019.

Image 3. Pavement breakage due to heavy vehicles
Source: Author's elaboration. 2020.Wear and dirt

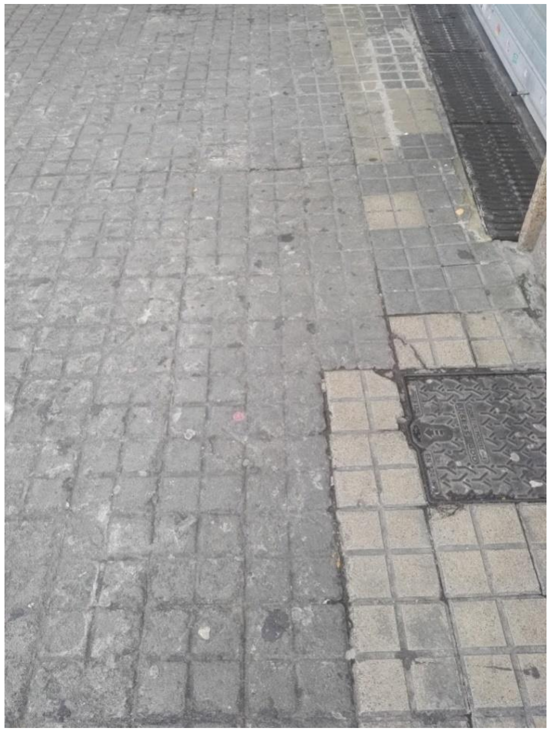


Image 4. Wear and dirt
rce: Author's elaboration. 2019.

.

Image 5. Improper bike lane clearance
Source: Author's elaboration. 2020.

From the table presented we can classify the different problems into two groups:

- ***Problems related to the design of urban space.***

  Basically, these are those related to rain drainage, inadequate protrusions and slopes, the distribution of street uses, insufficient visual contrast between the pedestrian route and the rest of the pavement and the lack of visual and tactile signage and, obviously, the selection of inappropriate materials.
- ***Problems related to materials.***

  These are usually due to the use of materials that are not resistant to pressure, wear or stains, excessively absorbent of water and solar radiation; but also, to their placement on unstable basis or by means of inappropriate adhesives.

Although for the first group it is necessary to define a series of recommendations for the design of the public space, for the second it is necessary to analyse the physicochemical behaviour of the different materials used.

Approximation to pedestrian space design criteria

Although the objective of this article is not to delve into the design of urban space, it is proposed to provide here some of the elements that must be considered to guarantee accessibility, safety and drainage of rainwater:

- **All street furniture and signage should be aligned without interfering with the pedestrian route and be located on a strip**

of vegetation along the pavement, with a high capacity to absorb rainwater.

- **Lanes for bicycles and personal mobility vehicles must be located between the line of street furniture and the road, separated either by a change in height, or by physical obstacles.**
- **The longitudinal slope of the streets should not exceed 5% and the transverse slope should be between 1% and 2%.**
- **The pavement intended for the pedestrian route should have a minimum width of 1,8 meters, 1 meter width for each expected simultaneous user and have benches and shaded areas along the route.**
- **The pavement of the area intended for the pedestrian route should be light in tones and present a difference in light reflectance of at least 30 points with respect to the adjacent pavements.**

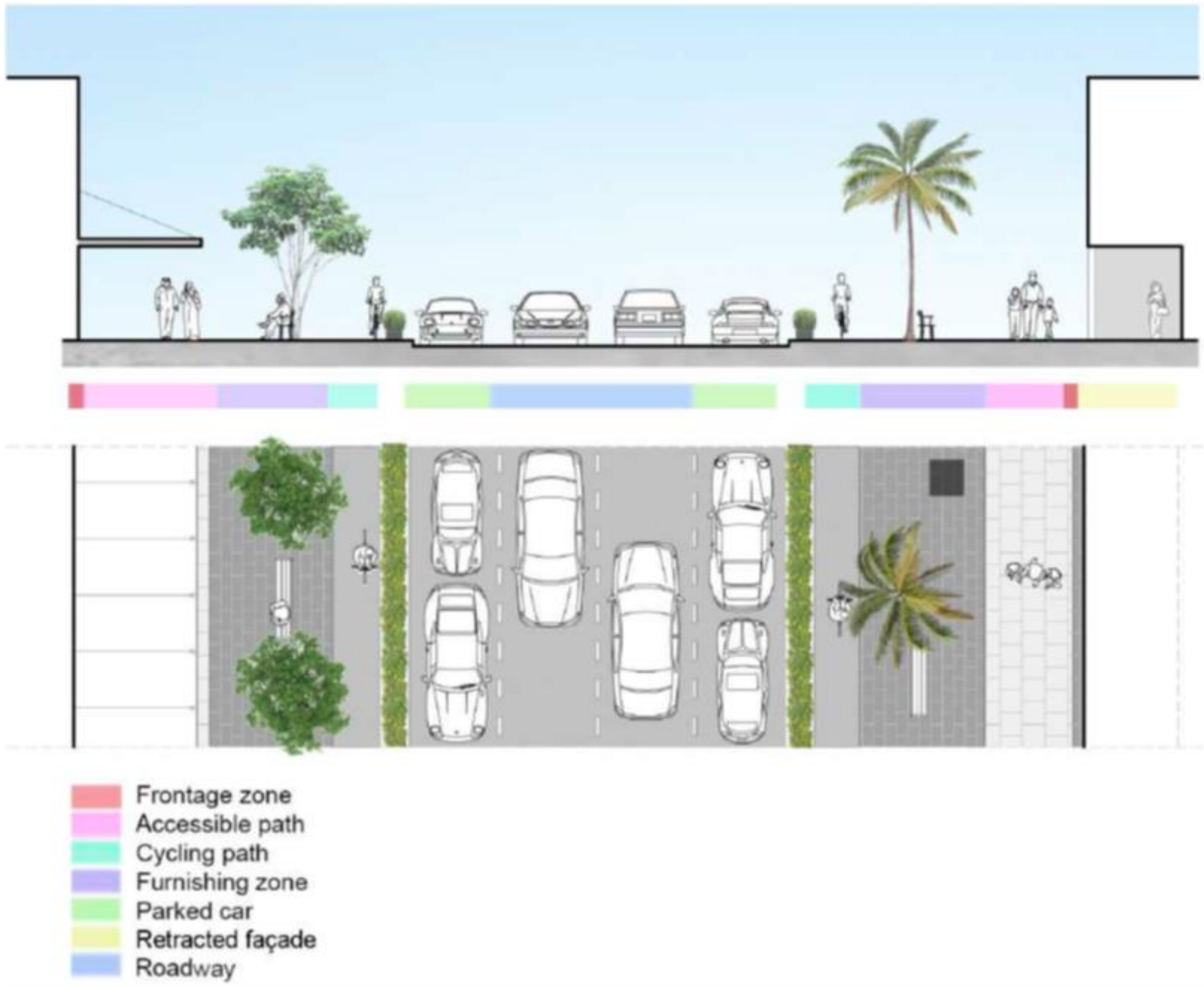


Image 6. Street section with benches and shaded area (UAE Universal Design Code) (UAE, 2020)
Source: Image by the author.

Analysis of the physicochemical characteristics of the installed pavements

When analysing the different materials used in urban pavements, asphalting and continuous concrete pavements have been discarded since, although they are economical, their useful life, in good conditions of cleanliness, preservation of their integrity and non-slip characteristics, is very short.

Pavements on unstable pavements, such as dry laying on a sand base, have also been discarded, since these usually deform and lose their integrity.

Thus, the most common materials for flooring have been grouped into four large groups:

- **Pressed concrete tiles.**
- **Slate slabs.**
- **Granite slabs.**
- **Limestoneslabs.**

To compare them, a set of characteristics considered important was analyzed, which are described below:

- **Mechanical resistance: quantifies the load it can withstand before breaking.**
- **Hardness on the Mohs scale: It measures scratch resistance, on this scale the mineral with the lowest value is talc (1) and the one with the highest value is diamond (10), iron has a value of 4.**
- **Abrasion resistance: Determines potential surface wear from use. The laboratory test determines the wear resistance on a scale of 1 to 5.**
- **Slip resistance: It determines the probability of slipping on a certain material in dry and wet conditions, using a test that simulates the movement of a shoe.**
- **Water absorption: Prevents breakage in the event of frost but also prevents the absorption of dirt.**

- **Stain resistance: Determines the ease of cleaning with different products on a scale of 1 to 5, subjecting the parts to different agents. The highest value indicates that it can be cleaned with water.**
- **Rubber adhesion: Analyzes the ease of adherence of chewing gum. Chewing gum is one of the products that contributes the most to deteriorating the appearance of floors.**
- **Coefficient of expansion: It determines the expansion and contraction movement of materials according to the ambient temperature. A higher value will require larger joints between the pieces.**
- **Medium density: It allows an approximation, among other things, of the necessary weight and thickness of the pieces, although especially in rocks, the density is not usually homogeneous throughout its volume.**
- **Lifespan: It expresses the number of years that the material fulfils the function for which it was created, as well as its appearance. In the case of pavement, it also expresses the number of years during which the pavement is maintained without being replaced.**
- **Albedo: Measures the percentage of radiation that any surface reflects with respect to the radiation that falls on it. A totally black body has an Albedo 0 and an absolute white one an Albedo of 1. The smaller the Albedo, the more the material contributes to global warming and radiates more heat to users.**
- **Resistance to bacteria: Analyzes their bacteriostatic capacity. Depending on porosity, the different materials may or**

may not be bacteriostatic, i.e. they prevent the proliferation of bacteria and, therefore, health risks and unpleasant odours.

Table 2. Physicochemical characteristics of the materials used as flooring

	Pressed Concrete Tile	Slate	Granite	Limestone
Mechanical resistance	300x300x 45 8kN	300x600x4 0 7.9kN	300x600x40 5.5kN	300x600x40 4.7kN
Hardness in the Mohs Scale	4	3	5.5>7	3
Abrasion wear	CLASS 4	CLASS 4	CLASS 5	CLASS 3>4
Slip resistance	40>65	40>60	40>60	40>60
Water Absorption	<6%	0,4%>1,8 %	<1.6%	2%>6%
Stain resistance	CLASS 1>4	CLASS 2>4	CLASS 1>5 depending on the type of granite	CLASS 1>4
Chewing gum adhesion	Adheres	Adheres	Adheres	Adheres
Coefficient of expansion	± 11x10-6 °C-1	± 11x10-6 °C-1	± 10x10-6°C-1	± 12x10-6 °C-1
Density	2.4g/cm3	2.4>2.9g/c m3	1.7>2.4g/c m3	1.9>2.7g/c m3
Lifespan (years maintaining anti-slip	<15	>15	>15	>15

characteristic and appearance)				
Albedo	**0.10>0.35**	**0.10>0.20**	**0.12>0.18**	**0.30>0.45**
Resistance to bacteria	**No**	**No**	**No**	**No**

Source: Author'selaboration

As can be seen from the comparative table, in which the most favourable characteristics have been highlighted in green, no material satisfactorily solves all the problems described. So, what characteristics should urban pavement have to meet all the needs of users and installers?

Desirable characteristics in materials used as urban pavement

For a better analysis, these characteristics were grouped according to the three typical components of sustainability: social, environmental and economic aspects.

Social aspects:

- **Present and maintain a high resistance to slipping throughout its useful life. Therefore, a surface that remains above a value of 70, dry and wet, in the pendulum test.**
- **Guarantee the integrity of the pavement throughout its useful life (to prevent falls and deterioration of urban space). That is, an abrasion resistance of 5.**
- **Resist stains, gum and bacteria. Non-porous and easy to clean with water.**

- **Resist pressure from vehicles and heavy loads. Breaking strength greater than the 8 kN of pressed concretetiles.**
- **Reduce noise pollution. No surface roughness or need for major joints.**
- **Reduce installation and cleaning efforts.**
- **Lighter thancurrentfloors.**
- **Present and maintain an appearance compatible with any urban environment and design requirements. Therefore, allowing the application of different colors and textures.**
- **Improve accessibility for users with limitations. For example, allowing the inclusion of grooves or buttons for guidance and warning of hazards to people with low vision.**

Ecological aspects:

- **Prevent the deterioration of natural environments. Avoid materials extracted in natural environments.**
- **Maximize the use of recycled materials.**
- **Minimize the use of energy and water in its production, packaging, transportation, placement and maintenance.**
- **Minimize their contribution to global warming. Therefore, it should have a high Albedo.**
- **Maximize the useful life of the pavement. It should ensure that it maintains its characteristics and appearance unaltered, at least for 25 years.**
- **Minimize packaging and the use of plastic.**
- **Maximizere cyclability.**

Economic aspects:

- **Reduced installation and maintenance costs.**

- **Competitive price.**
- **Present great structural resistance to cold and hot climates. And, therefore, not be porous.**

Stone coalescence and its manufacture

After analysing and discarding various types of natural and artificial materials (improved concretes, rocks with high quartz content, metal pavements, asphalt agglomerates, ceramics, etc.) we observed that minerals in isolation have some of the desired characteristics and that their combination in some igneous rocks, such as some specific types of granite and basalt, have characteristics very close to desirable. However, both its location in specific parts of the planet and its lack of homogeneity led us to rule out this option.

In this selection process, we were struck by quartzite, a metamorphic rock consisting of recrystallized sandstone rich in quartz, very common in the Iberian Peninsula, more homogeneous and hard than granite, as well as less porous. In addition, we discovered that this was the rock used preferentially for the construction of Roman Empire roads (a large part of which still exist) in the Iberian Peninsula.

The fact that this rock is the product of recrystallization and that this means an improvement in its qualities, led us to study it more carefully and to investigate if there was any industrial process with similar characteristics.

This is how we learned about mineral particles coalescence, which consists of compacting several stone powders under high pressure

and, once compacted, performing a heat treatment, at a temperature lower than the melting temperature of the mixture, obtaining a consolidated and compact piece.

This manufacturing process provides great cohesion of the powders, creating strong bonds between the particles, which end up joining together in a single block in the shape of a mould.

The fact of knowing this procedure led us to study the possibility of obtaining rocks industrially, since, if their formation in nature is the result of compaction and heating over millennia, it might be possible to achieve the same result.

Since the industrial process of ceramics basically consists of pressing and firing clays, we established a collaboration agreement with several companies to test our hypothesis.

So, using their facilities, we analyze the quartzite components, formulate an analogous mixture of pulverized minerals, amalgamate them homogeneously, and subject them to high pressure and quasi-melting temperatures.

After several tests, the result was to obtain a rock almost identical to natural quartzite with improved physicochemical qualities thanks to the homogenization of its components and the balanced application of pressure and heat.

Once the size of the particles and the necessary pressure and temperature have been determined, we test with the components of other rocks such as granite, basalt and various types of sandstones, as well as the components of concrete. In all cases, the results were rocks similar in appearance to the original, but with improved

physicochemical characteristics. A thickness of 20 mm was determined for the manufacturing process because it was estimated that this would provide sufficient strength for heavy vehicles to travel on it.

Thus, samples of a set of rocks produced were taken and subjected to the same tests to which the pavements were subjected, obtaining the results shown in the following table, in which it should be considered that the samples examined had half the thickness of the pavements compared.

Table 3. Comparison of physicochemical characteristics of Induced Coalescence Stone with materials used as urban pavement

	Concrete Tile	Slate	Granite	Limestone	InducedCoalescencestone
Mechanicalresistance	300x300x45 8kN	300x600x40 7.9kN	300x600x40 5.5kN	300x600x40 4.7kN	300x600x20 14.18 kN
Hardness in the Mohs Scale	4	3	5.5>7	3	9
Abrasionwear	Class 4	Class 4	Class 5	Class 3>4	Class 5
Slip resistance	40>65	40>60	40>60	40>60	>70 wet and dry
Water Absorption	<6%	0,4% >1,8 %	<1.6%	2%>6%	<0.02%
Stain resistance	Class 1>4	Class 2>4	Class 1>5	Class 1>4	Class 5

			depending on the type of granite		
Chewinggumadhesion	**Adheres**	**Adheres**	**Adheres**	**Adheres**	**Does notstick**
Coefficientofexpansion	**± 11x10-6 °C-1**	**± 11x10-6 °C-1**	**± 10x10-6°C-1**	**± 12x10-6 °C-1**	**± 6.5x10-6°C-1**
Density	**2.4g/cm3**	**2.4>2.9g/cm3**	**1.7>2.4g/cm3**	**1.9>2.7g/cm3**	**2g/cm3**
Lifespan (years maintaining anti-slip characteristics and appearance)	**>15**	**>15**	**>15**	**>15**	**>50**
Albedo	**0.10>0.35**	**0.10>0.20**	**0.12>0.18**	**0.30>0.45**	**0.10>0.35**
Resistanceto bacteria	**No**	**No**	**No**	**No**	**Bacteriostatic**

Given the excellent results obtained, which showed that it met all the desirable characteristics in an urban pavement, the economic viability of the manufacturing process was analyzed. A first approximation allowed us to estimate that the manufacturing costs were slightly or much lower than the production costs of natural stone, depending on the type of stone and very similar to those of manufacturing concrete slabs.

Design and prototyping

Once the commercial viability of this new product was established, the design and production of samples was carried out.

When selecting the stones to be reproduced, their beauty and application in urban environments were considered, but also the impossibility of current extraction or the environmental impact that this would entail.

Thus, the rocks of Pamukkale in Turkey, the basalt of the Svartifoss waterfall in Iceland, the granite of Mount Rushmore in the United States, the sandstone used in the pyramids of Gizah in Egypt and the sandstone of Montjuïc in Barcelona, used from Roman times until its closure in the middle of the 20th century, were selected. both for the construction of buildings and for paving the old town. It was also decided to reproduce the pressed concrete slabs commonly used in the streets of Barcelona.

Image 7. Pamukkale Landscape
Source:Wikipedia. Antoine Tavenaux, available at https://es.wikipedia.org/wiki/Archivo:Pamukkale_30.jpg.

Image 8. Svartifoss Waterfall
Source: Wikipedia. Andreas Tille, available at
https://commons.wikimedia.org/wiki/File:SvartifossSummer.jpg.

Image 9. Mount Rushmore
Source: Wikipedia. B.Badgett, available at

https://commons.wikimedia.org/wiki/File:Mountrushmore.jpg.

Image 10. Pyramids of Gizah
Source: Wikipedia. Ricardo Liberato, available at
https://commons.wikimedia.org/wiki/File:All_Gizah_Pyramids.jpg.

Image 11. Temple of the Sagrada Familia
Source: ***Wikipedia. Sagrada Familia, available at***

https://commons.wikimedia.org/wiki/File:Passion_Facade_of_the_Sagrada_Fam%C3%ADlia_(6).jpg.

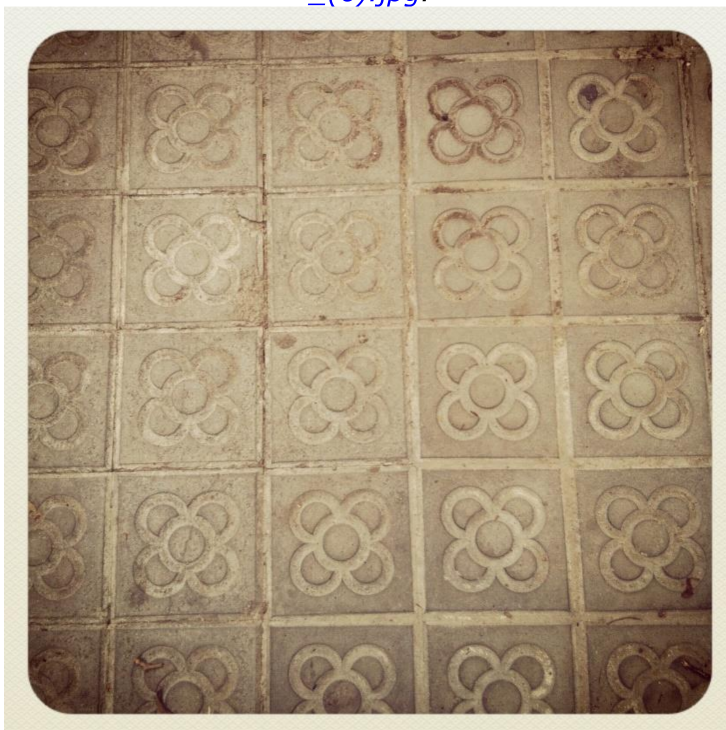


Image 12. Tipicalpavement in Barcelona
Source: ***Wikipedia. Francesc Bonnin, available at https://commons.wikimedia.org/wiki/File:Panots_de_Barcelona.jpg.***

Subsequently, the components of all the selected materials were photographed and analyzed to reproduce them as accurately as possible.

In the case of pressed slabs, the design was improved, as the indentations on the surface, made to maintain a certain degree of slip resistance when the piece begins to wear, also generate noise when suitcases or trolleys are rolled over them. Since the new material made the indentations unnecessary, it was redesigned to prevent noise.

A system of indentations for Svartifoss basalt and Pamukkale limestone was also designed so that they could be used as a guide for blind people at pedestrian crossings. In this case, a usability test

was carried out to collect data on possible improvements before its final design.

Image 13. Usability test of the guide for blind people at pedestrian crossings Source: Photo by the author.

Finally, samples of the different models were manufactured from the designs, which, when subjected to the laboratory tests, described above, obtained identical results.

Image 14. Pamukkale Sample
Source: Photo by the author.

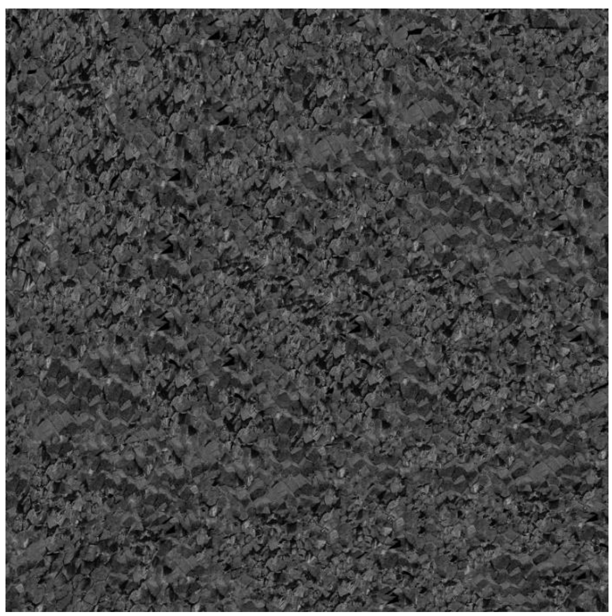


Image 15. Svartifoss Sample
Source: Photo by the author.

Image 16. Rushmore Sample
Source: Photo by the author.

Image 17. Gizah Sample
Source: Photo by the author.

Image 18. MontjuïcSample
Source: Photo by the author.

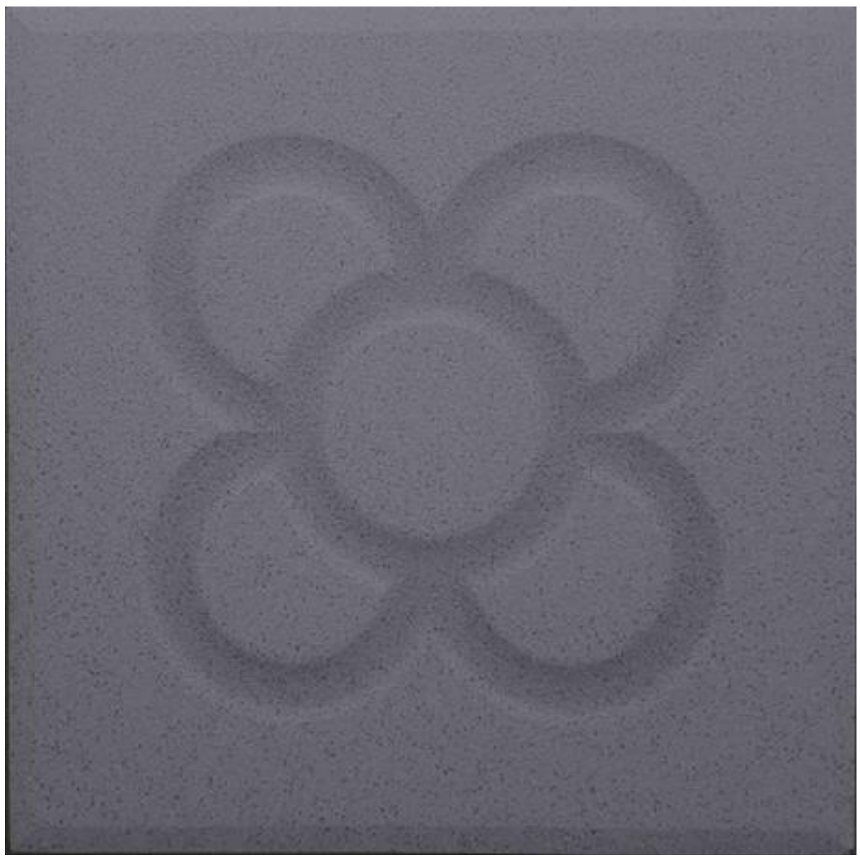


Image 19. Silent Sample for Barcelona
Source: Photo by the author.

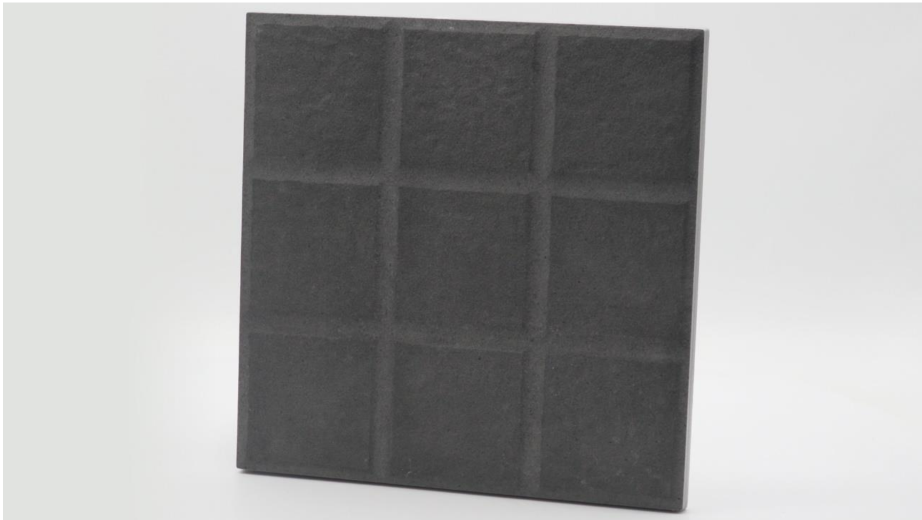


Image 20. Silent 9-squares sample
Source: Photo by the author.

Results

In view of the results, Access Safety decided to start marketing this new product.

To date, the materials have been installed in several municipalities, with excellent results, withstanding ice, steep slopes, intensive use and dirt.

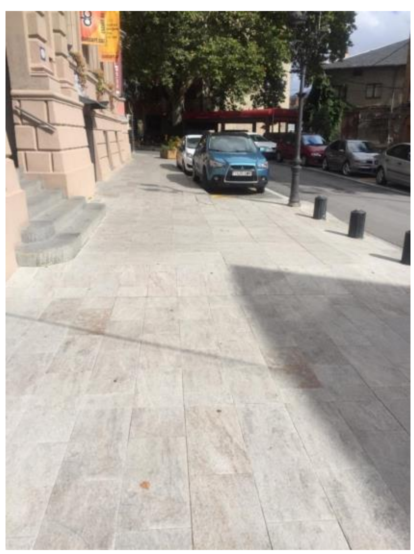


Image 21. Rushmore parts installed in urban space
Source: Photo by the author.

Image 22. Montjuïc tiles installed in a historical environment
Source: Access Safety.

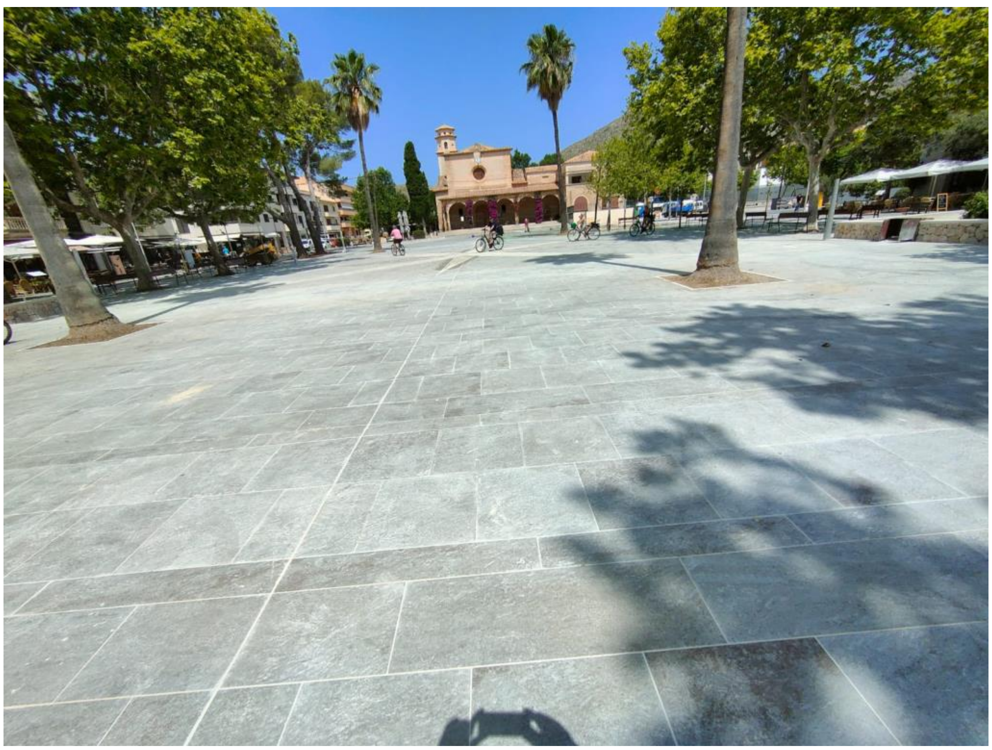


Image 23. Installation in Pollença Main Square in Mallorca
Source: Access Safety

When presenting the product, several municipalities made the demand to design induced coalescence stones**emulating the natural stone they had used to date. To do this, we studied and were able to verify that it is possible to meet this demand (to date one type of marble and two types of sandstone have been reproduced), verifying that the process of design and manufacture of specific stones is economically viable from about 3.000m2.**

In conclusion, it can be said that, inspired by nature, we have developed a product that helps to protect it, while improving cities for people, since:

At environmental level

- **Prevents erosion and waste that quarries produce in the natural environment.**
- **Achieves 0 waste in the production process.**
- **Integrates recycled materials and quarry waste as part of its components.**
- **Reduces the pollution produced by transporting them, because the material is produced in factories based in Fujian (China), Morbi (Gujarāt, India) and Modena (Italy) to reduce the distance to the clients and with the same energy consumption, it is possible to transport up to 5 times more square meters than other materials.**
- **Contributes to the environmental efficiency of urban space and buildings, since the long-life cycle of our products is more than 50 years and their recyclability is 100% at the end of their cycle.**
- **Avoids the use of detergents in urban space.**

- **Reduces the warming effect of urban pavements.**

At economic level

- **Reduces the time it takes to lay the flooring, as its lower weight facilitates the tasks of transport on site and its placement.**
- **Provides the same aesthetic qualities as natural stone with greater durability and lower cost.**
- **Drastically reduces maintenance and cleaning costs, for example in wages, machinery and detergent products.**
- **Ensures its durability in any climate, by increasing its resistance to cold and warm weathers.**

At social level

- **Helps prevent accidental falls of pedestrians, cyclists and motorcyclists, as well as collisions, traffic and work accidents.**
- **Reducesnoisepollution.**
- **Eliminates the presence of bacteria, stains and odors on urban pavement.**
- **Reduces the positioning efforts of operators.**
- **Improves the aesthetic aspects of public space and buildings.**
- **Adapts the product to local tradition and design criteria, bringing the aesthetic characteristics of our products closer to the customer's needs.**

References

ACCESS SAFETY. Site. Available in: http://www.access-safety.es/en/about-us

ASTM International (2020). ASTM C1353 – Standard Test Method for Abrasion Resistance of Dimension Stone Subjected to Foot Traffic.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: A review. Renewable and Sustainable Energy Reviews, 29, 394–416.

CEN (2017). EN 17210: Accessibility and usability of the built environment — Functional requirements.

CEN (2016). EN 1339 – Concrete paving flags — Requirements and test methods.

CEN (2014). EN 1341 – Slabs of natural stone for external paving — Requirements and test methods.

ISO (2018). ISO 21542:2011 – Building construction — Accessibility and usability of the built environment. Geneva: ISO.

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island—A review. Solar Energy, 103, 682–703.

UAE Universal Design Code. Dubai universal design code. Direct Access. 2020. Available in: https://e-inclusion.unescwa.org/sites/default/files/resources/United%20Arab%20Emirates%20Universal%20Design%20Code%20Final.pdf

Winter, J. D. (2010). Principles of Igneous and Metamorphic Petrology. Pearson.