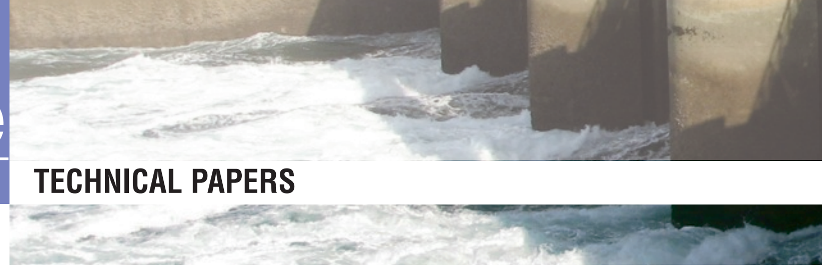

Basalt fibra: from earth an ancient material for innovative and modern application

This article focuses on some of the principal aspects of basalt fiber (the manufacturing techniques, the main products, a non-exhaustive overview of the main properties and characteristics, some remarks on the major environmental and energy aspects) and the related activities that ENEA is currently carrying out, mainly in the Trisaia research Centre. ENEA has signed a collaboration agreement with leading manufacturing companies worldwide for the study and development of basalt fiber applications. This gives the Agency the opportunity to focus its R&D activities on basalt fiber application areas more compatible with its own mission (new construction materials also in terms of energy efficiency, automotive solutions, etc.), making it one of the national reference entities as far as research on this material is concerned

Piero De Fazio

La fibra di basalto: dalla terra un materiale antico per applicazioni innovative e moderne

L'articolo si sofferma su alcuni degli aspetti della fibra di basalto (la tecnica realizzativa, i principali prodotti realizzati, un panorama non esaustivo delle principali proprietà e caratteristiche, alcune considerazioni sui principali aspetti ambientali ed energetici) e sulle attività che ENEA sta attualmente svolgendo principalmente presso il C.R. Trisaia. Grazie ad un accordo di collaborazione per lo studio e lo sviluppo delle applicazioni della fibra di basalto con una delle principali società produttrici a livello mondiale, ENEA ha la possibilità di affrontare in maniera sistematica e completa le problematiche di ricerca e sviluppo legate a questo materiale, focalizzandole sui settori applicativi più compatibili con la mission dell'Agenzia (nuovi materiali nel settore costruttivo anche in chiave di efficienza energetica, auto motive ecc.), diventando così uno dei soggetti di riferimento nel panorama nazionale della ricerca sulle applicazioni di questo materiale

Introduction

Basalt fiber (BF), known as "the green industrial material of the XXI-century", combines ecological safety, natural longevity and many other properties. It is not a new material, but its applications are surely innovative in many industrial and economic fields, from building and construction to energy efficiency, from automotive to aeronautic, thanks to its good mechanical and chemical performances. Hence basalt fiber has gained increasing attention as a reinforcing material

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especially compared to traditional glass and carbon fibers. In this context, several studies dealing with glass and carbon fiber reinforced composites consider the significance of basalt fiber as a new reinforcing material.
This article aims to provide a profile of basalt fiber material in particular with respect to its multiple characteristics and applications, illustrating also the activities that ENEA is carrying out in this particular research area.

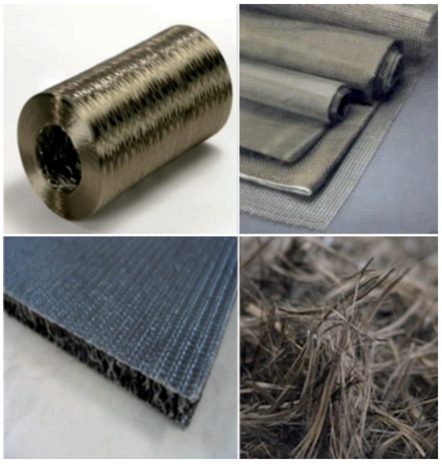
Basalt fiber

As it is well known, basalt is the name given to a variety of volcanic rock, known principally for its resistance to high temperatures, strength and durability, widely diffused all around the world, in which SiO_2 accounts for the main part, followed by Al_2O_3, then Fe_2O_3, FeO, CaO and MgO. For this reason, basalt rocks are classified according to the SiO_2 content as alkaline (up to 42% SiO_2), mildly acidic (43 to 46% SiO_2) and acidic basalts (over 46% SiO_2). Only acidic type basalts satisfy the conditions for fiber preparation.
Basalt applications are well known from roman age where this material was used in its natural form as a paving and building stone: actually basalt can also be formed into a continuous fiber having unique chemical and mechanical properties, so that it is ideally suited for demanding applications requiring resistance against high temperatures, insulation properties, acid and solvent resistance, durability, mechanical strength, low water absorption, etc.
Among others, two more characteristics must be highlighted:

1) basalt fiber can be suited for fire protective applications and so it can replace almost all applications of asbestos without any impact on human health, thanks to the fiber's size that make it non-breathable. In this regard, in 1998 an official list containing the names of the materials that can replace asbestos - *Decreto Ministero dell'Industria del Commercio e dell'Artigianato 26.03.1998 – Elenco contenente i nomi delle imprese e dei materiali sostitutivi dell'amianto che hanno ottenuto l'omologazione* - was published in Italy and among those materials there is also the basalt fiber;
2) basalt fiber is an eco-compatibility material, characterized from an easier recyclability if compared, for example, to glass fiber. Infact the principal problem in glass fibers recycling is that they melt during incineration, sticking to the inside of the incineration chamber. The result is a costly clean-up effort and significant downtime. Basalt, instead, has a melting point of about 1400 °C; this means that after some composite material containing basalt fibers is incinerated, the only product left is an unmolten, fully usable basalt that can be swept from the incineration. And this is naturally a considerable added value.

Basalt fibers are produced from basalt rock using single component raw material by drawing and winding fibers from the melt. Once the basalt fibers have been produced, they are converted into a suitable form for particular application, such as (figure 1):

a) continuous fiber, made of a bundle of parallel strands without twisting; thickness of a fiber usually ranges from 7 to 24 microns. It is the basic material, directly produced by the melting process of volcanic rock, from which it is then possible to get any other products with different manufacturing methods;



1 - Continuos basalt fiber; 2 - Fabrics;
3 - Basalt fiber panel; 4 - Chopper strands

FIGURE 1 Some basalt fiber products
Source: HG GBF

b) chopper strands, produced by cutting continuous basalt fiber; it is used in reinforcing the cement and concrete:
c) fabrics with different weights and weaving of various purpose: they can be used as external reinforcement for concrete in many structural systems, filtering, fire-proof, electrical, roofing, etc;
d) basalt fiber composite rebar (BFRC), which has the potential to replace steel in reinforced concrete, structures exposed to salt water, etc. wherever the corrosion problem exists.

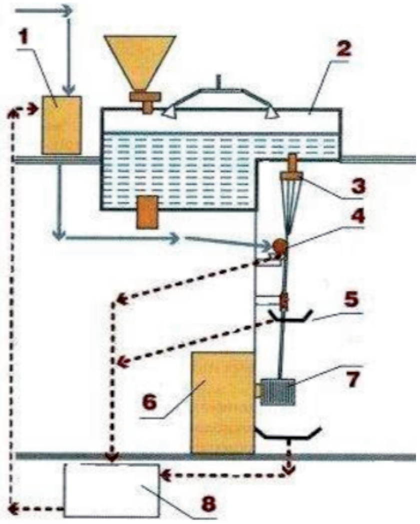
Just this last product is very interesting for potential research and application.
As well known, the steel tends to corrode if not protected adequately. There are many ways to limit the oxidation: adding an extra layer of concrete to increase the distance of the inner steel from the outer surface, using stainless steel - more expensive solution than simple steel - or bars obtained from glass fibre pultrusion. However this last solution is limited because of the lower resistance of the glass fibre in the alkaline environment associated with concrete. Using pultruded bars made with basalt fibres may be a right solution for this problem, given that basalt fibers are more resistant than glass fibres in the alkaline environment and, moreover, cannot corrode. Therefore, pultruded bare made with basalt fibres should insure good durability to the reinforced concrete, because they do not react in alkaline environments and with corrosive elements. As a result, it could be possible to have a lighter building, because of a lower weight of the reinforcement (a pultruded bar weighs about 1/3 of a steel bar having the same dimensions), and, wherever it could be acceptable, a reduction in the concrete thickness.
Some more consideration may be made about advantages by using this material, particularly in terms of primary energy consumption. If we still consider the potential use of basalt fiber rebar in construction sector in place of traditional steel reinforcing bars - in respect of which they have comparable mechanical properties - it is possible to calculate that this replacement leads to an energy savings of about 9,12 kWh/kg of basalt used. Infact the total energy required for the production of basalt fiber is 4,96 kWh/kg while the production of a similar amount of steel, taking into account different density (each kg of basalt corresponds to 2,91 kg of steel), requires a power consumption of 14,08 kWh. Assuming the use of basalt in the order of 5% of the steel used in construction sector in Italy, it is rather easy to calculate an energy savings of about 3.920.000 MWh /year. A similar value is made from a 500 MW electric power station working 8.000 h/year.
Reducing energy demand also induces lower emissions of CO_2 into the atmosphere. In the same assumption made earlier, CO_2 emissions in the atmosphere would be to drop by about 775.000 tons/year.

A short history

The French Paul Dhé was the first with the idea to extrude fibers from basalt; he was granted a U.S. patent in 1923.
Around 1960, both the U.S. and the Soviet Union (USSR) began to investigate basalt fiber applications, particularly in military field. In 1970 U.S. glass companies imposed a research strategies that favoured glass fiber than basalt fiber, while in Eastern Europe research was nationalized by the USSR's Defense Ministry.
After the breakup of the Soviet Union in 1991, the results of Soviet research were declassified and made available for civilian applications.
Today, basalt fiber research, production and most marketing efforts are principally based in some of countries once part of the Soviet Union (Georgia, Ukraine, the same Russia) and in China.

Production process

In many ways, basalt fiber technology production is similar to glass fiber one, but it requires less energy. This aspect, together with an easy availability of raw material all over the world, justifies the lower cost of basalt fibers compared to glass fibers.
BF are extruded from basalt rocks through a melting process without the application of additives. The manufacturing process can be summarized as shown in figure 2.
Quarried basalt rock is first crushed, then washed and moved into melting baths in gas-heated furnaces. under temperature of 1.460-1.500 °C. Here, the process is simpler than glass fiber processing be-



1. Tank for sizing 2. Furnace 3. Bushing
4. Sizing applicator 5.Tray for used sizing collection
6. Winder 7. Spool 8. Tank for used sizing

FIGURE 2 Basalt fiber production: general scheme
Source: Composite market web portal

cause the basalt fiber has a less complex composition.

Molten basalt flows from furnace through a platinum-rhodium bushing with 200, 400 ,800 or more holes and the fibers can be drawn from the melt under hydrostatic pressure. Then a sizing is applied to the surface of the fibers by a sizing applicator to impart strand integrity, lubricity, and resin compatibility. Finally, a winder allows to realize some large spools of continuous basalt filament.

The production process, particularly temperature levels in the furnace, is of considerable importance in relation to final mechanical properties of basalt fibrous materials (rovings, etc). Infact it has been reliably determined that low variations in chemical composition of basalt rocks have a minor effect on the level of mechanical of continuous basalt fibers while the greatest effect comes from direct molding conditions of the fibers (drawing temperature and the period of melt homogenization).

For example, for the same basalt chemical composition, a fiber drawing temperature increase of 160 °C (from 1.220 °C to 1.380 °C) increased their strength from 1.3 to 2.23 GPa and modulus of elasticity from 78 to 90GPa.

Great importance on final properties has also the fiber dimension: as the filament diameter increases of 3-4 m, the strength value decreases from 2.8 to 1.8 GPa.

Chemical and mechanical properties

Basalt fibers are characterized by a good resistance against low and high temperatures and are superior to other fibers in terms of thermal stability, heat and sound insulation properties, ablation resistance, vibration resistance and durability.

Basalt fiber is raised, from a performance standpoint, between the carbon fiber and the glass fiber, even if among others, it has a great advantage: it is well-compatible with carbon fiber. The consequence is that high efficient hybrid materials can be manufactured by adding small (pre-determined) amount of carbon fibers to basalt fibers. The obtained thread, differing insignificantly in cost (owing to small content of expensive carbon fiber) will demonstrate considerably better elastic properties compared with basalt fiber (notice that elastic modulus of basalt fiber is around 11.000 kg/mm^2, whereas that of carbon fiber is 22.000-56.000 kg/mm^2).

However, from a properties point of view, glass fiber, in its various form and chemical composition, can be considered as the reference material for a better understanding of basalt fiber properties.

Both are inorganic but they are manufactured by different processes.

Glass fibers are produced from melted charge (composed of quartz sand, soda, limestone, fluxing agents, etc.) to obtain glass, from which fibers are obtained by blow with steam, air or at centrifuge.

Basalt fiber is obtained, as already shown, from melted of basalt rocks without any additives.

Table 1 shows the average values of some principal indicators of basalt fiber and glass fiber.

From the table 1 it is possible to observe that:

– the modulus of elasticity of basalt fibers is higher at least 18% than that of glass fibers, particularly E-glass fiber, and, as known from literature, very closely approximates the modulus of elasticity of high-modulus and high-strength fibers made of magnesium - aluminosilicate glass (S-glass rovings).

- The application temperature of basalt fibers products are markedly higher (from -260 °C to 700 °C) compared to glass (-60 °C to 250 °C).
- Vibration-resistance of basalt fiber is also much higher than that of glass fiber. That is why BF finds widest application in wide range of constructions, subjected to heavy vibration and acoustic loads: transport vehicles (notice that initially basalt fibers were applied in aerospace military industry and shipbuilding), engineering, etc. Besides, basalt fiber articles serve as effective sound-insulator, which is not broken itself under effect of acoustic vibrations that owes, for instance, their exclusives application as insulation in aircrafts.

Among these various properties and characteristics, basalt fiber resistance in acidic and basic environments should be highlighted especially if compared with glass fiber, for the implications that this has in common applications of this material, such as concrete reinforcement in form of chopped or bars.
Obviously, chemical resistance of basalt fibers principally depends upon their chemical composition even if it is very important to evaluate the fiber surface condition, especially in the case of surface-active media (alkali, some salt solutions, and so on); the ratio of silicon, aluminium, calcium, magnesium, and iron oxides is of great importance. For instance, the presence of iron oxides imparts to basalt fibers higher chemical

	Basalt fiber	Glass Fiber
Thermo-physical properties working temperature (°C)	-260 °C ~ 700 °C	-60 °C ~ 250 °C
Caking temperature (°C)	1100 °C	600 °C
Thermal Conductivity	0.031~0.038 w/m.°K	0.038~0.042 w/m.°K
Physical properties filament diameter (μm) density (kg/m3) elastic modulus (kg/mm2)	7 ~ 15 2560 10000 ~ 11000	6 ~ 17 2500 ~ 2600 Up to 7200
Tensile strength MPa	4150 ~ 4800	4150 ~ 4800
Residual Tensile strength under heat treatment (%)	20° 100 200° 95 400° 82 600° 76	20° 100 200° 92 400° 52 600° caking
Chemical resistance (loss of weight) (%)	2N HCl 2.2 2N NaOH 6.0 H2O 0.2	2N HCl 38.9 2N NaOH 2.75 H2O 6.2
Water absorption for 24 hours (%)	0.02	1.7
Vibro resistance (loss of weight) (%) At temperature 200°C 450°C 900°C	0 0.01 0.35	12 41 100
Acoustic characteristics Sound absorption coefficient	0.95~0.99	0.8~0.92

TABLE 1 *Comparative characteristics of fiber*
Source: ENEA

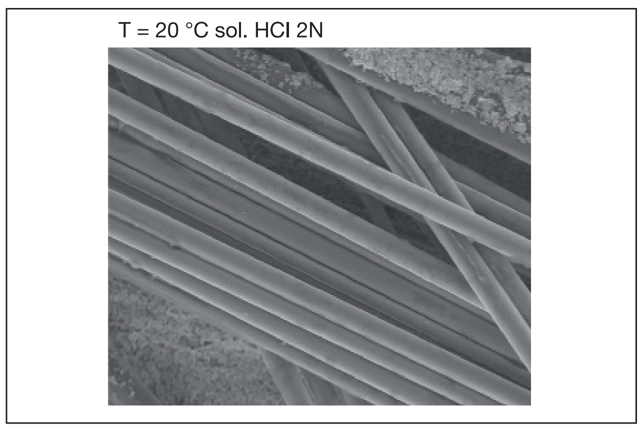


FIGURE 3 Basalt fiber production after 32 days
Source: UNICAL

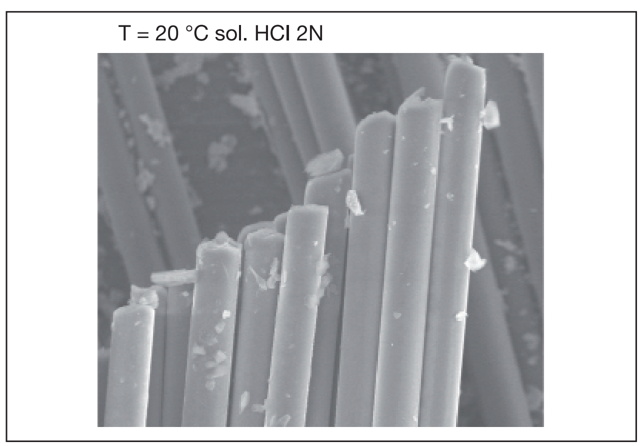


FIGURE 4 Glass fiber after 32 days
Source: UNICAL

and heat resistance as compared with glass fibers. In particular BF have high acid resistance, which is greater than the resistance of E-glass and S-glass fibers, but is somewhat less than the resistance of specific chemically resistant zirconium glasses.
At short-term exposure in strong mineral acid solutions, no fiber strength was observed while a long-term (more than 100 h) impact of hydrochloric acid solutions can cause strength reductions of 15%-20%. This reduction proceeds more slowly for basalt rovings with smaller filament diameter than for glass rovings, as shown in figures 3 and 4.
Regarding the resistance of basalt fibers to the influence of various alkali media, it has been considered for different times and at different levels in many researches. Alkali resistances of basalt fibers and glass fibers having different chemical composition, in various model alkali media (alkali, alkali-free, quartz, and zirconium), were compared qualitatively. Analysis of the strength decrease enables to arrange the glass and basalt fibers studied, in the following descending sequence by alkali resistance: zirconium > basalt > quartz > alkali > alkali-free. As may be inferred from this sequence, expensive zirconium-containing glass fibers are followed by relatively cheap basalt fibers having higher mechanical properties. Therefore, basalt fibers demonstrates a higher alkali resistance if compared with the majority of glass fibers. This is the reason why basalt fibers have been used as reinforcement of in Portland cement concrete, which is an alkaline medium, attracting the attention of researchers and users of these fibers.

ENEA and basalt fiber

The interest of ENEA in basalt fiber research dates back to the project called "basalt fibers and their composites to reinforce cementitious-based materials", funded in 2008 under the program *Industry 2015,* technological area *materials to high efficiency for building and bioclimatic architecture*.
It was a research program in collaboration with 8 SMEs and 2 other Italian public research organization, in addition to ENEA Trisaia Research Centre. One of the project targets was the possibility of producing, firstly on a smaller scale, basalt fibers of acceptable quality at competitive costs, through which to obtain all the final products, such as nets, chopper, rebar, fabrics, etc.
In March 2010 ENEA signed an agreement with HG-GBF, a Chinese company world leader in basalt fiber manufacturing. Main targets of this agreement are to deepen and enhance the research and development related to innovative industrial applications of basalt fiber and to implement research and innovation programs about BF application.
Among all basalt fiber application areas, ENEA, according to its mission, has focused its interest mainly on the aspects of materials related to energy efficiency, construction, boating and automotive sectors.
The *UTTRI-TEM* (Metrology and Material Technology Laboratory) of ENEA Trisaia Research Centre has engaged part of its staff resources to basalt fiber R&D especially within non-destructive controls and durability, to test and qualify BF, in coordination with the *ENEA UTT MATERIALI* and in collaboration with both the operational resources available in other ENEA research centers particularly active in materials sector - Brindisi Research Centre - and some Italian public Universities, localized in the southern part of Italy, such as Palermo University and Calabria University.
More in detail, the UTTMATB-COMP of ENEA Brindisi Research Centre is researching on the application of short basalt fibers as reinforcement for concrete and for thermoplastic and thermosetting polymer matrices. Palermo University is involved with basalt fiber reinforced composites particularly targeted to the boating sector. Calabria University is researching with ENEA Trisaia on an eco-cement mortar reinforced with short basalt fiber.
Hg GBF has provided all the needed material required by ENEA to execute tests, in particular, given the basalt fiber application areas consistent with ENEA policy purposes: fabrics with different weave, nets, basalt fiber rebar from 8 to 16, chopped fiber of different length, continuous basalt fiber.
Tests are carried out by ENEA primarily to understand and research on the properties of a material - basalt fiber - that is not widely used and known in the Western world. In many cases research is in progress and yet still limited to few applications. The agreement with HG GBF allows ENEA to exploit Chinese knowhow and materials, learning more about the basalt fiber potential in all its forms and applications, making it the reference point in a virtuous cycle link-

ing producers to end-users through validation and research performed by an independent organization.
Particularly, the following tests are carried out in the laboratories of the Technical Unit for Technolgy Transfer of Trisaia Research Centre: mechanical characterization of basalt fiber rebar and durability tests; characterization of BF insulating panels (thermal conductivity); durability and destructive tests on basalt fabric for structural applications; and, more generally, study of material durability.
Some of these tests are still in progress because they need long time – as in the case of durability tests– or in planning stage, such as BF rebars characterization; others have already been performed.
It is the case of experimental tests for measuring the thermal conductivity of a thermal insulation basalt fiber panel.
Given that the energy efficiency of the building depends primarily on the efficiency of the insulating material, the determination of its thermal characteristics is the first step towards the definition of a more efficient technological system.
The experimental measurements were made by using the method of heat flow with the NETZSCH apparatus (Model HFM 436/0) according to the standard procedure defined in compliance with UNI EN 12667. They showed that the basalt fiber panel tested – with a density of 240 kg/mc - has a thermal conductivity of 0.032 W/m K at the stated temperature of 10 °C, strictly comparable to that of traditional insulation materials such as fiberglass and rock wool having a much lower density.
The test results also showed the increase in thermal conductivity with temperature. Figure 5 shows a benchmarking depending on the thickness required for the same conductivity of a basalt fiber panel (red block) in a ranking of the most common materials used for insulation.
If compared to other materials, probably cheaper, the added value of the basalt fiber insulating panel can be the fire resistance.
Test results will be soon published in an ENEA internal report. Moreover, comparative tests with other materials used as insulation panels for energy efficiency will be published on a specialized national magazine.
At the Materials Laboratory of Trisaia research Centre some more tests were performed on fabrics, normally

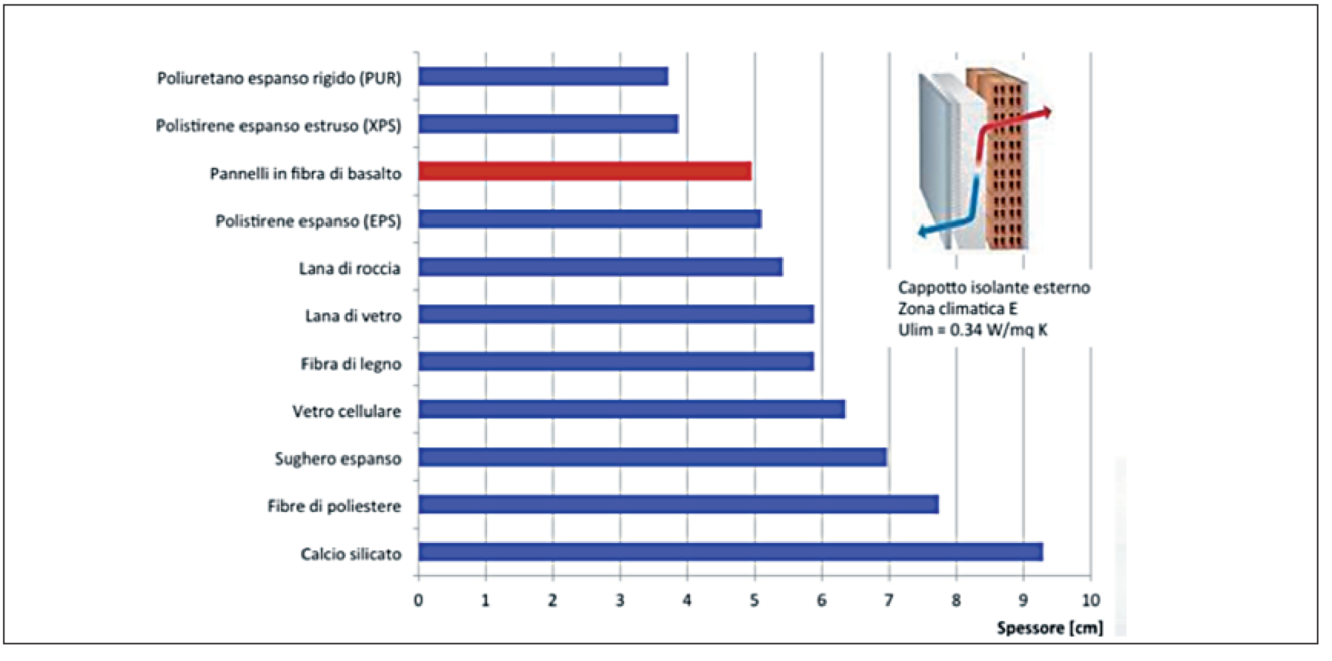


FIGURE 5 Benchmarking of basalt fiber panel
Source: ENEA

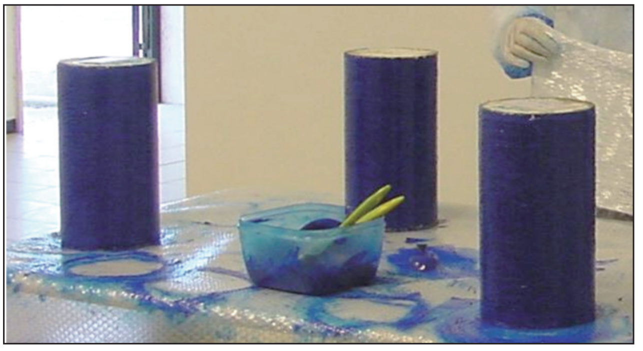


FIGURE 6 Test preparation
Source: ENEA

	fca [Mpa]	a	fc/fc0
Unconfined	*27,1*	*0,0041*	*1*
GFRP	*37,3*	*0,010*	*1,38*
BFRP	*51,5*	*0,016*	*1,90*

TABLE 2 *Test results*
Source: ENEA

used as external reinforcement for concrete in many structural systems (figure 6). Main objective of the experimental activity was to investigate on the effectiveness of confinement based on basalt fibers pre-impregnated in epoxy resin (BFRP), and to compare the performance (in terms of peak strength and ultimate axial strain gains) of different confinement materials, in particular glass fiber reinforcement laminates jacketing (GFRP). The investigation was carried out on 18 concrete cylindrical specimens with a diameter of 150 mm and a height of 300 mm - 8 unconfined, 5 confined with uniaxial basalt laminates with unit weight of 200 g/m^2, 5 confined with uniaxial glass laminates with unit weight of 250 g/m^2 .

A low compressive resistance concrete was reproduced to simulate many deficient existing structures; the specimens were wrapped by using a commercial epoxy resin, and tested 90 days from casting in compression through monotonically applied loading in force control, according to UNI EN 12390-3.

Test results are shown in table 2 and will be soon published in an internal ENEA report.

It is important to emphasize the good behavior of basalt fiber fabric reinforcement. In this case the added value can be eco-compatibility of this material, its easier recyclability if compared to other material with similar mechanical characteristics.

Conclusions

As a result of its characteristics and properties, basalt fiber can be really considered as the material of our future for a green and sustainable development. If we consider the environmental impact of the whole complex of technological processes on obtaining an exploitation of basalt fibers, it is much lower than that of glass, carbon or mineral fiber material in general.

In this context, along with the development of the basalt fiber industry and applications, more and more researchers begin to research on the basalt fiber. An indicator of this particular situation can be the increasing number of the published papers about basalt fibers, especially from 2004. The pre-published papers are mainly overview articles about the basic properties of basalt fiber and its manufacture. As the development of basalt fiber applications increased, these published papers began to focus on the related basalt fiber reinforcement sectors: civil engineering, transportation infrastructures, research and development on resin-based composite material. There are also ever more applications for basalt patents.

However there can be a great risk: in many cases the applications of basalt fiber precede basic research. Conversely, in order to have a better and more scientific application of basalt fibers, it is necessary to strengthen a qualifying and analysis system of static, dynamic, extreme environments (high temperature, low temperature, chemical corrosion, freezing and thawing, etc.) properties of basalt fiber. Only in that way, theoretical model and design methods can guide the practical application. This can be the rule of ENEA which could also contribute to fill the basalt fiber gap, closely connected to the condition that the international engineering code authorities have not provided specific design guidance for its use.