BASALT CHARACTERIZATION FROM COMMERCIAL QUARRIES ON HAWAI'I ISLAND AND FEASIBILITY STUDY RESULTS FOR A CONTINUOUS BASALT FIBER MANUFACTURING OPERATION

Rodrigo, Romo[1*], Kyla, Defore[2]

[1]: Pacific International Space Center for Exploration Systems, Hilo USA; rfvromo@gmail.com
[2]: Pacific International Space Center for Exploration Systems, Hilo USA; deforeky@hawaii.edu

[*]: corresponding author

Keywords: Basalt Characterization; Continuous Basalt Fiber (CBF); Sintering;

Abstract:
The Pacific International Space Center for Exploration Systems (PISCES) is a state agency of the State of Hawai'i attached to the Department of Business, Economic Development and Tourism (DBEDT). PISCES' objectives are to promote the aerospace industry in the state of Hawai'i and/or to support economic development through technologies/processes related to research work in Planetary exploration, especially In-Situ Resource Utilization (ISRU).

In ISRU research, PISCES has been exploring how to use Hawaiian basalt as a feedstock in manufacturing and construction for lunar or Mars applications. Sintered basalt samples have resulted in materials possessing mechanical characteristics superior to those of concrete. However, variations in the chemical composition of basalts used has produced a wide range of results in the products of sintered materials. In response, PISCES has collected and analyzed the chemical composition of basalt from various sources on the island to characterize and better identify which samples product the best sintered materials.

As part of an economic development initiative, PISCES contracted the consulting firm SMA to conduct a feasibility study to determine whether a Continuous Basalt Fiber (CBF) manufacturing plant would be a viable venture in Hawaii. CBF manufactured in Hawaii could be used in-state or exported for use in the production of pultruded FRP products like rebar, woven fabrics for composite applications, shells for concrete-filled tubes or other structural/strengthening applications.

This paper will show the results of the basalt characterization research PISCES has conducted and the results of the CBF market feasibility study performed by SMA.

1. Hawaiian Basalt as a Feedstock for Manufacturing and Construction

Between 2015 and 2016, PISCES in collaboration with NASA's Swamp Works developed interlocking paver tiles made of sintered Hawaiian basalt to robotically build a vertical take-off & vertical landing (VTVL) pad. The basalt used for the tiles was a product of a Hawaii Island quarry.

These tiles were constructed using sub-150µm basalt fines with no additives. The fines were packed into a ceramic mold and placed into a kiln, then sintered at 1,149º C. The mechanical properties of the resulting material exceeded those of residential concrete and met the requirements of the test (Table 1).

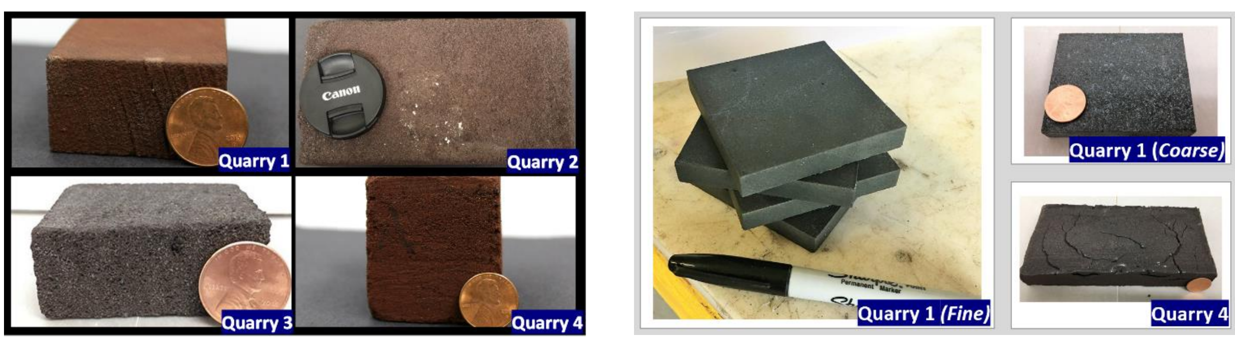
Additional sintering tests of the basalt fines at a higher temperature 1,176.6º C produced a different material with significantly stronger mechanical properties (Table 1). PISCES is currently continuing research in this field.

Table 1: Structural Properties of Hawaiian Sintered Basalt			
Sintering Temp	Density (g/cm^3)	Compressive Strength[1] (MPa)	Flexural Strength (MPa)
1,149º C	1.699	21.48	4.93
1,176º C	2.64	212.54	40.35

2. Characterization of Basalt Obtained from Commercial Quarries

PISCES began experimenting with basalt sintering using basalt aggregate from only one local quarry. When basalt from other quarries was used for testing to compare results, fines from other locations produced widely varying results in structural characteristics.

So far, PISCES has sintered and analyzed basalt aggregate from four quarries on Hawaii Island. For both thermal profiles shown above, quarries 1 and 3 created the most cohesive bricks whereas quarries 2 and 4 created bricks with structural problems like cracking and crumbling. Figures 1a & 1b below show all four quarried materials sintered at 1,149º C and 1,176º C. So far, only material from quarry 1 and quarry 4 have been sintered at 1,176º C, and only quarry 1 has been sintered at grain sizes larger than 125 µm producing bricks with a textured surface.



(a) (b)

Fig. 1 (a). Basalt aggregate from four Hawaii Island quarries sintered at 1,149º C produced various qualities of bricks depending on their source. **(b).** Basalt aggregate from quarries 1 & 4 sintered at 1,176º C produced various qualities of brick depending on source location and grain size.

Due to the variation in brick quality from each quarry, it was important to investigate the chemical makeup of each aggregate sample to determine if there were any significant differences

[1] Compressive Strength and Flexural Strength (Modulus of Rupture) tests were performed by NASA's Engineering Directorate Laboratories and Test Facilities Division, Kennedy Space Center, FL in accordance with ASTM C133.

between them. Energy Dispersive X-Ray Fluorescence (EDXRF) analysis was used to gauge the chemical composition of each sample. Table 2 illustrates the chemical profiles of aggregate samples from each of the four quarries.

Table 2_EDXRF Chemical Abundance Values for Island Quarries

	Na_2O%	MgO %	Al_2O%	SiO_2 %	K20 %	CaO %	TiO_2 %	FeO %	Fe_2O_3 %	MnO %	P_2O_5 %
Quarry 1	*2.4*	*6.78*	*13*	*50.4*	*0.35*	*10.1*	*1.77*	*10.5*	*11.69*	*0.17*	*0.26*
Quarry 2A	*2.34*	*8.89*	*12.3*	*49.5*	*0.34*	*9.61*	*1.71*	*10.7*	*12.21*	*0.16*	*0.3*
Quarry 2B	*1.71*	*18.6*	*8.76*	*46.1*	*0.22*	*6.73*	*1.22*	*12*	*13.74*	*0.17*	*0.3*
Quarry 3	*2.39*	*5.45*	*13.4*	*51*	*0.4*	*10.6*	*1.93*	*10.4*	*11.77*	*0.16*	*0.26*
Quarry 4	*2.17*	*13.3*	*11.2*	*47.6*	*0.28*	*7.87*	*1.5*	*11.5*	*12.98*	*0.17*	*0.31*

Testing results showed that samples from quarries 2 and 4 (which produced poor-quality bricks) contained significantly higher amounts of MgO. These samples are thought to contain minerals abundant in MgO such as Forsterite Olivine. Forsterite has a melting point of 1,898.9 °C. It was assumed that Forsterite would not sinter at the current thermal profiles, possibly resulting in points of weakness and lesser-quality bricks.

3. Continuous Basalt Fiber Manufacturing Feasibility Study for Hawai'i.

As part of its core objective to develop and diversify Hawaii's economy, PISCES contracted SMA[2] to conduct a comprehensive market feasibility study. The study's main goal was to determine if a Continuous Basalt Fiber (CBF) manufacturing operation in Hawaii County could benefit the local economy. The study looked at many factors including the projected market growth of the CBF industry worldwide, the current supply and demand of CBF, and the necessary costs of running such an operation in Hawaii.

The basalt samples collected at four commercial quarries in Hawai'i indicated that two locations (Quarries 1 & 3) possessed the chemical makeup within, or close to, the desirable parameters required for basalt fiber extrusion (Table 3). Coincidentally, these were the quarries that produced the higher quality sintered material.

Table 3: Recommended Composition of Basalt for CBF Extrusion[3] (%)

Source	SiO_2	Al_2O_3	CaO	MgO	$NA_2O + K_2O$	TiO_2	Fe_2O_3 + FeO	Others
Excelement.com	50-60	14-19	5-10	3-5	3-5	0.5-3.0	9-14	0.05-1.0
Quarry 1	50.4	13	10.1	6.78	2.75	1.77	22.19	
Quarry 3	51	13.4	10.6	5.45	2.79	1.93	22.17	

[2] SMA Inc. 18400 Von Karman Ave, Ste 500. Irvine, CA 92612. www.smawins.com
[3] Chemical constituents of basalt rocks; www.excelement/basalt-fibre-technology/

According to SMA's analysis, the CBFmarket was worth $178 million in 2018 and is expected to grow to $405 million in the next decade. The current market is dominated by Chinese and Russian CBF manufacturers. Some production is happening in Europe and a plant in the U.S. is expected to begin operations this year.

SMA's analysis incorporated a 30-year financial model for a 6,600 metric-ton plant producing various types of CBF roving. The model was based on prices of $1.50, $2.50 and $4.00 per pound of low, medium and high-quality roving.

Based on these assumptions and an estimated average selling price of $2.38 per pound of basalt roving, the venture would produce roughly $1 billion in free cash flow and $450 million in net income during the 30-year operating period of the plant.

The study identified that the main obstacles a Hawaii-based CBF operation faces include but are not limited to:

- High energy costs;
- High labor costs;
- Shipping costs to and from Hawaii.

The next step in this process is to locate a facility where Hawaiian basalt from local quarries can be tested and validated for its fiber making quality. PISCES is now seeking companies and/or laboratories to complete this goal.