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Report of Investigation

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BASALT FIBER COMPOSITE REINFORCEMENT FOR CONCRETE

Prepared by:
Vladimir B. Brik
Research & Technology, Inc.
Madison, Wisconsin

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BASALT FIBER COMPOSITE REINFORCEMENT FOR CONCRETE

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EXECUTIVE SUMMARY

A unique process of producing continuous amorphous basalt fibers has been developed in the Ukraine. These fibers have exceptional strength and stiffness with ultimate tensile strengths in excess of 200-300 ksi and moduli in the range of 20-30 msi. During high speed spinning attenuation (with velocities between 20 m/sec and 80 m/sec), these fibers are braided into roving containing about 200 elemental fibers with diameters ranging from 7 μm to 15 μm.

This final report focuses on an evaluation of the feasibility of using composite rebar in concrete reinforcement based on studies of the properties of basalt fiber and reinforced composite. The availability of a corrosion-resistant replacement for steel without greatly increased material cost (i.e., stainless steel, coated steels, etc.), will create an immediate demand for the product wherever corrosion is a problem. The use of this product will reduce maintenance and replacement of reinforced concrete in these locations.

A number of laboratory and bench-scale tests of roving basalt fibers and basalt-fiber reinforced composites have been provided. Roving containing continuous basalt fibers 9 μm-15 μm in diameter exhibit exceptional mechanical characteristics: tensile strengths from 375 ksi to 147 ksi (2,625 MPa to 1,014 MPa), and moduli from 23.5 msi to 14.49 msi (160 GPa to 100 GPa) combined with excellent flexibility properties. Mechanical performance/price ratio of roving basalt fiber is higher than fibers currently available in the U.S. for use as reinforcement in composites.

The pultrusion and Resin Transfer Molding (RTM) epoxy-bonded basalt-fiber composite specimens containing roving RB9, RB12 and RB14 have been produced, tested and compared with E-glass fiber composite in accordance with ASTM standards. RTM basalt fiber composites that utilize roving RB12 (12-μm elemental fibers) under optimum conditions (resin, fiber content, fiber direction, dimension, etc.) show tensile strengths and moduli of elasticity roughly twice that of E-glass fiber composite: (quasi-isotropic) basalt, 85 ksi and 5 msi; e-glass, 30 ksi and 2.5 msi; (uniformly) basalt, 220 ksi and 13.5 msi; E-glass, 160 ksi and 6 msi, respectively.

The fiber-reinforced concrete utilized low-cost coarse needles basalt fiber 50-350 μm in diameter and 50-70 mm in length, and chopped roving elemental fibers 7 μm in diameter and 70 mm in length (10% coarse and 3% roving fibers) prepared using *casting* and *extrusion* methods, respectively. The coarse basalt fibers (diameter over 50 μm) are not flexible and appear to have brittle properties, but they exhibit high chemical resistance in cement and alkaline media. Both the coarse and chopped roving basalt fibers distributed uniformly throughout Portland cement impart strength (tensile, compression), fatigue and flexural properties to the concrete two to four times higher than that of conventional or extrusion concrete, and two to three times that of cast concrete. Basalt fibers have the highest mechanical performance/price compared to carbon, Kevlar, Aramid and other ceramic fibers used as reinforcement; therefore, they have a high potential for cost-effective applications in cement and concrete products.

IDEA PRODUCT

This progress report focuses on the technical characteristics of basalt-fiber composite/concrete. Basalt fibers exhibit a high level of mechanical characteristics (tensile strength, modulus) and chemical stability in cement media. The chemical stability of basalt fibers in cement and alkaline media is higher than that of E-glass fibers. An evaluation of the mechanical characteristics of basalt-fiber composites is provided. The technical characteristics of basalt fiber reinforced concrete are considered and suitable basalt fibers for fiber-reinforced concrete applications are defined.

CONCEPT AND INNOVATION

The concept is based on the unique mechanical and chemical properties of basalt fibers and basalt-fiber composites, which can potentially replace steel bar in reinforced-concrete applications. More specifically, roving basalt fibers containing about 200 elemental continuous fibers in amorphous state with monodiameters between 7 μm and 14 μm are considered to be a revolutionary new class of materials for concrete construction. The application could be reinforcing composite rebars or reinforcing dispersed chopped basalt fibers. The rebars, produced by using suitable organic (epoxy) or non-organic (mineral) bonding material, consists of 80% continuous amorphous basalt fibers and show ultimate tensile strengths in excess of 200-300 ksi and moduli between 20 and 30 msi.

It is anticipated that basalt-fiber rebar or chopped roving fibers reinforcement could replace steel rebars and fibers in structural concrete wherever corrosion is problem, providing higher strengths and durability. Coarse basalt fibers are economically competitive with currently used fibers for fiber-reinforced concrete.

IDEA PROJECT INVESTIGATIONS AND PROGRESS

BASALT FIBER CHARACTERISTICS

Basalt fibers are manufactured in a single-stage process by melting pure raw material. They are environmentally safe and non-toxic, possess high heat stability and insulating characteristics, and have an elastic structure. When used for composite materials, they provide unique mechanical properties. They could easily be processed into fabric using existing standard equipment. In fact, continuous roving basalt fiber can be used to produce a wide range of composite materials with high reliability characteristics using standard equipment.

The mechanical characteristics of roving depend on the diameter of the elemental fibers. For example, for roving RB9, RB12 and RB15, containing, respectively, elemental fibers of 9-µm, 12-µm and 15-µm diameter, the tensile strength ranges from 375 ksi to 147 ksi (2,625 MPa-1,014 MPa), and moduli from 23.5 msi to 14.49 msi (160 GPa-100 GPa). The 9-µm elemental fibers show higher tensile strength and modulus than both 12-µm and 15-µm elemental fibers.

The Mossbauer, nuclear and paramagnetic resonance spectroscopic methods provide evidence that the variation of mechanical properties (tensile strength, modulus of elasticity) in continuous fibers is associated with the strength of the chemical bonds between oxygen and primary metallic elements (Si, Al, Ir, Ti, Ca) in the one-dimensional longitudinal quasi-amorphous structures created during the high-velocity spinning attenuation process. The number of Al atoms in these structures increases as the velocity of attenuation increases (20-80 m/sec). RB9 is produced with a higher attenuation velocity than RB12 or RB15. Therefore, one-dimensional structures in RB9 contain more Al atoms, which provide the strongest chemical bonding with oxygen in a short-range configuration that imparts excellent flexibility properties. The strength of the O-Al bond creates the exceptional longitudinal (axial) mechanical properties of continuous elemental fibers. Both the high diffusion mobility of oxygen atoms and strong O-Al chemical bonding are responsible for the creation of one-dimensional longitudinal (axial) structures in a short-range order configuration.

At a low velocity of attenuation (coarse fiber diameter less than 15 µm) the formation of oxygen with other elements in an amorphous structure becomes probable. The lower the velocity of attenuation (below critical speed), the more probable nucleation of a three-dimensional crystalline phase becomes. During low-velocity attenuation the O-Al short-range ordered structures in one-dimensional configurations are decomposed into a three-dimensional crystalline structure state that drastically reduces the mechanical characteristics of the fibers. Therefore, a decrease in the velocity of attenuation increases the number of other metallic atoms (Si, Ti, Ir, Ca) that can be involved in the creation of a crystalline structure rather than an amorphous structure. The critical speed of attenuation depends on the chemical content of the basalt mineral rock material.

The tensile strength of continuous basalt fibers (diameter less than 14 µm) is about twice that of E-glass fibers, and the modulus of elasticity is about 15-30% higher. Basalt fibers in an amorphous state exhibit higher chemical stability than glass fibers. When exposed to water at 70°C, basalt fibers maintained their strength for 1200 hrs, whereas the glass fibers did so for only 200 hrs.

TECHNICAL CHARACTERISTICS

Tables 1 and 2 quantify the technical characteristics of continuous roving basalt fiber and twisted roving basalt fiber:

TABLE 1 Continuous Roving Basalt Fiber

Linear density	50-2640 g/km
Acceptable deviation for the linear density	8-10%
Breaking load	15-550 N
Temperature of operation in atmosphere	700 °C

TABLE 2 Twisted Roving Basalt Fiber

CHARACTERISTICS	R -9-330*1	R-9-330*1*2
Linear density (g/km)	330+-10	670+-8
Fraction of substances removed by calculation (%)	0.8	0.8
Twist	right	left
Break load (N)	105	205

Basalt Fiber

Basalt fabrics are manufactured from roving using special emulsions (lubricants). Experimental batches of these fabrics are being manufactured in the Ukraine as follows:

- Fabric width, mm 900
- Fabric thickness, mm 0.166-1.16
- Surface density, g/m^2 67.1-1281.

Basalt fibers exhibit excellent adhesion with polymer (epoxy) binder material. Basalt-fiber reinforced composite can be bonded in composite with fiber content up to 80% (Figure 1).

Basalt-Fiber Composite

Two different types of polymer (epoxy) bonded composite specimens have been prepared and tested to identify their mechanical properties (tensile strength, modulus of elasticity) and ability to be bent without cracking:

- pultrusion epoxy-bonded basalt fiber composite rod (rebar) with 3 different diameters (0.12″-0.125″, 0.195″-0.204″, and 0.30″-0.312″; and
- resin transfer molding basalt fiber composite specimens (width, 0.980″-0.977″; thickness, 0.123″-0.128″, gage length 5″-10″).

Basalt fiber composite rods containing about 80% fibers were prepared using different roving: RB-9 (9-µm diameter elemental fiber), RB12 (12-µm diameter fiber) and RB14 (14-µm diameter fiber). The mechanical characteristics were determined for composite rods with diameters of 4.8 mm-5.0 mm (0.195″-0.204″) made with roving RB9 (9-µm fibers) and roving RB14 (14-µm continuous basalt fibers).

Resin Transfer Molding (RTM) standard rectangular composite specimens were produced using roving RB12 (fiber volume approximately 44%) consisting of five plies of wide-weave fabric. RTM composite specimens were tested at the Basic Industrial Research Laboratory (BIRL) at Northwestern University in comparison with E-glass fiber composites. The resin used was Shell's EPON-862 epoxy with curing agent *W* for both basalt and E-glass fiber composite specimens.

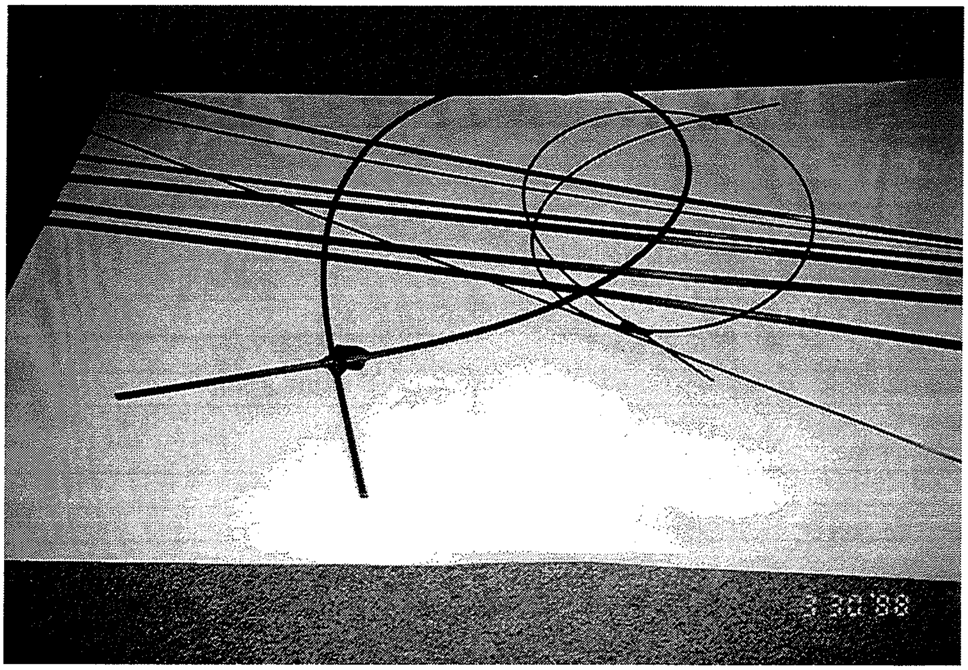

FIGURE 1 Basalt-fiber composite bar specimens produced through the pultrusion process (2.8 mm-3.0mm; 4.8mm-5.0mm; and 8.0mm in diameter).

The composite rod specimens were tested at the University of Wisconsin, Madison, using Material Test System (MTS) 810 machine (maximum load 20,000 pounds), as shown in Figure 2a; joint stock company Techkomplect, Universal Material Test Machine 1253Y-90 in Kharkov; and at the Research Institute of Construction Buildings in Kiev, test machines WPM VEB Thuringer Industriewerk Rauenstein, Masch.Typ FMI (Load 1 ton), FM40 (Load 40 tons) and FM 100 (Load 100 tons), as shown in Figure 2b.

The tensile stress-strain diagrams were recorded using two types of tensometer gages: (1) Ing Holle Feinmechanische Werkstatten, Magdeburg Spielhogenstr 26, and (2) Extensometer Model 632.118-20. The tensometer gage was fixed on the composite rod specimen after preloading over 200 lbs. Examples of pultrusion basalt-fiber composite rods are shown in Figure 1.

Two methods were used to hold basalt composite rod specimens during tensile strength tests. Some of the specimens were epoxy glued at both ends. Other rod specimens were prepared using metallic tubes (aluminum or steel) that were swaged at both ends of each specimen. Both methods are shown in Figure 3.

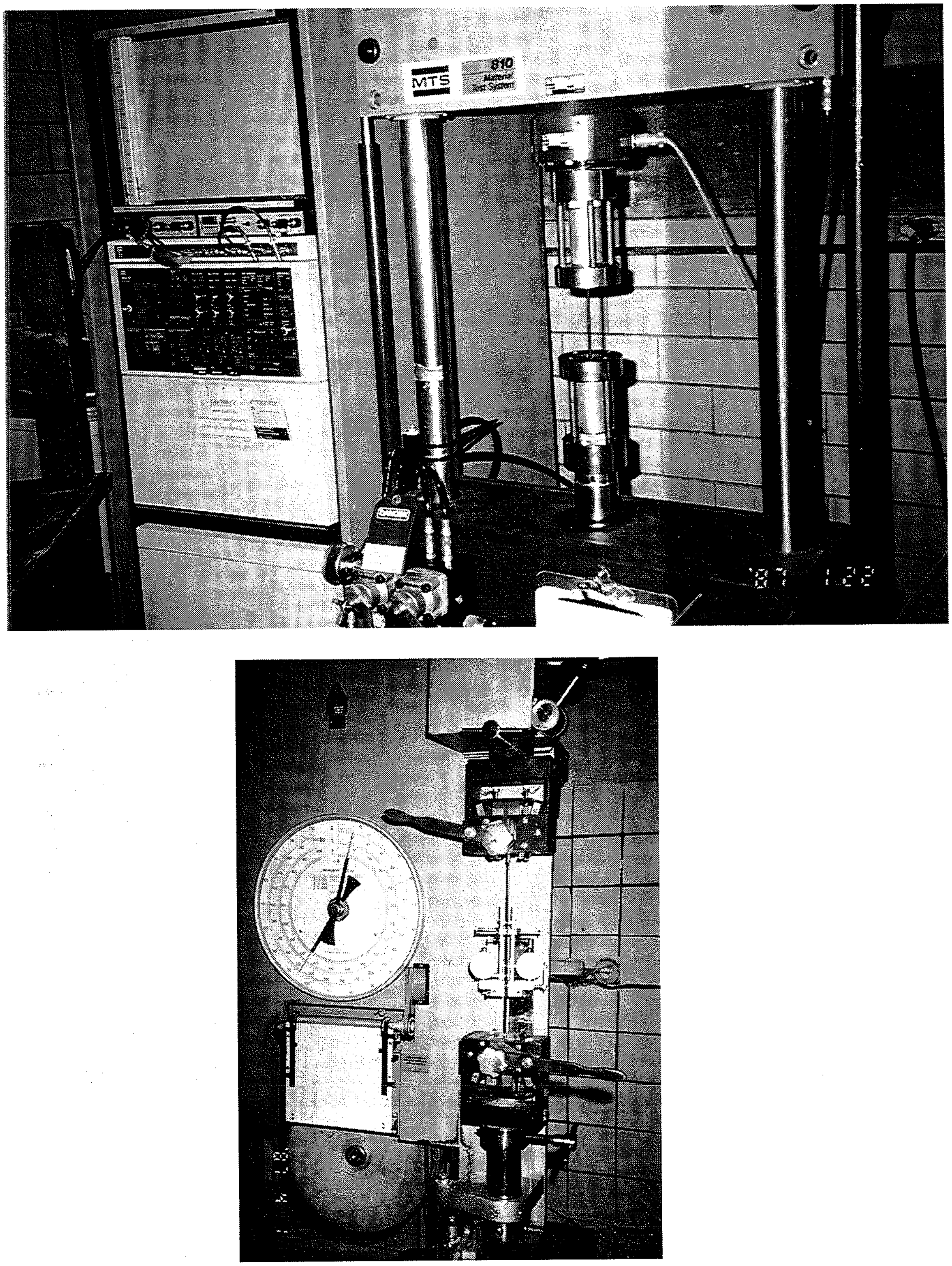

FIGURE 2 Test Equipment. Top: Material Test System (MTS) 810 machine, maximum load 20,000 pounds. Bottom: Industriewerk Rauenstein, Masch.Typ FMI (1-ton load) and FM40 (40-ton load).

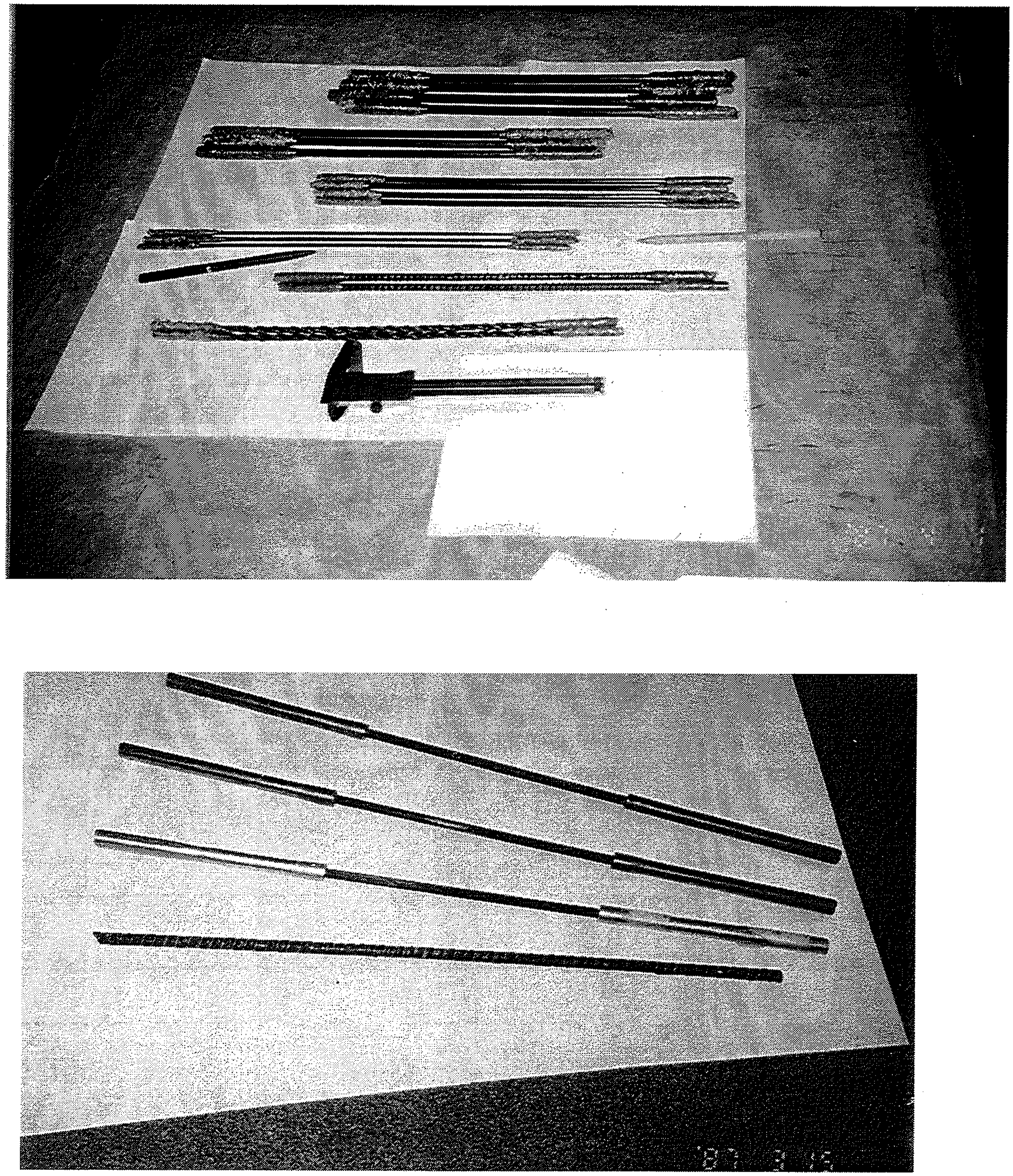

FIGURE 3 Basalt-fiber composite rod specimens used in tensile-strength test. Top: epoxy glued. Bottom: metallic tube swaged.

Unfortunately, not all composite rod specimens (epoxy-glued or swaged) were tested to failure because both the metal tubes and epoxy-glued ends started to slip when the stress during loading exceeded 150 ksi-180 ksi. Therefore, the real maximum tensile strengths of the basalt composite rod specimens were not completely defined (see dashed lines on the tensile stress-strain diagrams in Figure 4). The tensile stress-strain curves show that the moduli of basalt composites roving RB-9 and RB-14 vary from 8.3 msi to 15.0 msi (57 GPa-105 GPa) with the variation in fiber diameter; the tensile strengths and mechanical properties also vary based on the fiber diameter. This can be explained in terms of the aforementioned bonds created between oxygen atoms and metallic elements (Al, Si, Ti, Ir, Ca, etc.) in one-dimensional longitudinal (axial) quasi-amorphous configurations. At the high velocity of attenuation of 7 μm-9 μm basalt fibers, O-

Al molecules are more likely to form such configurations than other oxygen-metal molecules due to the high chemical bond strength between oxygen and aluminum. During high-velocity fiber attenuation, the other metallic elements are fixed in an amorphous state with the remaining oxygen atoms. The chemical bonding of oxygen with metallic atoms in the short-range configurations creates the longitudinal (axial) mechanical properties of the fiber. Therefore, roving and composite continuous basalt fibers with different diameters exhibit different tensile strengths, moduli of elasticity and flexural properties. Epoxy-bonded basalt-fiber composite rod specimens (with diameters over 8.0mm) can bend over 90° without cracking. These basalt fiber composites provide about three-fourths the stiffness of carbon-fiber composites. The bending properties of basalt-fiber composite-bar specimens with different diameters are illustrated in Figure 1. The results of mechanical tests of basalt-fiber composite-rod specimens are compared with those for steel bars in Figure 4. The mechanical performance/price ratios of basalt fiber in comparison with other fibers, used as reinforcements in composite are shown in Figure 5.

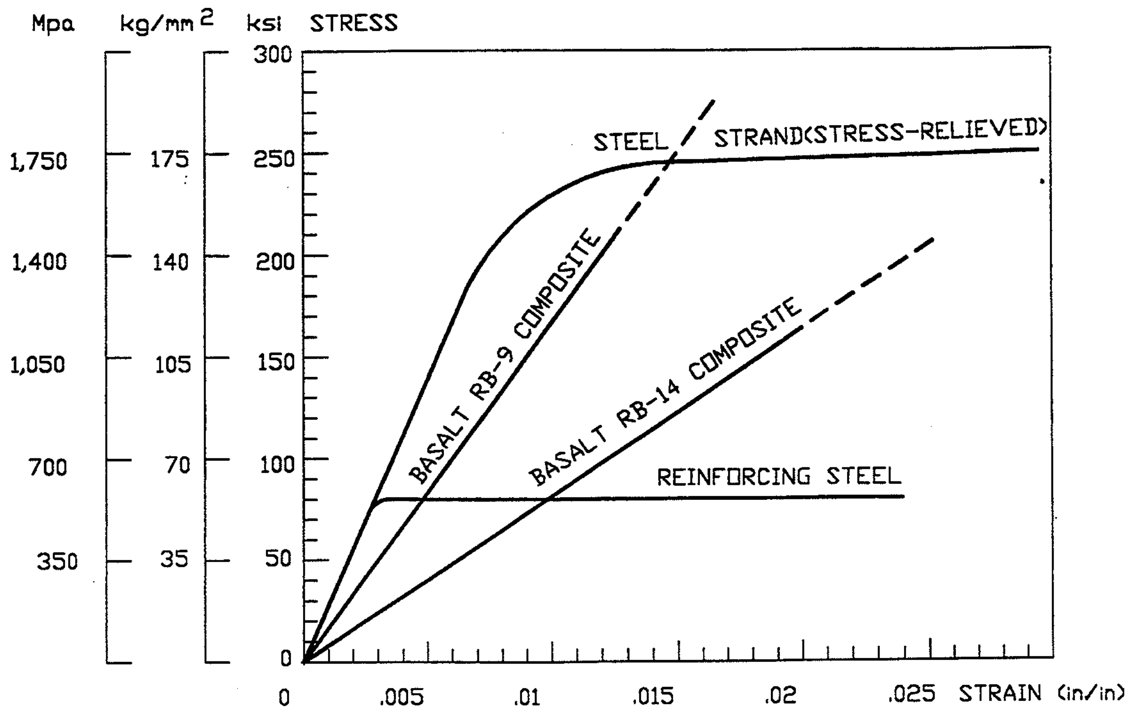

FIGURE 4 Basalt-fiber composite rod tensile stress-strain diagram in comparison with steel.

Characteristics of RTM Standard Basalt-Fiber Composite Specimens

Resin Transfer Molding (RTM) epoxy-bonded basalt-composite panel specimens (five plies of wide-weave basalt fabric containing roving BR-12) were tested (Tables 3-5) and compared with E-glass composite in accordance with ASTM standards. The composite is roughly equal to a 0°/90° laminate. The resin used was Shell's EPON-862 epoxy with curing agent *W*. The fiber volume (*Vf*) was calculated at approximately 44%. The test data show composite materials which are quasi-isotropic. Properties of unidirectional composites can only be inferred, not directly calculated.

Under optimum conditions (resin, fiber content, fiber direction, dimension, etc.), RTM basalt-fiber composites containing roving RB12 show tensile strengths and moduli of elasticity roughly twice that of E-glass fiber composite: (quasi-isotropic) basalt, 85 ksi and 5 msi; E-glass, 30 ksi and 2.5 msi; (uniformly) basalt, 220 ksi and 13.5 msi; E-glass, 160 ksi and 6 msi, respectively.

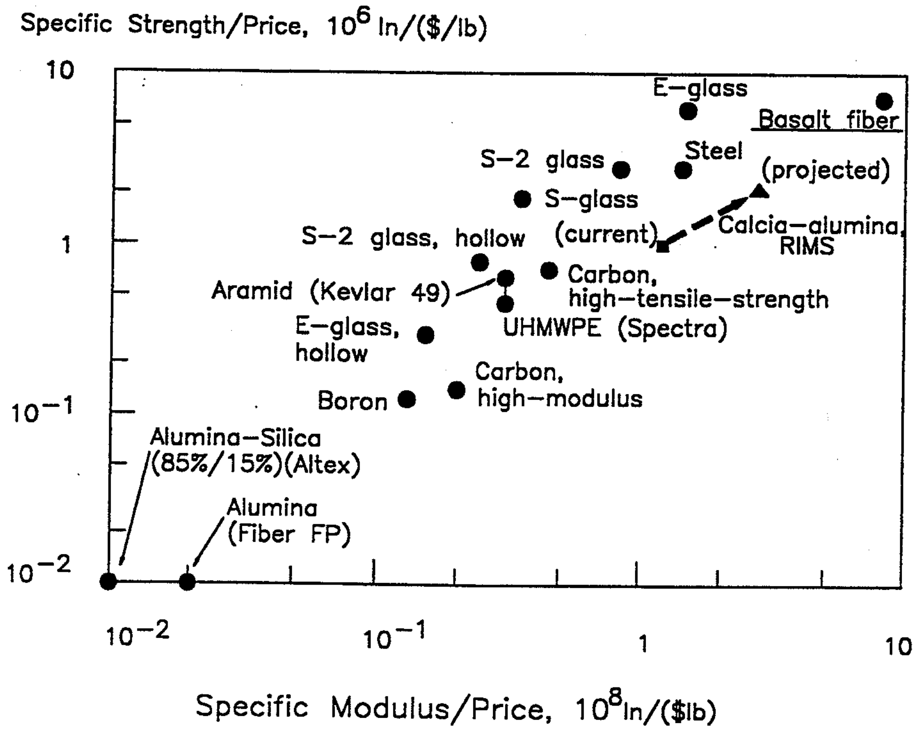

FIGURE 5 Mechanical performance/price ratios of basalt fiber compared to other fibers used as reinforcements in composites.

TABLE 3 Parameters for Resin Transfer Molding (RTM) Epoxy Bonded Basalt Fiber Composite Panels

Vol	12.70in^3	Volume of the RTM mold in cubic inches
Wt	258.9gr	Weight of the fiber preform in grams
Wc	397.55gr	Weight of the resultant composite panel in grams
Rhom	1.2003gr/cm^3	Density of the resin in grams per cubic centimeter
Em	0.433msi	Modulus of elasticity of cured neat resin in million pounds per square inch
Xtm	12.5ksi	Strength of cured neat resin in thousand pounds per square inch
Ec	4.92msi	Modulus of elasticity of the composite in million pounds per square inch
Xtc	83.95ksi	Strength of the composite in thousand pounds per square inch

TABLE 4 RTM Basalt Composite Specimens

Specimen	Width (in.)	Thickness (in.)	Failure Load (lbs)	Ultimate Strength (psi)	Elastic Modulus (msi)	Poisson's Ratio
1	0.980	0.128	10,340	83.738	4.52	0.128
2	0.980	0.128	10,340	83.738	4.52	0.128
3	0.977	0.123	10,512	87.475	5.40	0.205
4	0.977	0.126	10,040	81.558	4.61	0.210
5	0.980	0.128	10,368	83.952	4.98	0.177
average	0.979	0.128	10,368	83,952	4.92	0.193
std.dev.	1.64E-03	2.05E-03	1.97E+02	2.17E+03	3.60E-01	4.3E-02

TABLE 5 Result of Calculations

Wm	138. 85gr	Weight of the resin in grams
Volm	$7.05in^3$	Volume of the RTM mold in cubic inches
Volf	$5.65in^3$	Volume of the RTM mold in cubic inches
Vm	0.56%	Matrix volume of the composite in percent
Vf	0.44%	Fiber volume of the composite in percent

Predictions

Assume that one half of the fibers are oriented at 0° and one half at 90° and that the fibers oriented at 90 ° do not contribute to axial properties. Conservatively, then:

- Ef: 20.60msi Modulus of elasticity of the fibers (million pounds per square inch)
- Xtf: 334ksi Strength of the fibers (thousand pounds per square inch)

TABLE 6 RTM Composite Modulus and Strength Predictions Based on the Rule of Mixtures

Fiber Volume Vf (%)	Composite Modulus Ec (msi)	Composite Strength Xc (ksi)
0.30	6.48	109
0.35	7.49	125
0.40	8.50	141
0.45	9.51	157
0.50	10.52	173
0.55	10.53	189
0.60	12.53	205
0.65	13.54	221
0.70	14.55	237
0.75	15.56	253

Figure 6 shows the variation of composite modulus and strength based on fiber volume content.

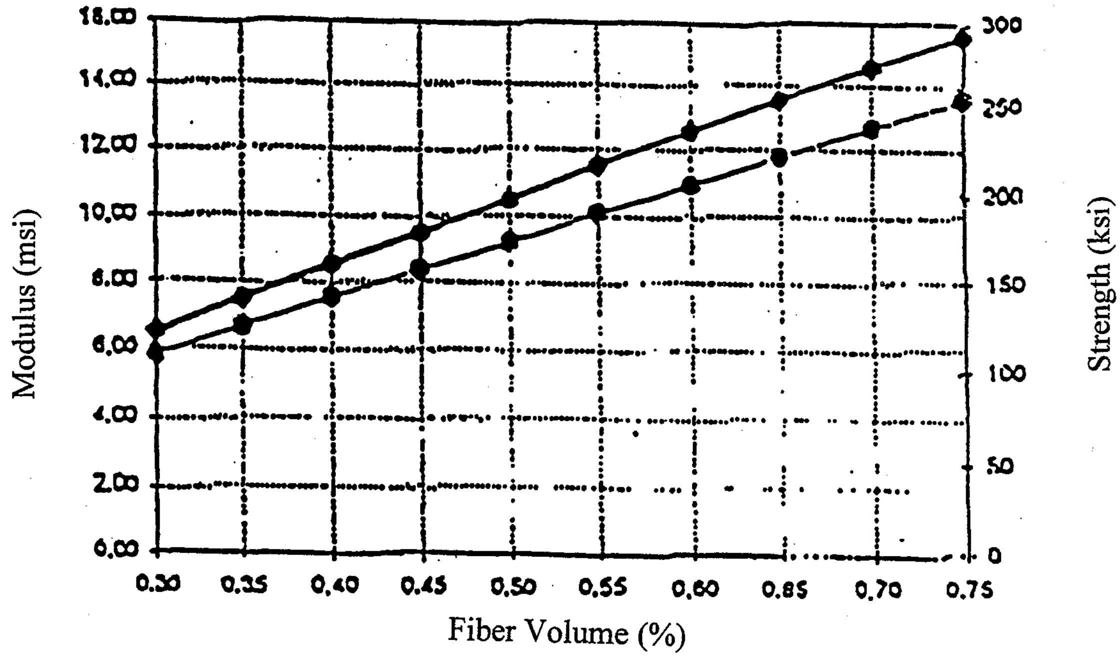

FIGURE 6 RTM composite modulus and tensile strength variation based on fiber volume content.

TECHNICAL APPLICATIONS OF REINFORCING BASALT FIBERS

To manufacture basalt-fiber composite, basalt fibers are twisted at a thickness of 80-420 gram/km. The process employs the following proportions: epoxy resin ED-20, 100 gr; isomethylhydro-phenol anhydride, 70 gr; UP6 606/2, 4 gr. To obtain a periodic profile in order to increase cohesion under reinforcement, the surface of the basalt-fiber composite bar (roving basalt fiber at a thickness, TEX, of 300 gram/km) is twisted before the polymerization process that takes place at 160°C. The equipment includes an annealing chamber, a percolation bath, wringing and calibrating dies, polymerization chambers, and a pulling device. The strength characteristics of reinforced basalt-plastic is reduced while the epoxy resins are changed to epoxy-phenolic and phenolic resins at 10% and 20%, respectively. Due to high flexibility properties, continuous roving basalt fiber is available for use in wire and cable using polymer bonding materials.

The mechanical characteristics of resin bonded basalt-plastic wire are as follows:

Characteristics	Diameter of wire, mm		
	0.9	1.0	1.5
Tensile strength, kg/mm^2	147.2	136.5	108.8

Benefits

The service life of basalt-fiber/plastic structures in construction buildings is several times longer than that of metallic structures. Moreover, the maximum effect of the new material can be achieved while exposed to harsh environments. To produce basalt-fiber reinforced plastics, epoxy, phenolic, silicon, organic and polyether binder resins are used. The basalt-fiber composite rebar (diameter 1-15mm) is produced using the pultrusion technology process. The mechanical-physical properties of basalt-fiber plastic bar composite are compared with the properties of steel bar in Table 7.

TABLE 7 Basalt-Plastic Compared to Steel Bar

Characteristics	Basalt-plastic	Metal- hot-rolled steel ST3
Fracture loading, MPa		
tensile	1080 - 1380	390 - 450
bending	670 - 700	250
compressing	460 - 480	180
Module of elasticity: tensile, MPa	89, 000 - 93, 000	2, 000, 000
Fracture elongation , %	1.5 - 2.0	42
Water absorption within 24 hours, %	0.01	-
Density, g/cm^3	1.8	7.8

The strength of reinforced basalt-plastic is reduced when the epoxy resins are changed to epoxy-phenolic and phenolic resins at 10% and 20%, respectively.

ONE-DIRECTIONAL BASALT COMPOSITE

One-directional basalt composite bars (Table 8) can replace metal reinforcement for use in the building industry, fencing, road blocks, power lines, etc. Basalt-plastic composite bar is a rope of basalt fibers, tied together by a polymer binder. This bar is manufactured on an industrial scale on standard equipment.

TABLE 8 Technical Characteristics of One-Directional Basalt Composite

Tensile strength	1400-1600
Compression strength	420-440
Bending strength	800-850
Density (g/cm3)	1.95
Content of the polymer binder (%)	20-25

Benefits

The tensile strength of basalt-fiber reinforced plastic is 2.0-2.5 times higher, and the density 4.2-5.0 times less, than that of steel. One kg of basalt-plastic reinforcement replaces 9 kg of steel, reducing the weight of construction structures. Experimental lots of pavement decks K-2 (995 x 985 x 80 mm) reinforced with basalt-fiber plastic composite bar (diameter 5.0 mm) have been produced in Kiev at the Darnitsky Plant of Construction Materials. Metal consumption per sq.m is 2.4 kg, compared to 1.4kg of basalt plastic. Basalt-plastic composite bars have lower specific gravity, higher corrosion resistance, and better workability than their metallic counterparts.

BASALT-PLASTIC PIPES

Applications

Basalt-plastic pipes can be used in shaft lining, land reclamation, agriculture (to carry gases and water), and also as a protection shield during geological or geophysical works.

Description

Basalt-plastic composite pipes are manufactured by wrapping binder-impregnated basalt fibers around a tube that provides structural support, with subsequent polymerization. The equipment used to manufacture glass-reinforced plastic tubes should be adequate for basalt-plastic composite pipes. Technical characteristics are:

- Density, g/cm^3 1.8-2.0
- Binder content (%) 28-32
- Axial compression strength, MPa 550-600
- Collapsing internal pressure, Atm 250-300

Benefits

Basalt-plastic pipes possess high corrosion resistance and low water absorption. They could replace wooden and metal structures. Articles made of basalt plastic have high corrosion stability in saltwater media. Trial test results are given in Table 9.

TABLE 9 Stability of Basalt Plastic in Various Environments

Chemical agent	Sustaining time, twenty-four hours	Change of sample mass, %	Decrease of strength, %
Distilled water	1 30	0.05 0.052	2.1 2.11
Sea water	1 30	0.058 0.062	2.27 2.3
10% solution of sulfuric acid	1 30	0.042 0.132	3.21 21.42
10% solution of hydrochloric acid	1 30	0.048 0.206	2.18 18.22
10% solution of caustic soda	1 30	0.058 0.204	4.12 28.56

BASALT-CEMENT MATERIALS

Basalt fiber reinforced concrete has been prepared using basalt fibers of different diameters: coarse basalt fiber needles (50-350μm in diameter and 50-150mm in length); and chopped roving (7μm in diameter and 50-70 mm in length). The concrete specimens were prepared using Portland cement mixed with 10-15% coarse basalt fibers. The extruded specimen (5mm thickness) containing Portland cement mixed with 3% chopped roving basalt fiber was prepared at the NSF Center for Science and Technology of Advanced Cement-Based Materials Laboratory, Northwestern University, Illinois.

The low-cost coarse basalt fibers (diameter 50-350μm) are chemically stable in cement and alkaline media, but provide lower mechanical characteristics than continuous amorphous roving basalt fiber. As opposed to continuous basalt fibers with diameters less than 15μm, coarse basalt fibers are not flexible and appear to have brittle properties when bent over 15-45°.

Both the coarse and chopped roving basalt fibers distributed uniformly throughout Portland cement provide strength (tensile, compression), fatigue, and flexural properties to the fiber-reinforced concrete two to four times higher than that of the conventional or extruded concrete and two to three times higher than that of the cast concrete. Table 10 shows that chopped roving basalt fiber increases the mechanical characteristics of the fiber-reinforced concrete (stiffness, toughness and fracture properties) more than the low-cost coarse basalt fibers. We suggest using chopped basalt roving with elemental-fiber diameters over 12μm, because 7-μm thickness basalt fiber fractures during mechanical rotation mixture with cement. The concrete containing basalt fibers (Figure 7) exhibits the highest mechanical performance/price ratio of high performance materials including carbon, Kevlar, Aramid and other ceramic fibers.

TABLE 10 Mechanical Characteristics of Conventional and Fiber-Reinforced Concrete

Characteristics	Concrete	Basalt Fiber-Reinforced Concrete	
		(Coarse Fibers , 10%)	(Chopped roving, 3%)
		Cast -Molding	Extrusion
Density, kg/m^3	2,400	2,100	2, 400
Strength, MPa:			
tensile	3.6	10.0	15
compression	43	50	70
flexural (MN/m ^{3})	7	20	30

Basalt fiber-reinforced concrete has been used in the Ukraine as a construction material. Figure 8 shows a concrete structure specimen containing low-cost coarse basalt fibers (diameter between 50 and 250 μm).

The concrete used to manufacture pavement slabs was prepared using the following mix proportions (kg/m^3):

- cement 450
- basalt fiber 9
- sand 448
- NaOH 0.0056
- crushed stone 1360
- water 189

Basalt Fiber-Reinforced Concrete

A series of compositions of coarse basalt fibers dispersed in concrete have been developed in Ukraine. One example of cast concrete has the following composition: Portland cement, 24%; river sand, 36%; coarse basalt fibers, 10%; water, 30%.

Tests on fiber-reinforced concrete using coarse basalt fibers (freezing and thawing, storage in water, etc.) consistently shows increased stability and strength. Basalt-fiber concrete also possesses radio-transparent high-damping properties. Its durability at northern altitudes is estimated to be 100 years. The low-cost coarse fibers provide the cost-effective use of basalt fiber-reinforced concrete in manufacturing a large assortment of high-strength, fire-resistant structures.

The unique characteristics of the material are that its tensile strength is 2-3 times greater than that of conventional heavy concrete, and its ability to stretch is 4-5 times greater. Therefore, it becomes possible to produce non-metallic structures or structures containing 40-60% less metal. Articles with an increased resistance to cracking can be used in various types of construction work.

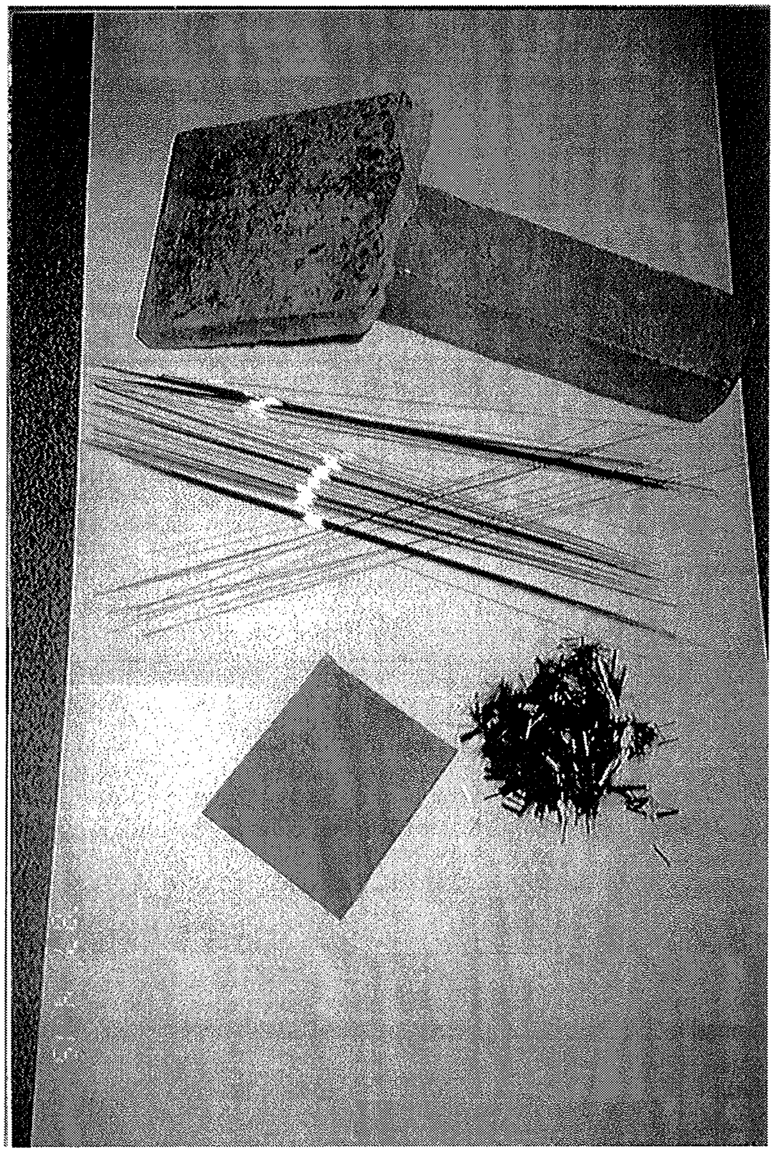

FIGURE 7 Basalt fiber-reinforced concrete specimens: conventional fiber-reinforced concrete containing 7% of low-cost coarse basalt fiber (top) and extruded fiber-reinforced concrete containing 3% chopped roving with 7μm basalt fibers (bottom).

PLANS FOR IMPLEMENTATION

The high mechanical performance/price ratio of continuous roving basalt fiber suggests a rather high potential for concrete and composite reinforcement applications in the U.S. market. The use of domestic basalt can significantly reduce the price/pound ratio for roving basalt fibers. The mechanical performance/price ratio of roving basalt composite as a reinforcement in concrete is the highest of the currently available fiber materials.

Exploring the feasibility of using domestic U.S. basalt mineral to manufacture continuous basalt fibers is necessary for cost-effective and successful implementation of the basalt fiber composite technology in the U.S.

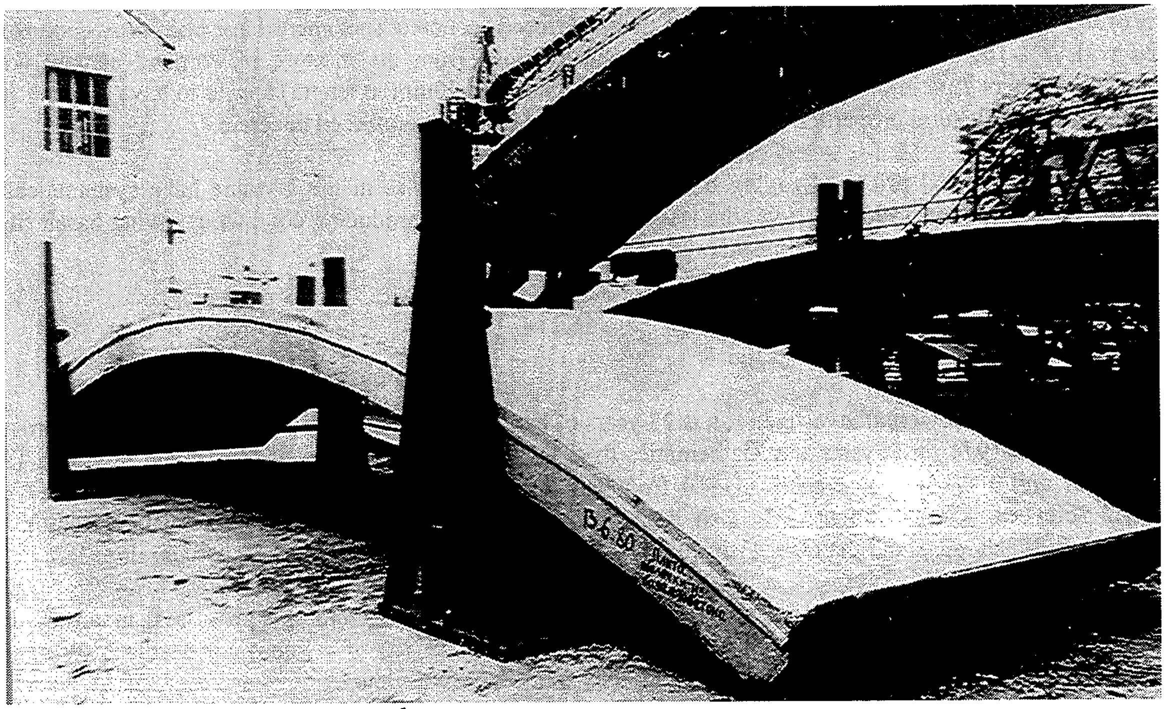

FIGURE 8 Basalt fiber-reinforced structure (18m length, 3m width, 0.04 m thickness) for use as core of agricultural buildings.

BASALT FIBER MARKET

The world market for basalt fiber is believed to be a multi-billion dollar market. Unfortunately, the commercial price of continuous roving basalt fiber and composite containing roving basalt cannot be precisely defined because it is currently manufactured on an industrial scale only in the Ukraine. The economic situation in the Ukraine is very unstable at the current time and experience shows that the price of basalt fiber and fabric composite can change drastically in a short period of time. For example, between 1990 and 1996 the commercial price of roving basalt fibers increased from US $0.4-$0.5/kg to US $2.1-$2.9 /kg, and the price of basalt fabrics increased from US $1.5-$2.5/kg to US $5.0-$10.0/kg. The price of roving basalt fiber made from local (North America) basalt mineral is estimated to be about US $1.0/kg when produced on an industrial scale.

CONCLUSION

An adequate number of laboratory and bench-scale tests to evaluate the feasibility of using basalt fiber as concrete reinforcement have been performed and relative advantages evaluated.

Continuous basalt fibers, 7μm-15μm in diameter, exhibit exceptional mechanical characteristics (tensile strength, modulus) in combination with excellent flexibility and chemical stability in cement and alkaline media. The epoxy-bonded pultrusion basalt-fiber composite containing 80% fibers (9μm-15μm in diameter) provide mechanical characteristics superior to those of glass-fiber reinforced composites currently available in the U.S.

Under optimum conditions (resin, fiber content, fiber direction, dimension, etc.), standard basalt-fiber composite specimens containing roving RB12, produced by RTM, show tensile strengths and moduli of elasticity twice that of E-glass fiber composite. Basalt-fiber composite rod (rebar) could potentially replace steel bar in reinforced concrete, providing higher strength and durability in areas where corrosion is a problem.

Tests of the mechanical characteristics of basalt fiber-reinforced concrete specimens have been provided. Concrete reinforced with 7%-10% coarse basalt fiber and concrete extruded from the mixture of Portland cement with 3% continuous basalt fibers 7μm in diameter (chopped roving fibers 50mm-70mm in length) appear to have a higher level of strength, modulus and flexural properties than conventional and glass-fiber reinforced concrete.

Because the commercial prices of roving basalt fiber and basalt fabrics in the Ukraine have systematically and drastically increased between 1990 and 1996, the investigator recommends producing continuous roving basalt fiber and basalt fiber reinforced composite from domestic mineral in the U.S.

INVESTIGATOR PROFILE

Dr. Vladimir B. Brik, the principal investigator, has 25 years of experience in materials science and materials processing. He received a Ph.D. (1974) in Physics and Mathematics from the Institute for Physics of Metals and Research Training and Experience, and a Doctor of sciences (1990) from the Institute for Problem Materials Science of the National Academy of Sciences, Kiev, Ukraine. He also holds two MS degrees—one in Materials Science from the Kiev Polytechnic Institute, Ukraine, and the other in Applied Mathematics from Kiev State University, Ukraine.

Dr. Brik has conducted extensive research in areas such as materials technology processes, materials analysis techniques, and materials science. He is an Assistant Professor at the University of Wisconsin at Madison, Wisconsin. In 1993, Dr. Brik founded a corporation to facilitate technology transfer between the Ukraine and the U.S. A branch of the company was also incorporated in Kiev to identify materials and processes that could be candidates for use in the U.S.

Professor Jouse Pincheria from the Civil and Environmental Engineering Department at the University of Wisconsin, Madison, Wisconsin, and Professor Surenda Shah of the Northwestern University, Illinois, are serving as consultants to Dr. Brik on the materials evaluation tasks of the project.

Dr. V. Brik has published over 80 papers and a book, and has been awarded 10 patents.

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