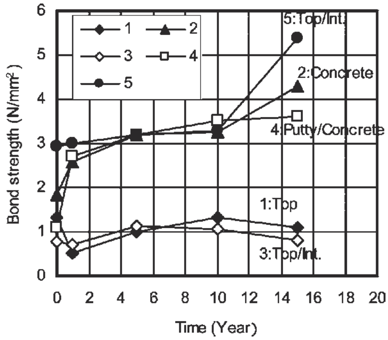

Fig. 7 Change in bond strength of surface coating materials with time

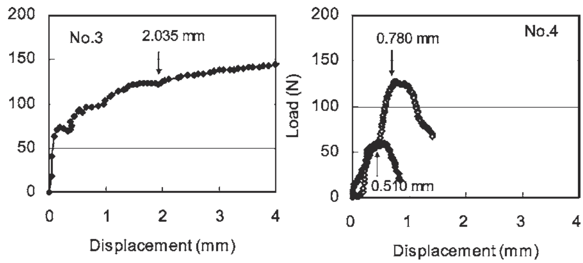

Fig. 8 Elongation performance

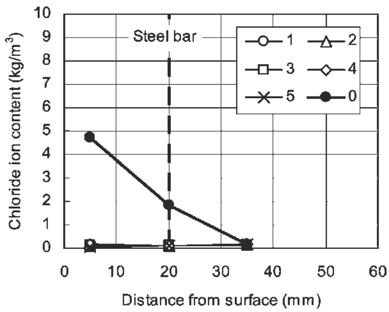

Fig.9 Chloride ion profiles in concrete

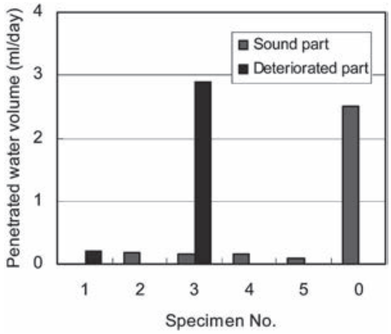

Fig. 10 Water permeability

A New Construction Material—Non-Corrosive Basalt Bar Reinforced Concrete

by V. Ramakrishnan and R.K. Panchalan

Synopsis: A desire to constantly upgrade the structural integrity and life of buildings and bridges has brought about new developments in the area of concrete technology. The use of corrosion free basalt fiber composite bars as reinforcement for concrete is one such innovation. This paper presents the results of an experimental investigation that was carried out for the first time anywhere in the world to evaluate the performance of concrete beams reinforced with basalt fiber composite bars. The experimentally determined ultimate moment capacities of basalt bar reinforced concrete beams were compared with the calculated ultimate moment capacities evaluated according to ACI-318 Building Code recommended design procedures. It was found that the actual ultimate moments of beams reinforced with *plain basalt bars* were much less than the calculated ultimate moments due to bar pullout failure. The *modified basalt bars*, which were provided with slots, corrugations and anchors, did not slip and the actual ultimate moments matched or exceeded the calculated moments. The bond strengths between the basalt bars (plain and modified) and concrete were also determined (ASTM C 234).

Keywords: basalt bars; basalt cables; basalt fiber reinforced concrete; basalt fibers; bending; bond; compression; impact; toughness; ultimate moment capacity

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INTRODUCTION

Basalt is the most common rock type in the earth's crust (the outer 10 to 50 km). Basaltic magma is commonly produced by direct melting of the earth's mantle, the region of the earth below the outer crust. The ocean floor is mostly made of basalt. Huge outpourings of lava called "flood basalts" are found on many continents. Basalt composes mainly of silica and alumina with lime, magnesium oxide and ferric oxide found in lesser percentages.

Basalt fibers are manufactured in a single-stage process by melting naturally occurring pure basalt rock. They are environmentally safe, non-toxic, non-corrosive, non-magnetic, possess high heat stability and insulating characteristics. The tensile strength of continuous basalt fibers 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^{o} C, basalt fibers maintain their strength for 1200 hours, whereas the glass fibers do so only for 200 hours (1,8).

Basalt composite bars are made by utilizing basalt fibers and a resin epoxy binder. They are non-corrosive and consist of 80% fibers. They have a tensile strength three times that of the steel bar normally used in building construction. Wherever corrosion problems exist, basalt fiber composite bars have the potential to replace steel in reinforced concrete. Currently there are many FRP bar companies that market their products. Most of them are made of E-glass fiber and thermosetting resin. However these bars lack sufficient durability under extreme environments. These bars are costly, and are also non-resistant to alkalis (2,3). Basalt bars do not possess these disadvantages and can be effectively used in various applications such as highway barriers, offshore structures and bridge decks.

The above mentioned advantages alone could warrant a sufficient argument for substitution of the basalt bars in place of steel on a large scale. Other advantages of the basalt bar are that its weight is one-third of the weight of steel and the thermal expansion coefficient is very close to that of concrete. The high mechanical performance/price ratio of basalt fiber composite bar, combined with corrosion resistance to alkaline attack, are further reasons for replacing steel in concrete by basalt fiber composite bars.

Basalt rock can be used to make not only basalt bars but also basalt fabrics, chopped basalt fiber strands, continuous basalt filament wires and basalt geo-mesh. Some of the potential applications of these basalt composites are: plastic polymer reinforcement, soil strengthening, bridges and highways, industrial floors, heat and sound insulation for residential and industrial buildings, bullet proof vests and retrofitting and rehabilitation of structures.

There is no published information available on the behavior of the basalt fiber composite bars and therefore there was a need for this research.

RESEARCH OBJECTIVES

Concrete Reinforced With Basalt Fiber Composite Bars

The main aim of this part of the investigation was to evaluate the performance of concrete beams reinforced with basalt fiber composite bars instead of the traditionally used steel bars. The following were the objectives of the investigation:

- To determine the ultimate failure load of the beams.
- To observe the bond strength between the bar and concrete.
- To study the modes of failure of the beams subjected to flexural loading.
- To compare the calculated and actual cracking and ultimate moments.

TEST RESULTS AND DISCUSSION

Concrete Reinforced With Basalt Composite Bars

Tension Test On Basalt Bars--Tension tests were done on 14mm and 6mm diameter basalt bars and also on a 6mm diameter cable. The ultimate tensile strengths were found to be 1458 MPa, 707.5 MPa and 308 MPa respectively. The average modulus of elasticity values for the bars and cables were 103.5 GPa and 110.4 GPa respectively. The bars experienced a brittle type of failure (Fig.1). The cable broke into two pieces without any splintering of the fibers, unlike both the bars (Fig. 2).

Phase I: Flexure Test on Plain Basalt Bar Reinforced Concrete Beams--
A total of six beams designed and cast in the Rama Materials lab, reinforced with basalt bars were tested. Research & Technology Inc, Madison, USA, supplied the basalt bars. The beams were designed using ACI-318 Building Code recommended design procedures. The beams that were designed and cast in the lab are referred to as BRC-A to F in the discussion, and the details of the beams are given in Table 1. The beams were tested in flexure after a 14-day curing period. The beams failed with a single crack instead of multiple cracking, which indicated slip of the reinforcing bars (Fig. 3a). All the actual ultimate moments were much less than the calculated ultimate moments due to bar pullout failure (Table 2). After the testing was done the beam edges were cut using a diamond tipped saw. The slip of the basalt bar was clearly visible at both the ends with a distinct mark left in the concrete at the original placing of the reinforcement (Fig. 3b). Two beams, BRC-E & F, were tested with increased development lengths. The spans for the beams were 0.75m and 0.9m respectively. Beam BRC-E failed in flexure, but at a higher load than beams BRC-A to D, due to the increased development length, whereas beam BRC-F failed suddenly with the breaking of the reinforcement. It was a sudden and brittle failure. The measured and calculated cracking moments are also compared in Table 2. A typical load-deflection curve of a *plain* basalt bar reinforced concrete beam is given in Fig. 7.

Phase II: Flexure Test on Concrete Beams Reinforced with Plain Basalt Bars and Discontinuous Basalt Fibers--Research & Technology Inc. supplied 8 beams. Five beams (BRC-1 to 5) were reinforced with basalt composite bars. Four of these beams were also 3-dimensionally reinforced with basalt fibers. Three beams (P1 to P3) were plain concrete (control) beams. The details of these beams are given in Table 3.

The beams were tested in bending. Beams BRC-1, 2, 3 & 5 had small amount of fibers, due to which, a ductile failure was observed. In beam BRC-4, there were no fibers; hence a brittle failure was observed. All three plain concrete beams failed instantaneously, at the appearance of the first crack. The failure was brittle and sudden, whereas all the beams reinforced with the basalt bars had a gradual failure after considerable amount of deflection. As expected, the addition of reinforcement, either in the form of small fibers or composite basalt bars converted the brittle failure into a ductile failure. The actual ultimate moments were very less when compared to the calculated ultimate moments of the beams due to slip of the bars. But the actual cracking moment was more than the calculated cracking moment due to the addition of basalt fibers. Table 4 shows the actual and calculated ultimate moments of the beams. The results indicate slip of the reinforcing bars.

Phase III: Bond Test on Basalt Bars and Cables (ASTM C 234)--The results obtained from Phase I and II revealed that the actual ultimate moments of basalt bar reinforced concrete beams were less than the theoretically calculated ultimate moments. This was due to bond failure between bars and concrete. To avoid this type of failure the Principal author and Research & Technology Inc, had developed basalt cables with corrugations, rods with slots, barriers and anchors (Fig. 4), for improving the bond between the bars and the concrete. The primary task in this phase was to study the bond between modified basalt bars and concrete. There are several tests that can determine the bond quality of the reinforcing element. One of these is the pullout test (Fig. 5a). In this test, the concrete is subjected to compression and the reinforcing bar is subjected to tension, and both the bar and the surrounding concrete are subjected to the same stress. The pull out test was done according to ASTM C234 91-a(5).

First the plain basalt bar reinforced specimens were tested for the bond strength at an age of 21 days. As the load was applied the plain basalt bars started slipping and there was no bond between the reinforcement and the concrete. It was also found that the grip of the testing machine was slipping i.e., it was not holding the bar properly as the basalt fibers in the bar were crushed and powdered. There was also a slip in the anchoring end leaving a scratch mark on the bar. Therefore, the anchorage was done using a chuck, which held the specimen in its place at the anchoring end. The specimen was then tested and the plain basalt bar slipped and the marks on concrete were distinctly seen on the bar (Fig. 5b).

Then the 4-slot basalt bar was tested with both the lower and upper horizontal position of the reinforcement. The 4-slot basalt bar did not slip and hence there was no bond failure. But the basalt bar itself failed due to tension failure (Fig. 5c). The failure was brittle. The 8-slot basalt bar also failed in a similar manner to that of 4-slot basalt bar. The 2mm cables were also tested for the bond strength. At first a single cable was tested for the bond strength. The single cable failed in tension and there was no bond failure. The failure of the cable was brittle in nature. Similarly two cables were twisted together and were also tested for bond. The results were similar to that of the single cable test. The cables failed due to tension and not due to lack of bond. When three cables twisted together were tested, the failure mode was the same as described above for the single and two cables. All the modified basalt bars and cables except the plain basalt bar had good bond with concrete. The failure was due to the tensile failure of the bars and the cables and not due to the bond slip.

Phase IV: Determination of Cracking and Ultimate Loads for Extremely Under-Reinforced Beams--Two extremely under-reinforced beams (152 x 229 x 1118) mm and (229 x 457 x 1321) mm, reinforced with *modified* basalt bars were tested to see whether adequate bond had developed between the bar and concrete. The reinforcement details of the beams BRC-1 and 2 are given in Table 5.

The beams were designed and cast in the lab, and are referred to as BRC-1 and BRC-2. The average cylinder compressive strength of the mix was 47 MPa. The reinforcement provided for one beam was less than the minimum required according to ACI code 318. Another beam was provided with the ACI recommended minimum reinforcement. Both beams were tested in flexure after the 28-day curing period. A development length of 203 mm was provided for both beams. The length between the two-point loading was 305 mm. Beam BRC-1 was reinforced with basalt cables 4.0mm. The first crack occurred at the calculated cracking moment (Table 6). After first crack, the beam failed suddenly breaking into two pieces, because the beam was extremely under reinforced. The bar broke without slipping, which indicated that there was good bond between the bar and the concrete (Fig. 6).

Beam BRC-2 was under reinforced with the minimum ACI 318 recommended reinforcement. The beam first had a flexural crack at 85% of the calculated cracking moment (Table 6), but ultimately the beam failed in shear. This was attributed to the fact that the beam was very deep. Even though the beam failed in shear, it took 88% of the calculated ultimate moment (Table 6). The beam did not fail due to slip of the bar, which indicated that there was a good bond between the 4-slot bar and the concrete. If the beam had failed in flexure rather than in shear the beam would have definitely carried more ultimate moment than the calculated moment. The overall test results indicated that there was sufficient bond strength and the bars did not slip even after the ultimate load was reached. The measured and calculated ultimate and cracking moments are compared in Table 6. The tests indicated that it is possible to make concrete beams reinforced with basalt composite bars. This testing gave adequate information to plan for testing other beams.

Phase V: To Determine Cracking And Ultimate Loads For Five Under-Reinforced Beams--A total of five beams of dimensions, 127 x 203 x 1346 mm , 127 x 203 x 1626 mm, 76 x 102 x 1143 mm, 152 x 254 x 1329 mm [Fe-Mn-Ni anchors], and 152 x 254 x 1329 mm [Ti-Ni anchors], reinforced with basalt bars were tested. Research & Technology Corp supplied the bars and the five beams were designed and cast in the Rama Materials Laboratory at SDSM&T. The beams referred to as BRC-3 to BRC-7 in the discussion, were designed according to ACI-318 Building Code recommended design procedures. The reinforcement details of the beams BRC-3 to 7 are given in Table 5. All the beams were designed as under-reinforced beams with the normal range used in construction. The average cylinder compressive strength of the concrete was 34.2 MPa. All beams were tested in flexure after a 28-day curing period. A development length of 203 mm was provided for all beams. The distance between the two-point loading was 152 mm for all beams.

Beam BRC-3 was designed as a lightly under reinforced beam with one corrugated basalt rod 9.0 mm. The first crack occurred at 95% of the calculated cracking moment (Table 6). After first crack the beam took **2.7 times more** moment than the cracking moment (Table 6) indicating very good bond strength between the bar and the concrete. The beam failed at 98% of the calculated ultimate moment (Table 6). The beam failed primarily in flexure and secondarily in shear.

Beam BRC-4 was also under reinforced. Two cables of 1524 mm length and 8 mm diameter were used as reinforcing bars. These cables were made in the laboratory by twisting three individual basalt wires into one. The beam first had a flexural crack at 76% of the calculated cracking moment (Table 6). After first crack the beam took **4.9 times more** moment than the cracking moment (Table 6) indicating very good bond strength between the bar and the concrete. The beam failed at 97% of the calculated ultimate moment (Table 6). The beam failed purely in flexure. Overall the performance of the beam was good and the wires split partially at failure indicating good bond strength. The cables did not slip even after the ultimate load was reached.

Beam BRC-5 was made of three basalt cables of 1041 mm length and 3.0 mm diameter (Table 5). The beam was under-reinforced. The cables were supplied by the manufacturer, unlike the one used in beam BRC-4 which was made in the laboratory. The beam first had a flexural crack at 95% of the calculated cracking moment (Table 6). After first crack the beam took **2.4 times more** moment (less than the other beams because it was under-reinforced, and the tensile strength of the bar was also less) than the cracking moment (Table 6) indicating very good bond strength between the bar and the concrete. The beam took **49% more** than the calculated ultimate moment (Table 6). The beam failed primarily in flexure and secondarily in shear. Overall the performance of the beam was good and the cables completely fractured at failure, indicating good bond strength. The cables did not slip even after the ultimate load was reached.

Beam BRC-6 was made with two basalt bars of 1219 mm length and 10 mm diameter (Table 5). The beam was lightly under-reinforced. The rods were supplied by the manufacturer and were provided with 1 Fe-Mn-Ni anchors (smart alloys) on each end of the bar to prevent slip. The actual cracking moment