BASALT FRP MINIBAR REINFORCED CONCRETE

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Abstract

MiniBar is a new non-corrosive structural macro fibre made from basalt fibre reinforced polymer (BFRP) material that has high tensile strength and many other attractive physical and mechanical properties. When added to wet concrete during mixing, the resulting MiniBar fibre reinforced concrete (MRC) in hardened condition has high flexural tensile strength and post-cracking residual strength. This paper describes the results of a study conducted to establish the performance of MiniBar reinforced concrete. The study included (i) fresh concrete properties (ii) hardened concrete properties such as compressive strength, flexural tensile strength (FTS), and average residual strength (ARS). MiniBar at dosages ranging from 0.35% to 4% by volume, which is 6.3 kg/m^3 to 72 kg/m^3 by weight, was mixed with concrete without any difficulty. There was no bleeding, balling or segregation in the concrete, demonstrating the ease with which large dosages of MiniBar can be mixed with wet concrete. Handling, placing, consolidating and finishing of concrete was possible without any special measures. Equations were derived to represent the variation of FTS with MiniBar dosage. Practical applications where MiniBar reinforced concrete was successfully used or is planned to be used in near future are presented.

Keywords: Basalt fibre, MiniBar reinforced concrete, average residual strength, flexural tensile strength, applications

1. Introduction

The advantages of the use of fibre in concrete are well known. Fibre will modify the cracking mechanism from macro cracking to micro cracking. Crack widths are reduced, and the ultimate tensile cracking strain capacity of the concrete is increased. The mechanical bond between the embedded fibre and binder matrix provides for redistribution of stresses. Additionally, the ability to modify cracking mode results in quantifiable

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benefits. Reduced micro cracking leads to reduced permeability and increased surface abrasion resistance, impact resistance and fatigue strength [1]. There are many different metallic and non-metallic micro or macro fibres available for use in fibre reinforced concrete. A new type of macro fibre known as MiniBars was recently made from basalt fibre and is gaining acceptance in the industry. This paper presents some of the salient features of MiniBar reinforced concrete (MRC).

1.1 Basalt Fibre

Fibre reinforced polymer (FRP) composite bars are currently being used as internal or near surface mounted reinforcement of concrete members in many parts of the world. One key element of FRP systems is the fibre used to make the FRP. Glass, carbon or aramid fibre has been traditionally used to make FRP reinforcing bars in the recent times. Basalt fibre is currently gaining popularity for FRP applications [2-5]. Basalt (solidified volcanic lava) is known for its resistance to high temperatures, strength and durability. Basalt fibre is extruded from molten basalt rock at diameters generally between 13 μm and 20 μm. Basalt fibre products are available from various sources around the world mainly from Russia, Ukraine, and China. BFRP fibre products are available in various forms such as bars, mesh, cages, spirals, fabric, and chopped fibre, and are useful as internal or external reinforcement of concrete structures. ReforceTech AS, Norway [6] is manufacturing basalt FRP reinforcing bars for internal reinforcing of concrete using an automated wet-lay up process [3,4].

1.2 Basalt MiniBar Fibre

Small diameters of naked basalt fibre make it hard to mix in wet concrete even at low dosages because of large surface area per kg of fibre. Recent trials with naked basalt fibre exhibited very low workability proving that naked basalt fibre may only serve to control plastic shrinkage of concrete. Recent flexural tensile strength (FTS) and average residual strength (ARS) tests also revealed that basalt fibre reinforced concrete with naked fibre has practically no improved flexural tensile strength due to the addition of fibre. The post-cracking residual strength was non-existent. Naked basalt fibre was also found to be not stiff enough to mix with wet concrete in large dosages.

To overcome the deficiencies of fibre reinforced concrete with naked basalt fibre, ReforceTech developed a novel basalt fibre based product called "MiniBars" that enables mixing of concrete with sufficiently large volumes of fibres without impairing the workability. MiniBars are like basalt fibre reinforced polymer (FRP) reinforcing bars but with an average diameter of about 0.66 mm and cut to a length of about 40 to 45 mm as seen in Fig.1.

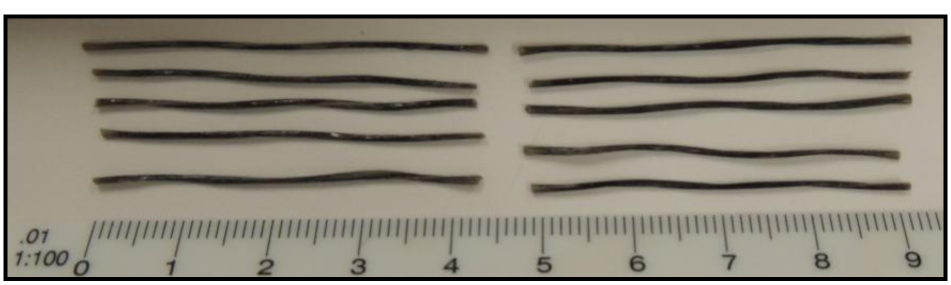

Fig. 1: MiniBar Geometry

1.2 Main Characteristics of MiniBars

The intention of developing MiniBars was to provide a macro fibre that would enhance the structural performance of concrete. Stiffer fibre also means it is possible to enable the concrete to be designed for loadbearing capacity with high flexural tensile strength and average residual strength. With a density of 1.9 gm/cc, Minibar has a density closest to concrete than the density of steel or synthetic fibre. This gives MiniBar an advantage over other fibres during mixing of concrete. Some of the main characteristics of MiniBar reinforced concrete that were envisioned at the onset of this development were:

- Tensile strength in excess of 15 MPa
- Average residual strengths (post-cracking strength) up to 17 MPa
- Elimination of reinforcing steel including wire welded mesh and steel rebars in select applications
- Zero corrosion and stronger concrete means thinner elements are possible
- The selection of the raw materials to eliminate the effects on alkaline attack on the MiniBar
- Improved usability with the density similar to the concrete. This has several advantages such as random placement, even distribution, easy mixing, good flowability and pumping, no floating or sinking, possibility of high volume fractions and high fibre count

The objective of this study was to evaluate the performance of MiniBar reinforced concrete, and to establish flexural and residual strength of such concrete to the desired level so as to implement in demonstration projects.

2. Performance Evaluation

Performance evaluation of MiniBar reinforced concrete in wet and hardened conditions is currently being conducted by several universities and our industry partners including (i) the University of Akron, USA (ii) NTNU - Trondheim, Norway under COIN program, (iii) Veidekke and (iv) The University of Florida and Florida Department of Transportation. This paper only outlines the following two aspects of research performed at the University of Akron:

(a) Constructability issues including observations on ease of mixing, handling, placing, consolidating and finishing, and maximum dosage considerations.
(b) Hardened concrete properties such as compressive strength, flexural tensile strength (FTS), and average residual strength (ARS).

2.1 Concrete Mixes

Concrete mixes with maximum aggregate size of 20 mm were used in this study. The MiniBar dosage ranged from 0.35% to 4% by volume, which translates to 6.3 to 72 kg/m^3 by weight.

The concrete used in the evaluation was made with Type I normal Portland cement conforming to ASTM C150. The coarse aggregate used in the tests was crushed limestone with a maximum size of 20 mm (~0.75 inch). The fine aggregate used in the tests was natural sand with absorption of about 1.5%. The high range water reducer used in the project was Axim ALLEGRO 122 with recommended dosage of 260 to 780 ml per 100 kg of cement. Typical mix proportions are shown in Table 1.

Tab. 1: Mix Proportions of Normal Concrete with 20 mm (0.75") Maximum Size Aggregate

Cement lb/yd^3 (kg/m^3)	Water lb/yd^3 (kg/m^3)	Fine Aggregate lb/yd^3 (kg/m^3)	Coarse Aggregate lb/yd^3 (kg/m^3)	Water Cement Ratio
675 (400)	275 (163)	1424 (845)	1424 (845)	0.407

2.2 Fresh Concrete

Physical inspection of wet concrete indicated that satisfactory workability was achieved with uniform distribution within the concrete, without balling or segregation even with the addition of MiniBar at 2% dosage by volume. The mixes obtained in this project demonstrated that it is possible, without any special precaution, to mix, handle, place, consolidate, and finish wet concrete mixed with MiniBar. Some amount of slump loss was observed. However, suitable water reducing admixtures (WRA) were used to achieve large slumps in the range of 125 to 200 mm. These mixes formed the basis for the demonstration projects described later in this paper.

2.3 Hardened Concrete Tests

2.3.1 Compressive Strength

The compressive strength of MiniBar reinforced concrete (MRC) was determined using 4 inch (101.6 mm) diameter x 8 inch (203.2 mm) long cylinders. The addition of MiniBar resulted in a ductile failure mode and prevented an explosive failure demonstrating good absorption of energy and retention of concrete integrity.

2.3.2 Flexural Tensile Strength (Modulus of Rupture)

Flexural tensile strength (FTS) was determined according to ASTM C78-07 using beam specimens. A plot of the FTS values obtained from the current tests is shown in Fig. 2. The FTS is determined from the maximum load that beam specimens 4 inch (101 mm) x 4 inch (101 mm) can carry over a span of 12 inches (305 mm) in a four point loading configuration (third point loading). The failure mode of test beams revealed that MiniBar bonded well with the surrounding concrete with little evidence of fibre pull-out. Fig. 3 shows one side of a typical broken beam which was forced open after failure to separate the beam into two pieces.

2.3.3 ACI 318-11 Equation for Flexural Tensile Strength (FTS)

Modulus of rupture of plain concrete (FTS) can be predicted with reasonable confidence. It normally ranges from $0.66\sqrt{f_c^{'}}$ to $0.83\sqrt{f_c^{'}}$, where f'_c is the specified compressive strength of concrete in MPa. ACI 318-11 [7] in Section 9.5.2.3 recommends the use of the following equation for modulus of rupture (FTS):

$f_r = 0.62\sqrt{f_c'}$ for normal weight concrete with f'_c in MPa (1)

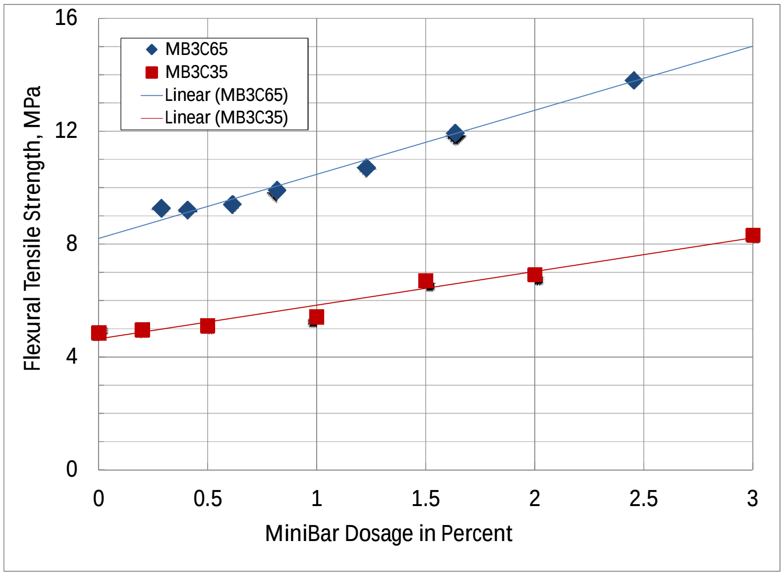

Fig. 2: Flexural Tensile Strength of MiniBar Reinforced Concrete

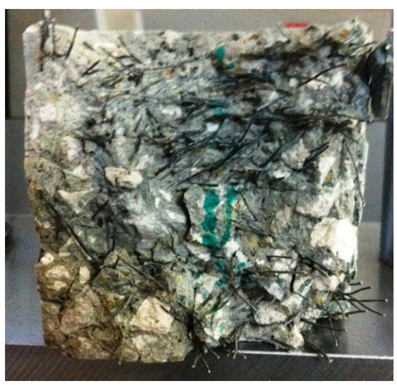

Fig. 3: Typical Failure Surface After Flexural Test

A similar flexural tensile strength equation is envisaged for MiniBar reinforced concrete. The following equation was found to be suitable for MiniBar reinforced concrete with a compressive strength of at least 62 MPa and maximum aggregate size of 20 mm:

$f_r = (0.62 + 0.62\, V_f^{0.45})\sqrt{f_c'} \leq 2.07\sqrt{f_c'}$ with $f_c' \geq 62$ MPa (2)

where, V_f is MiniBar dosage in percent by volume within the range of 0.35% to 4%. Equations (1) and (2) correspond to nominal flexural tensile strength. Suitable factors (strength reduction factors in ACI 318-11 or partial safety factors in European codes) must be included with the nominal strength to obtain the design flexural tensile strength to compare with the required strength (factored load effects). These design allowables must be used consistent with the design philosophy of the local building codes, design codes and standards.

The flexural tensile strengths of MiniBar reinforced concrete with concrete compressive strength less than 62 MPa [8] is less than what was determined from Eq. (2). Tests are currently underway to determine the FTS of lower strength concrete (some of the data points are shown in Fig. 2), but the following equations were suggested in the interim for preliminary design of demonstration projects:

$$f_r = (0.62 + 0.2\,V_f^{0.45})\sqrt{f_c'} \leq 0.82\sqrt{f_c'} \quad \text{with} \quad 27.5\text{ MPa} \leq f_c' \leq 48\text{ MPa} \tag{6}$$

$$f_r = (0.62 + 0.3\,V_f^{0.45})\sqrt{f_c'} \leq 0.92\sqrt{f_c'} \quad \text{with} \quad 48\text{ MPa} < f_c' < 62\text{ MPa}$$

where, V_f is MiniBar dosage in percent by volume within the range up to 1.5%.

2.3.4 Average Residual Strength (ARS) Tests

Average residual strength (ARS) of fibre reinforced concrete is one the major indicators of the post-cracking performance which is an indirect measure of flexural toughness of fibre reinforced concrete. The average residual strengths were obtained using ASTM C1399. The values obtained from the tests performed in this study are plotted in Fig. 4. This figure shows distinct increase in ARS values with increased dosage of MiniBar at an approximate rate of 4 MPa per 1% increase in MiniBar dosage by volume (V_f) for concrete strength of about 62 MPa.

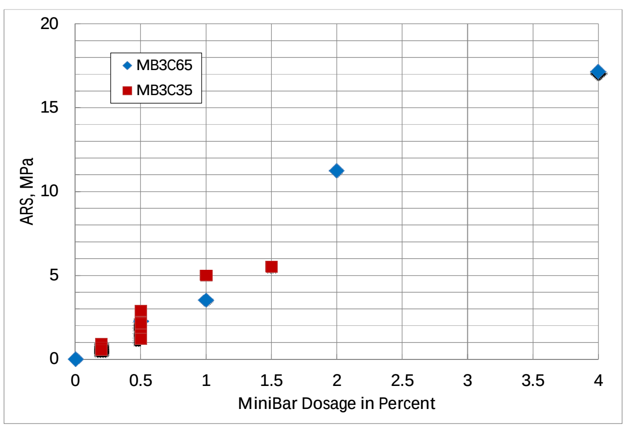

Fig. 4: Average Residual Strength

2.3.5 MiniBar Pull-out Tests Conducted at NTNU

MiniBar pull-out tests were conducted at the Norwegian University of Science and Technology [9]. Several designs produced by ReforceTech were tested to determine the pull-out strength of MiniBars for embedment lengths of 14 mm or 7 mm. The test results revealed that an average axial tensile stress of 905 MPa was developed by individual MiniBar for 14 mm embedment length.

3. Case Studies

Several practical applications have been successfully demonstrated in Europe showing the advantage of MiniBar reinforced concrete. Three such case studies are described in this paper.

3.1 Pontoons, Inner Walls and Façade Walls

Examples of successful implementation of MiniBar are pontoons, inner walls and façade walls (Fig. 5). Tab. 2 lists cost savings for various scenarios considered. The MiniBars have been found to be competitive for elimination of wire welded mesh for all three examples. The material cost savings ranges from 20 to 50%. Moreover, the opportunity to redesign the concrete elements without steel means thinner wall sections can be used to enable lighter construction. Further advantages such as faster production are also realized.

Fig. 5: Pontoon (Top), Façade Wall (Bottom Left) and Inner Wall (Bottom Right)

3.2 Veidekke Regional Head Office

NTNU is a part of COIN, a collaborative research group to achieve flexural tensile strength of 15 MPa in normal concrete. A test wall section was made initially as shown in Fig. 6 to verify the constructibility of MiniBar reinforced concrete in field applications. The final construction of walls of Veidekke regional head office was successfully completed. The actual walls were placed with a concrete pump. The finished wall is shown in the figure.

The concrete used was a self compacting concrete. The walls were poured in a single casting 11 Meters high by 33 meters long with no steel reinforcement or nets.

Tab. 2: Cost Advantages due to MiniBar Usage

Advantage	**Pontoon A BFRP**	**Pontoon B BFRP and MiniBars**	**Façade wall G3 MiniBars**
Reduced weight due to less cover layer	40% less weight, enables lower costs through value chain	40% less weight, enables lower costs through value chain	Thickness can be reduced but cost effective even without reduction
Reduced labor	From 2 days to 4 hours	From 2 days to 1 hour	Labor reduced but cost effective even without
Lower Cost of finished concrete application	Same cost at factory 5% saving installed	Lower Cost at Factory	Simply less cost than the steel nets 26% lower costs overall
Longer Life	Yes	Yes	Yes


Fig. 6: Exterior Wall Construction

3.3 Other Applications

MiniBars enable higher structural strength elements with high durability and light weight that are free of corrosion. Several other applications of MiniBar reinforced concrete are envisaged in the near future. Following are some of these applications being considered: shotcrete, bridge decks, pavements, double-Tee precast beams, roofing tiles, balconies, and agricultural Products. Other applications currently being planned are: inner walls (precast), bridge beams, sound, barrier or block walls, power or barrier poles.

4. Concluding Comments

MiniBar is a new non-corrosive structural macro fibre made from basalt fibre reinforced polymer (BFRP) with high tensile strength and small dimensions (0.66 mm diameter x 40 to 45 mm length). When added to wet concrete during mixing, the resulting MiniBar fibre reinforced concrete in hardened condition has significantly improved flexural tensile strength and high post-cracking residual strength.

MiniBar reinforced concrete mixes were made in the materials laboratory of The University of Akron. Several sets of test specimens were made with normal mix concrete with a maximum coarse aggregate size of 20 mm (0.75 inch) with several MiniBar dosages.

No major problem was faced in mixing MiniBar at dosages ranging from 0.35% to 4% by volume (6.3 kg/m^3 to 72 kg/m^3 by weight). There was no bleeding, balling or segregation in the concrete, demonstrating the ease with which large dosages of MiniBar can be mixed with wet concrete. The concrete was handled, placed, consolidated and finished normally without additional precautions. Good workability was achieved with acceptable slump.

Flexural tensile strengths (FTS) of MiniBar reinforced concrete were determined using ASTM C78-07 tests. FTS values were found to range from 8.9 Mpa up to 15 MPa for MiniBar dosage of 0.35% to 4% by volume (V_f) for 62 MPa concrete cylinder compressive strength. Equations were developed from the test results to represent mean FTS values.

The average residual strengths (ARS) were determined using ASTM C1399-10. The ARS determined from the tests ranged from 1.95 MPa to 17 MPa for MiniBar dosage of 0.35% to 4% by volume (V_f) for concrete strength of 62 MPa. Both the FTS and ARS values exceeded the expectations and the targets set initially.

A series of pull-out tests was conducted at NTNU for different MiniBar trials and for two different embedment lengths. The test results indicated that a 14 mm embedment of MiniBar in concrete was adequate to develop an average axial stress of 905 MPa.

Demonstration projects completed so far indicate excellent potential for the implementation of MiniBar reinforced concrete. Examples such as the external walls of Veidesekke head office building are presented in this paper. The constructibility of MiniBar reinforced concrete was satisfactory with good pumpability and consolidation. The desired exterior finish was obtained to the satisfaction of the owners. MiniBar reinforced concrete was demonstrated to be a cost effective alternative in this application and a few other applications.

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