Failure Mode of Basalt Fibre Reinforced Concrete Beams

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Abstract. The experimental tests were carried out to assess the failure model of basalt fibre reinforced concrete beams. Experimental research was focused on observing the behavior of the tested elements depending on the amount of shear reinforcement and the content of fibres. Model two-span beams with a cross-section of 80x180 mm and a length of 2000 mm were tested. The beams had a varied stirrup spacing. The following amounts of basalt fibres in concrete were used: 2.5 kg/m³ and 5.0 kg/m³. At the same time, the concrete beams without fibres were examined. The beams were loaded in a five-point bending test until they were destroyed. Shear or bending capacity of the element was determined. Fibre reinforced concrete beams were not destroyed rapidly. Failure mode of beams varied in dependence on the amount of shear reinforcement and fibre content in concrete. Larger number of diagonal cracks with a smaller width were observed in fibre reinforced concrete beams. Failure of beams of concrete without fibres was rapid with a characteristic brittle cracking. Basalt fibres revealed the ability to transfer significant shear stress after cracking in comparison to plain concrete.

1. Introduction
The failure mode of reinforced concrete elements due to transverse forces results from a complicated mechanism, related to the value and type of load, dimensions and geometric shape of the cross-section and material properties of concrete and reinforcement [1,2]. The main purpose of the fibres in concrete is to provide control of cracking and to increase the fracture toughness of the brittle matrix through bridging action during both micro and macrocracking of the matrix. Debonding, sliding and pulling-out of the fibres are the local mechanisms that control the bridging action [3-5]. The resultant composite concrete can have considerable ductility, often termed “toughness”. However, the ductility characteristic is dependent on the fibre type and dosage, tensile strength and anchorage mechanism.

Basalt fibres are obtained from basalt rocks through melting and drawing process. The basalt ore are formed by the rock magma. During the rock magma forming process, associated with high temperature, high pressure and ambient pressure drop, the basalt ore is formed, which has extremely high chemical stability and thermal stability [6, 7]. Therefore, the basalt fibre has inherited the basalt ore structure and performance characteristics, such as outstanding thermal stability, anti-corrosive performance, ideal heat insulation, sound absorption, and low moisture absorption. In addition, this fibre exhibits high strength and high module performance. The basalt fibres do not need any other additives, which make additional advantage in cost [8]. According to Sim et al. [9] the fibres have better tensile strength than the E-glass fibres, greater failure strain than the carbon fibres as well as good resistance to chemical attack, impact load and fire. These features, combined with lower cost, could make basalt fibres a suitable replacement for steel, glass, and carbon fibres in many applications [10]. However, previous studies on the use of basalt fibres in concrete are limited. Sim et al. [9]
investigated the properties of concrete containing continuous basalt fibre (produced from volcanic rock). Limited research has studied the effect of short basalt fibre on the mechanical properties of geopolymeric concrete [11-13]. Kabay [6] reported that the addition of short basalt fibres resulted in decrease in compressive strength and at the same time the enhancement of fracture energy and reduction of abrasive wear of concrete. Detailed discussion of basalt fibres influence on the fracture mechanics parameters can be found in [14].

The fibres can be used to improve the behavior of structure at the ultimate limit state, or to improve service conditions at the serviceability limit state. In the ultimate limit state, the addition of fibres can partially or completely replace the traditional reinforcement for tensile or shear [15]. However, the full potential of fibre reinforced concrete is still not fully exploited in practice. This is mainly due to a lack of specific rules for the type of concrete in building codes. The existing rules for conventional concrete can hardly be adopted for fibre reinforced concrete that is markedly non-linear since fibres start working after cracking of the concrete matrix [5, 13, 16, 17]. Considering potential applicability of basalt fibres, further experimental studies should be conducted on the use of this type of fibres in concrete for reinforced structures. The recognition of the failure mode of concrete elements with fibres is crucial for the development of design methods that take the presence of dispersed reinforcement in concrete into account.

In order to evaluate the failure mode of concrete beam with basalt fibres, experimental studies were carried out, in which the emphasis was placed on analysing the behavior of tested elements depending on the amount of shear reinforcement and the fibre content.

2. Experimental programme

2.1. Materials

The geometry and properties of basalt fibres were presented in Table 1. The basalt fibres were added to concrete at two contents of 2.5 and 5.0 kg/m$^3$, which gave volume fractions 0.095% and 0.19%, respectively (the content of basalt fibres suggested by manufacturer is 2.0 kg/m$^3$). The effect of fibres on concrete properties was referred to the results obtained for the reference concrete without fibres.

| Property          | Basalt fibres |
|-------------------|---------------|
| Fibre shape       | straight      |
| Length (mm)       | 50            |
| Diameter (mm)     | 0.02          |
| Tensile strength (MPa) | 1680        |
| Elastic modulus (GPa) | 89             |
| Density (kg/m$^3$) | 2660          |

Portland cement CEM I 42.5R was used to make concrete for model elements. The cement content was 320 kg/m$^3$. A mixture of sand and gravel with grain size up to 4 mm was used as aggregate. The maximum size of aggregate was limited to reduce its influence on toughening mechanism and to provide the homogenous fibre distribution in concrete. Table 2 gives the mix proportions for reference concrete. The modified polycarboxylate and phosphonate based super-plasticizer (1% related to cement mass) was used to minimize fibre clumping and enhance fibre dispersion in concrete.

| w/c | Cement [kg/m$^3$] | Water [kg/m$^3$] | Aggregate 0.125-2 mm [kg/m$^3$] | Aggregate 2-4 mm [kg/m$^3$] | Superplasticizer [kg/m$^3$] |
|-----|-------------------|------------------|---------------------------------|-----------------------------|----------------------------|
| 0.5 | 320               | 160              | 1329                            | 626                         | 3.2                        |
2.2. Concrete preparation and testing
The dry aggregate was mixed with basalt fibres followed by cement. The materials were dry mixed for 2 min before adding the water with super-plasticizer. Mixing continued for a further 4 min. The time of mixing was considered sufficient for the proper dispersion of fibres in the mix without causing a “balling” effect [3]. The specimens were vibrated in moulds and then stored under polyethylene cover for 24 hours.

The strength properties of concretes with fibres and reference concretes were determined. The test of compressive strength was carried out in accordance with PN-EN 12390-3 [18] using cubic samples with 100 mm side size. The flexural strength was determined on specimens of size 100×100×400 mm according to PN-EN 12390-5 [19]. The elastic modulus was determined in accordance with PN-EN 12390-13 [20] using cylindrical samples with a diameter of 150 mm and a depth of 300 mm. Each series consisted of 3 samples.

2.3. Model beam preparation and test method
Five series of two-span model beams with cross-sectional dimensions of 80×180 mm and length of 2000 mm were made, each containing 5 elements with various dosage of basalt fibre additions and with different stirrup spacing (Figure 1).

![Figure 1. Schema of reinforcement in beams tested](image)

The main reinforcement bars and stirrups were made of RB500 steel. The amount of main longitudinal reinforcement and shear reinforcement were calculated in accordance with PN-EN 1992-1-1 [21], assuming a load in the form of concentrated force in the middle of each span. In each test series, the top and bottom reinforcements were identical and consisted of two φ12 mm bars. The stirrups with diameter of φ6 mm were used. The A-I series was made with stirrups spacing designed in
accordance with the standard [21], then for each series the stirrups spacing was reduced. No stirrups were used in the A-V series. The shear span-depth ratio $a_d/d$ was equal to 2.7.

The beams were loaded in a five-point system. During the tests, the shear capacity and/or bending capacity of the beam were determined. The peak load and support reactions were also measured. Figure 2 shows the model beam during test.

![Figure 2. Model beam during test](image)

3. Test results of concrete properties

Table 3 presents the results of strength properties tests: compressive strength $f_{cm}$, flexural strength $f_{ctm}$ and modulus of elasticity $E_s$ in dependence on the fibre content in concrete ($V_f$) and changes in parameter mean values in relation to the reference concrete F0.

| Seria | $V_f$ [kg/m$^3$] | $f_{cm}$ [MPa] | $\Delta f_{cm}$ [%] | $f_{ctm}$ [MPa] | $\Delta f_{ctm}$ [%] | $E_s$ [GPa] | $\Delta E_s$ [%] |
|-------|-----------------|----------------|---------------------|----------------|---------------------|------------|----------------|
| F0    | 0.0             | 38.95          | -                   | 3.56           | -                   | 33.10      | -              |
| FB2.5 | 2.5             | 40.80          | 4.76                | 3.92           | 10.06               | 33.83      | 2.23           |
| FB5.0 | 5.0             | 39.33          | 0.99                | 4.14           | 16.39               | 35.91      | 8.51           |

The analysis of test results revealed that the addition of basalt fibres had no significant influence on the compressive strength $f_{cm}$ and the modulus of elasticity $E_s$. The increase in flexural strength $\Delta f_{ctm}$ for concrete with 5.0 kg/m$^3$ of fibres achieved 16%.

4. Beam test results and discussion

4.1. Destructive load

Table 3 shows the values of destructive load $P_{cr}$ and their increase $\Delta P_{cr}$ in comparison to the values of destructive loads for the reference beams (without fibres). In the case of concrete beams with basalt fibres, the increase in peak load ranged from 14% to 54%.
Table 4. Mean values of destructive load $P_{cr}$ and their increase $\Delta P_{cr}$ in particular series with basalt fibres

| Seria   | $P_{cr}$ (kN) | $P_{cr}$ (kN) | $\Delta P_{cr}$ (%) | $P_{cr}$ (kN) | $\Delta P_{cr}$ (%) |
|---------|---------------|---------------|---------------------|---------------|---------------------|
| A-I     | A-I-F0 80.6   | A-I-FB2.5 95.3| 18                  | A-I-FB5.0 106.7| 32                  |
| A-II    | A-II-F0 57.8  | A-II-FB2.5 70.2| 21                  | A-II-FB5.0 75.3| 30                  |
| A-III   | A-III-F0 60.7 | A-III-FB2.5 69.3| 14                  | A-III-FB5.0 93.5| 54                  |
| A-IV    | A-IV-F0 29.9  | A-IV-FB2.5 33.5| 12                  | A-IV-FB5.0 44.1| 47                  |
| A-V     | A-V-F0 33.1   | A-V-FB2.5 37.9| 15                  | A-V-FB5.0 49.4| 49                  |

The maximum load increase was observed for A-III-FB5.0 series beams. Comparing the value of the destructive load in the A-I-F0 series with a typical longitudinal and shear reinforcement in accordance with the guidelines [19] with the force value in series A-III-FB5.0, it can be concluded that reducing the number of stirrups by half while using concrete with the addition of basalt fibres in 5.0 kg/m$^3$ is enough to achieve required value of destructive force $P_{cr}$.

4.2. Failure mode and cracking
The A-I series beams, in which the shear reinforcement provided the transfer of transverse forces, were destroyed in the compression zone by concrete crushing with wide cracks perpendicular to the element axis, caused by bending. The structural element carried the loads as long as the adhesion of concrete and steel was not exhausted - the elements reached the phase of successive cracks formation, in which the number of cracks increased. Cracks developed up to the neutral axis of beam and the longitudinal steel bars were responsible for stress transfer. At the limit state, the reinforcement in the cracked sections reached the yield point and the element was destroyed. The stirrups in the support zones ensured the transfer of shear stresses, and prevented the beams from destruction due to shear.

In the other series (A-II to A-V), in the majority of cases the failure due to shear occurred in the span, where the spacing of stirrups was reduced. There were diagonal cracks due to shear in the support zone. The morphology of these cracks formation is varied. At first, the perpendicular cracks appeared as a result of exceeding the tensile strength of concrete. Perpendicular cracks appeared much later in the case of elements made of concrete with basalt fibres, due to their greater tensile strength. Rapid loss of the bearing capacity occurred when the shear cracks were accompanied by cracks associated with the loss of bond between steel and concrete. In some of the tested elements, a phenomenon of reinforcement slip occurred, as evidenced by splitting cracks. The phenomenon was caused by the lack or reduced number of stirrups in a given zone. In most cases, the destruction of the elements is a typical shear compression failure or shear tension failure. In the case of a beam series in which a slip of reinforcement occurred, the opening of the first inclined crack significantly increased, and a series of small diagonal cracks appeared at the level of the main reinforcement, which indicated the bond failure between the main reinforcement and concrete.

The beams of concrete with basalt fibres showed quasi-plastic features. The cross-section still carried full load after the crack appeared. In the reinforced beams of concrete with basalt fibres, after exceeding the limit stresses there was no case of element failure due to concrete crushing. The presence of fibres allowed the development of multiple diagonal cracks and widening of at least one of them prior to shear failure, which provided some warning about the imminence of failure. The elements were destroyed by the extreme crack opening caused by pulling out steel fibres from cement matrix. The rate of element destruction depended on the content and shape of the fibres in the concrete. Models of concrete beams with basalt fibre after reaching their maximum load capacity were not subjected to violent destruction, as in the case of ordinary concrete beams. This process was slower but still had a brittle character. The crack width in case of the concrete element without fibres...
was greater in comparison to the beams of fibre reinforced concrete. Figure 3 presents the mode of failure of A-V-FB5.0 beam.

Figure 3. Failure mode of A-V-FB5.0 beam

4.3. Shear stress analysis

The dependencies presented in Figures 4 and 5 describe the influence of basalt fibre content on the shear stress, calculated on the basis of the shear force at failure $V_{ult}$ according to formula $\nu_u = V_{ult}/bd$. The values of stress were determined at three supports. The graphs show the dependence of shear stress on the volume fraction of basalt fibres in concrete (F0 - 0; FB2.5 - 0.095%; FB5.0 - 0.19%).

Analyzing the shear stresses at the central support, it can be concluded that in the case of a series of concrete beams with basalt fibre, the higher the fibre content in the concrete, the higher the stresses at failure. The largest relative increase in shear stress due to the effect of dispersed reinforcement was obtained for the A-IV-FB5.0 series in comparison to A-IV-F0 series.

Figure 4. Shear stress $\nu_u$ versus fibre content $V_f$ at the central support
Figure 5. Shear stress $\tau$ versus fibre content $V_f$ a) at the left support, b) at the right support

In the case of reactions at edge supports, the advantageous effect of basalt reinforcement can be observed in series A-II, A-III, A-V (for both left and right supports), where edge supports transferred higher values of transversal forces. The dispersed reinforcement most effectively cooperated in transferring the shear stress in the A-V-FB5.0 series. The destruction in this series occurred on the central support (in the direction to the left support), with cracks due to the slip on the upper reinforcement. Shear stress in the A-I series, in which a different course of the plot on both supports was observed, results from the redistribution of internal forces. These beams were destroyed by bending, with intensive cracking, which causes a decrease in the stiffness of the span cross section. The stresses were then transferred to a span with greater stiffness.

5. Conclusions

The research work was aimed at assessing the impact of basalt fibres in the amount of 2.5 and 5 kg/m3 on the changes in the failure mechanism of two-span reinforced concrete beams. Basalt fibres did not show any effect on compressive strength and modulus of elasticity of concrete. However, they improve the flexural strength up to 16%.

Incorporation of basalt fibers into concrete did not change the failure mode dramatically, but it had an effect on the course of destruction. The results of two-span beams’ tests revealed that the basalt fibers had a positive effect on the value of destructive force. Basalt fibers directly influenced the shear capacity of concrete beams. The obtained results confirm the potential possibility of using fibers to replace the stirrups partially. The combination of stirrups and fibers can improve both the ultimate and serviceability limit states. Analyzing the shear stresses on the central support of two-span beams, it can be concluded that in the case of basalt fiber series, the higher the fiber content in concrete, the higher the stresses at failure. As a result of the investigation carried out, a significant effect of basalt fibers on the cracking resistance was found. The moment of first crack appearance in the fiber reinforced beams occurred later than in the beam without fibers and it was related to their content. The increase in the amount of dispersed reinforcement caused the increase in value of cracking moment.

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